DOCTORAL THESIS

Implementation and Demonstration of a Device-to-Device Communication System for Emergency and Critical Scenarios

Ali Masood

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Implementation and Demonstration of a Device-to-Device Communication System for Emergency and Critical Scenarios

ALI MASOOD

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree elsewhere.

Ali Masood

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Contents

List of Publications

The present Ph.D. thesis is based on the following publications that are referred to in the text by Roman numbers.

I Ali Masood, Navuday Sharma, M Mahtab Alam, Yannick Le Moullec, Davide Scazzoli, Luca Reggiani, Maurizio Magarini, and Rizwan Ahmad. Device-to-device discovery and localization assisted by UAVs in pervasive public safety networks. In *Proceedings of the ACM MobiHoc workshop on innovative aerial communication solutions for FIrst REsponders network in emergency scenarios*, pages 6–11, 2019

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III Ali Masood, Muhammad Mahtab Alam, and Yannick Le Moullec. Experimental characterization of ProSe direct discovery for emergency scenarios. In *2021 IEEE 7th World Forum on Internet of Things (WF-IoT)*, pages 891–896. IEEE, 2021

IV Ali Masood, Muhammad Mahtab Alam, Yannick Le Moullec, Luca Reggiani, Davide Scazzoli, Maurizio Magarini, and Rizwan Ahmad. ProSe direct discovery: experimental characterization and context-aware heuristic approach to extend public safety networks lifetime. *IEEE Access*, 9:130055–130071, 2021

V Ali Masood, Muhammad Mahtab Alam, and Yannick Le Moullec. Direct Discovery-based Cooperative Device-to-Device Communication for Emergency Scenarios in 6G. In *2022 European Conference on Networks (EuCNC) and Communications 6G Summit (Accepted)*. IEEE, 2022

Author's Contributions to the Publications

I In I, I was the main author, supported to carry out the simulations related to D2D discovery, analysed the results, prepared the figures, and wrote the manuscript except for the localization section (paper section: "4.1 Signal scanning and localization").

II In II, I was the main author, prepared the figures, wrote the sections related to D2D communications and wrote the manuscript.

III In III, I was the main author, developed a sidelink testbed to perform D2D direct discovery in the absence of base stations. I conducted performance evaluation experiments of direct discovery using developed testbed in real-time heterogeneous environments. I analysed the results, prepared the figures, and wrote the manuscript.

IV In IV, I was the main author, proposed an algorithm to perform energy-efficient and context-aware D2D direct discovery for PS scenarios. I conducted experiments and simulations. I analysed the results, prepared the figures, and wrote the manuscript.

V In V, I was the main author, proposed an application for technologies such as clustering, UE-UE-relay, UAVs and context-aware D2D communication to disseminate up-to-date important information (e.g., the number of people, their IDs and current locations) from an affected zone to external command center deployed by first responders. I performed the deployments, analysed the results, prepared the figures, and wrote the manuscript.

Abbreviations

2G	Second Generation cellular network
3G	Third Generation cellular network
4G	Fourth Generation cellular network
5G	Fifth Generation cellular network
A2G	Air-to-Ground
ABSOLUTE	Aerial BSs with Opportunistic Links for Unexpected and Temporary Events
ACK	Acknowledgement
B5G	Beyond 5G
BS	Base Stations
BSA-D2D	Base Station Aided D2D communication
CA	Carrier Aggregation
CAM	Cooperative Awareness Messages
CODEC	Cellular netwOrk baseD d2d WirEless Communication
COTS	Commercial-Off-The-Shelf
COUNTER-TERROR	COmmUNication in conTExt Related to Terror Attacks
CU	Cellular Users
D2D	Device-to-Device
D2D	Device-to-Device
DENM	Decentralized Environmental Notification Messages
DL	Downlink
DMRS	Demodulation Reference Signals
DNS	Domain Name System
EC	European Commission
FDD	Frequency Division Duplex
FP7	Framework Programme 7
Gbps	Gigabits-per-second
H2020	Horizon 2020
HSS	Home Subscriber Server
ICT	Information and Communication Technologies
KPIs	Key Performance Indicators
LCMSSER	Location-based Control and Management System for Safety and Emergency Rescuing
LMRS	Land Mobile Radio System
LoS	Line-of-Sight
LTE	Long-Term Evolution
MCN	Multilayered Communication Network
MCS	Modulation and Coding Scheme
METIS	Mobile and wireless communications Enablers for Twenty-twenty Information Society
MIB-SL	Master Information Block SL
MINLP	Mixed-Integer-Non-Linear Programming
MME	Mobility Management Entity
NACK	Negative-Acknowledgement
NATO	North Atlantic Treaty Organization

NICER	Networked Infrastructure-less Cooperation for Emergency Response
NIST	National Institute of Standards and Technology
NLoS	Non-Line-of-Sight
NPSTC	National Public Safety Telecommunications Council
NR	New radio
NR	New radio
NUC	Next Unit of Computing
OAI	OpenAirInterface
OSA	OAI Software Alliance
OS-A	On-Scene Available
PDCCH	Physical Downlink Control Channel
PER	Packet Error Rate
PF	Proportional Fair
PLMN	Public Land Mobile Network
PRBs	Physical Resource Blocks
ProSe	Proximity Services
PS	Public Safety
PSBCH	Physical Sidelink Broadcast Channel
PSCCH	Physical Sidelink Control Channel
PSDCH	Physical Sidelink Discovery Channel
PSFCH	Physical Sidelink Feedback Channel
PSN	Public Safety Network
PSS	Pervasive Spectrum Sharing
PSSCH	Physical Sidelink Shared Channel
PSSS	Primary Sidelink Synchronization Signal
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QoS	Quality of Service
R&D	Research and technological Development
RL	Reinforcement Learning
RSUs	Road-Side Units
Rx	Receiver
SARSA	State Action Reward State Action
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SCI	Sidelink Control Information
SINR	Signal-to-Interference-plus-Noise Ratio
SL	Sidelink
SLSS	Sidelink Synchronization Signals
SLSS ID	SLSS Identification
SNR	Signal-to-Noise Ratio
SPS	Science for Peace and Security
S-RSRP	Sidelink Reference Signal Received Power

SSSS	Secondary Sidelink Synchronization Signal
SyncRef	Synchronization Reference
TDD	Time Division Duplex
TETRA	TErrestrial Trunked RAdio
Tx	Transmitter
UAV4PSC	UAV-Assisted heterogeneous networks FOR Public Safety Communications
UAVs	Unmanned Aerial Vehicles
UICC	Universal Integrated Circuit Card
UL	Uplink
URLLC	Ultra-Reliability Low Latency Communication
V2X	Vehicle-to-Everything

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1 Introduction

Today wide-area wireless communication systems are broadly divided into two main groups: commercial cellular networks and emergency and critical wireless communication systems or dedicated public safety networks (PSN) [6]. Commercial cellular networks are designed according to the needs of a customer and business point of view. Whereas, PSNs provide communication to first responders or public safety services like police, law enforcement agencies, fire department, etc. [6].

Commercial cellular networks have been attracting global investment and RD activities for over two decades, leading to excellent and rapid innovation in commercial cellular systems. This community has grown steadily and developed advanced standards such as 2G, 3G, 4G, and 5G. 5G networks provide high multi gigabits per second (Gbps) peak data rate, large network capacity, and highly reliable low latency communication (URLLC). Whereas PSNs have importance both socially and economically. Unfortunately, the PSNs are not able to attract the same level of investment and RD activities. As a result, PSNs are not advanced as commercial networks. Generally, PSNs provide communications in public safety (PS) scenarios [6].

1.1 Public safety scenarios

Each year, thousands of people suffer because of disasters and this situation worsens if first responders or public safety services are not able to take proper actions on time. Any emergency situation can be referred to as a disaster that can affect routine procedures causing deaths, illness, injuries and property damage [7, 8]. For classification purposes, disasters are generally categorized into two main groups: natural and man-made disasters. Both of them can be further divided into different subgroups [9, 10], as shown in Fig. 1.

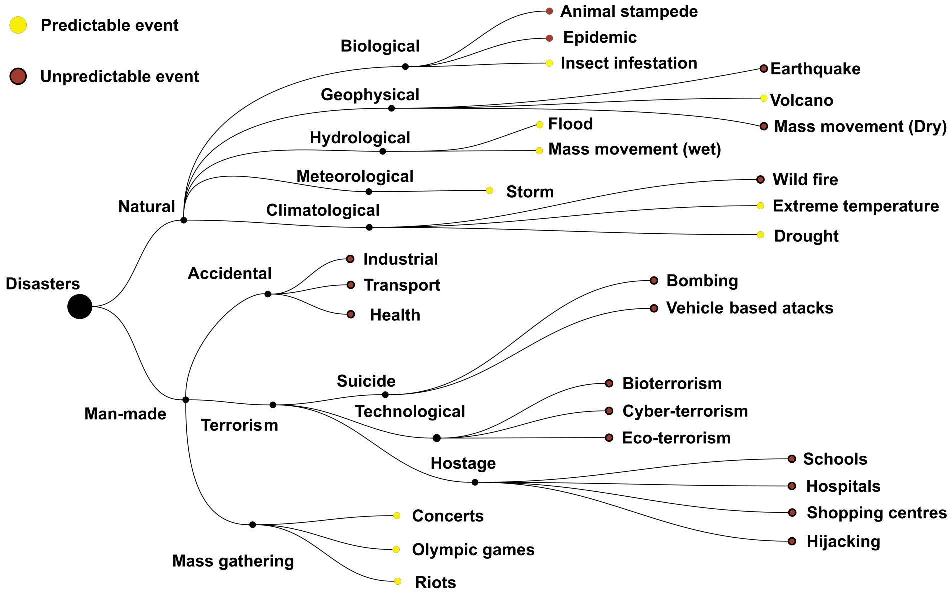

Figure 1: A taxonomy of disaster types [2].

1.1.1 Natural disasters

People depend on key facilities for ensuring viable and safe societies; such facilities include e.g. transportation systems, energy and fuel subsistence systems, information and communications infrastructure, schools, hospitals, emergency rescue services, etc. [11, 12]. It is observed that natural disasters can disable some of the key infrastructure facilities in affected areas up to 72 h or even longer, which not only threatens the lives of people but can also isolate such areas from the outside world [13]. Risk management techniques help to manage natural disasters, estimating which areas will become isolated or not [14]. Studies assess the conditions of key facilities before, during, and after disasters, which can help to manage and reduce their consequences [15, 16, 17]. It is worth observing that people often use social media platforms to request aid during natural emergencies [18, 19]. While the information shared on social media is very ambiguous. Different machine learning methods have been proposed that could differentiate between spam and clear signal, thus allowing to identify who actually needs aid [20, 21]. More details about natural disasters can be found in [2].

1.1.2 Man-made disasters

Man-made disasters are the consequence of different human actions. Man-made disasters can be broadly categorized into three main subgroups: accidental, mass gathering and terrorism [22]. Accidental disasters are caused by human error, negligence, and technological failure. For instance, fires, industrial and transport accidents, structural failures and collapses, and nuclear explosions or radiation. Many studies on risk assessment propose quantitative, qualitative, and hybrid techniques to examine and assess risk solutions to avoid such events [23, 24]. A mass gathering is an event for a common purpose when a large number of persons come close together at one place; it can take place indoor or outdoor environments. The gathering could be organized for a defined period, be instantaneously motivated by participants or organizers, or be due to an emergency situation [22]. Terrorism is the deliberate use of violence for creating fear in order to achieve political and social objectives. Terrorist activities are diversified, having a large range of targets, including citizens, government officials, law enforcement officers, public buildings, or government buildings [25]. Terrorism can be further categorized into three main types: suicide attacks, technological attacks, and hostage situations. More details about man-made disasters can be found in [2].

1.2 Main challenges for the first responders in PS scenarios

The emergency scenarios, i.e. man-made and natural disasters, are broadly classified into two types of events: predictable and unpredictable, as illustrated in Fig. 1. In predictable emergency scenarios, public safety services can foresee the severity of potential damage; and have a reasonable time to prepare for and respond to the expected disaster. PS services prepare an effective strategy organizing resources and put high efforts into reducing the impact of a disaster. The prior planning ensures a well-organized response to provide quick disaster relief during and after a disaster. The main goal of PS services is to provide quick relief that can protect people, animals and infrastructures as well. Disaster relief can include medical assistance, search and rescues operations, evacuations, etc. For instance, in a predictable man-made disaster that could take place during a mass gathering (e.g. protest, strike, etc.), PS services arrange additional police force to provide security and safety arrangements for the crowd and ensure avoiding any undesired incident. Fire and rescue teams are also fully prepared to meet any incident. In a predictable natural disaster, for example, floods, rescue teams evacuate the possible affected area for prevention.

Generally, during or after the predictable emergency incident, damaged infrastructure is a major cause of the formation of isolated areas and the main factor that slows down the rescue process. The emergency rescue teams can gain access to the disaster site (e.g. using rescue boats and helicopters) with a slight or without direct life threat and provide disaster relief immediately.

On the other hand, in unpredictable emergency scenarios, public safety services may not get enough time for prior planning to reduce the impact of a disaster that is due to the abruptness of the incident. Thus, a great amount of effort has to be put into disaster prevention to reduce the impact of a disaster and relief phase to speed up the rescue process. Typically, wildfires and earthquakes are considered unpredictable natural disasters. Human failures and terrorist attacks are common examples of unpredictable man-made disasters. For instance, in the case of terrorist attacks, rescue and law enforcement teams cannot immediately step into a disaster zone to counter the situation because of serious life threats, unclear information and situational facts (i.e., number of terrorists, their positions, the number and type of weapons used and severe consequences, etc.) Thus, the response time for disaster relief becomes very long.

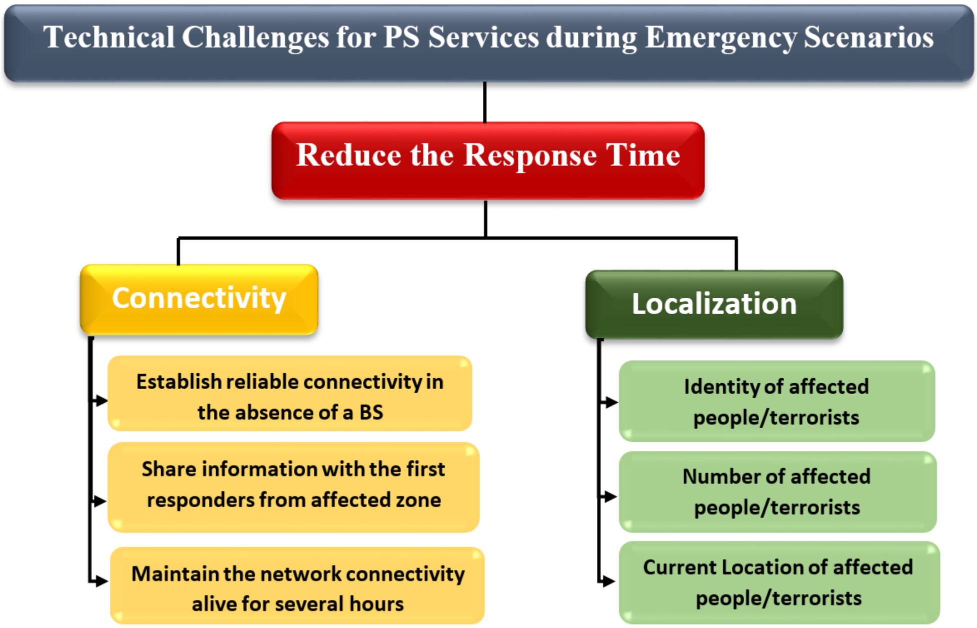

Figure 2: Technical challenges for PS services during emergency scenarios [2].

It is observed in emergency scenarios (e.g. earthquakes, floods, terrorist attacks) that the availability of the cellular base stations (BS) cannot be guaranteed and is often unavailable due to e.g. physical damages. Thus, people who are stuck inside the affected zone cannot communicate with first responders. The first responders do not obtain the basic but important information such as the number of affected people, their locations and identity, etc. Due to unclear information, the first responders remain unable to take immediate actions to provide relief, even after many hours. Consequently, the response time may become very long [7, 26]. The main challenges for the first responders from an information and communication technologies (ICT) point of view in such incidents are to establish reliable connectivity in the absence of a BS, obtain up-to-date critical information with the first responders, disseminate the critical information from the affected zone to the external deployed command centre, and maintain the network connectivity alive for several hours [2], as illustrated in Fig. 2. However, existing classical PSNs are not designed to deal with these challenges and cope with the first responders during disaster situations to speed up the rescue process.

1.3 Existing public safety networks

PSNs can play a significant role to save lives and infrastructure. However, existing PSNs are not best suited for emergency scenarios (e.g. floods, earthquakes, terrorist attacks, etc.) because BSs may not be available. Whereas, a proper communication infrastructure is required for the classical PSNs to operate. Existing PSNs can be broadly classified into two categories: Land mobile radio system (LMRS) and broadband networks [27, 28].

LRMS networks is a legacy technology that has been used for communications in PS scenarios for decades. LRMS is a narrowband wireless technology. LMRS networks are being used mainly in military and PS applications to provide voice and data communications for a mission-critical response. Project 25 and TErrestrial Trunked RAdio (TETRA) standards are used for LMRS based digital radio wireless communications. Project 25 also known as P-25 or APCO-25, is used by PS services and government agencies in North America. Whereas, TETRA provides the same services in European and Asian countries.

Broadband networks allow high data rates and highly reliable low latency communication applications, which cannot be supported by LMRS networks. With steady evaluation of broadband network, the American national public safety telecommunications council (NPSTC) along with other organizations decided to use long-term evolution (LTE) standard for next-generation PSNs in 2009. The 700 MHz band has reserved for LTE based PS communications in 2012. After this decision to use LTE, the NPSTC started a strong collaboration with the third generation partnership project (3GPP) to evolve the LTE standard while introducing new features required for PS communications. The objective of 3GPP standardization is to establish a common standard with maximum technical commonalities for both commercial cellular networks and PSNs, which will benefit both communities.

To enable PS applications, the 3GPP proposed proximity services (ProSe), initially in Release 12, to enable D2D communication especially for PS scenarios over a new interface called sidelink PC5. ProSe provides mainly two services to enable D2D communication over sidelink interface: ProSe direct discovery and ProSe direct communication. Chapter 2 provides a detailed description of D2D communication and the evolution of D2D communication in 3GPP.

1.4 Why D2D communications for PSNs?

Device-to-device (D2D) communication supports both commercial and PS applications. The application of PS is considered one of the most essential applications of D2D communication. D2D communication allows direct communication between two user equipment (UEs) or on-scene available (OS-A) in proximity regardless of the availability of a cellular BS [29].

D2D communication can operate in three different scenarios, as illustrated in Fig. 3: in-coverage, partial coverage, and out-of-coverage [30]. In the in-coverage scenarios, UEs are inside the radio coverage of a BS and they are assisted by that BS to perform D2D communication. The BS assigns the resources and shares the synchronization signals with the UEs. Network-assisted D2D communication decreases the interference and improves the quality of service (QoS), but increases the burden on the BS [31]. In a partial coverage

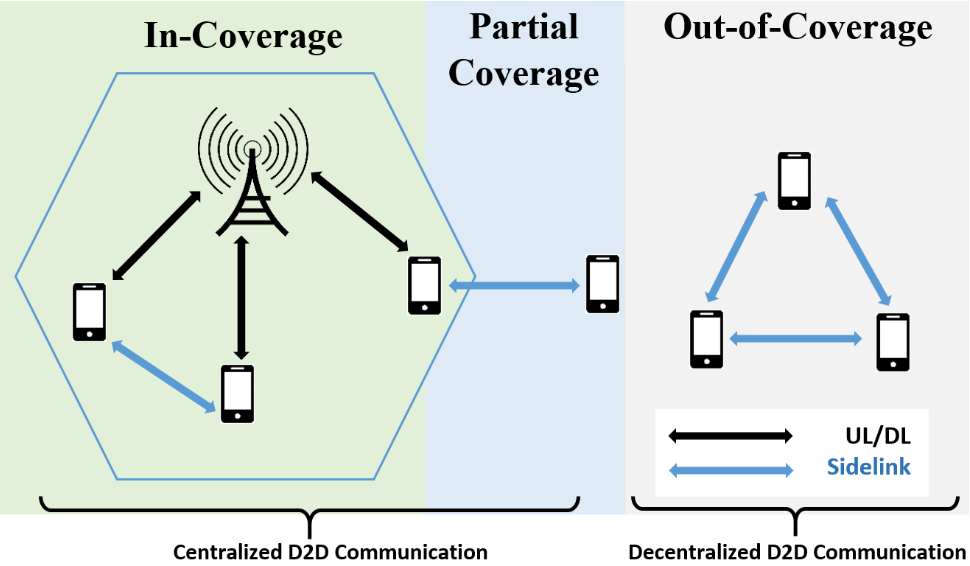

Figure 3: Visualization of the D2D communications in three different scenarios.

scenario, an out-of-coverage or remote UE is assisted by another UE within the radio coverage of a BS to perform D2D communication [32]. Finally, in an out-of-coverage scenario, UEs are outside the radio coverage of a BS. Remote UEs use pre-configured parameters to perform D2D communication [30].

D2D communication can play a significant role to design future reliable PSNs. It is envisioned in emergency scenarios that on-screen available devises such as smartphones, which have D2D-enabled features, can be exploited to provide up-to-date crucial information to first responders from the affected zone.

1.5 Problem statement and Research Questions

In emergency scenarios (e.g. earthquakes, terrorist attacks, fires, etc.), first responders do not get enough time for prior planning to reduce the impact of a disaster and provide disaster relief. It is observed is such situations that the BSs are often unavailable due to physical damages. Therefore, affected people are not able to communicate with first responders. As a result, the first responders remain unable to take immediate actions to provide disaster relief, even after many hours, due to unclear information such as the number of affected people, their locations and identity, etc. Consequently, the response time may become very long. From ICT point of view, the main challenges for first responders in such emergency scenarios are to establish reliable connectivity in the absence of a BS, locate affected people inside the emergency zone, get up-to-date important information from the emergency zone, and maintain the network connectivity alive for several hours.

Therefore, the main goal of my PhD work is to propose an autonomous solution for PSNs to overcome the aforementioned challenges. In this PhD thesis, I address the following research questions (RQ):

1. RQ1: What architecture can provide fundamental information to first responders in emergency scenarios? i.e., what enabling technologies are required to disseminate

the critical information from the affected zone to first responders?

2. RQ2: How to create a real-time heterogeneous environment for D2D communication performance analysis when the base stations are not available and what are the suitable parameters to obtain reliable connectivity and maximum range in such a scenario?

3. RQ3: In out-of-coverage scenarios, a D2D-enabled UE transmits the discovery messages with a fixed period. A UE will keep transmitting the messages even if the first responder has already discovered it, or UE does not have any new information to transmit. If a UE transmits redundantly it will consume more energy, and eventually, it will die out swiftly in the network. Hence, how to avoid redundant transmission of information and optimize the communication to improve the lifetime of the network significantly without compromising on the reliable transmission of critical information?

4. RQ4: How to implement autonomous, energy-efficient, context-aware and intelligent PSN to provide up-to-date critical information in a few minutes (as a response time) to first responders in emergency scenarios; and demonstrate it in a real-life scenario?

1.6 Thesis contribution

I select an applied research method to overcome the aforementioned challenges faced by first responders and propose an autonomous solution for PSNs from an ICT point of view. This PhD thesis makes the following contributions:

1. Contributing towards RQ1, A comprehensive descriptive analysis of PS scenarios, D2D communications, evolution of D2D communications in 3GPP, existing PSNs, recent related funded Projects and the emerging techniques for future PSNs has been presented in [Publication I and Publication II]. This contribution helps me in order to understand the challenges faced by first responders in emergency scenarios, as well as, how to develop the future PSN which can cope with first responders during emergency scenarios and speed up the disaster relief.

2. Then, I have developed a hardware/software testbed to perform ProSe direct discovery-based D2D communication in the absence of BS. Experimental measurements have been carried out to characterize the performance of ProSe direct discovery in real-time heterogeneous environments. The experimental data have been collected in order to evaluate the baseline performance of direct discovery in terms of reliability of successful discovery message reception, and maximum discovery range in three different scenarios: i) indoor line-of-sight (LoS), ii) indoor non-line-of-sight (NLoS), and iii) outdoor (LoS). The experimental results highlight the impact on the direct discovery due to the carrier frequency, transmission power, transmitter (Tx) and re-ceiver (Rx) gains, the distance between transmitter and receiver in heterogeneous scenarios [Publication III]. These contributions are in line with RQ2.

3. Contributing towards RQ3, I have proposed an energy-efficient and context-aware intelligent algorithm for direct discovery based on the current position and battery level of a UE [Publication IV]. Which can help first responders to locate and trace the affected UE in emergency scenarios. The proposed algorithm avoids redundant transmissions without compromising the transmission of critical information, and

enhances significantly the lifetime of UEs (20-52%) in the D2D network compared to the baseline approach.

4. Furthermore, I suggest a novel architecture based on context-aware ProSe direct discovery along with unmanned aerial vehicles (UAVs) as a possible solution to implement the future PSN in beyond 5G, as shown in Fig. 4. I propose an application for technologies such as clustering, UE-UE-relay, UAVs and context-aware D2D communication to disseminate up-to-date important information (e.g., the number of people, their IDs and current locations) from an affected zone to external command center deployed by first responders. I present an empirical demonstration of cooperative D2D communication in PS real-life scenarios wherein cellular BSs are nonfunctional. In addition, I analyse the performance of implemented prototype in terms of reliable connectivity and latency [Publication V]. Under specific emergency scenarios, the impact of this work is that it is possible to deploy the equipment, establish connectivity, and pass information from the affected zone to deployed command center in approximately one minute and forty seconds in a real-time lab environment, and four minutes and thirteen seconds in a real-life outdoor scenario. These contributions are aligned with RQ4.

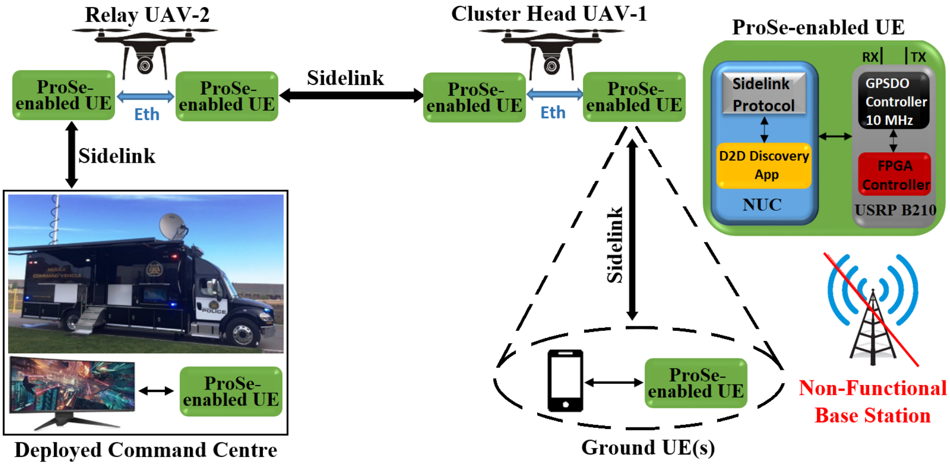

Figure 4: Suggested novel architecture for UAV and D2D communication assisted public safety network for emergency scenarios wherein cellular BSs are non-functional

1.7 Thesis organization

The remainder of this PhD thesis is organized as follows.

- Chapter 2: This chapter provides the overview of D2D communication, and the evolution of D2D communication in 3GPP standards starting from initial Release 12 to the latest Release 17. This chapter also discusses ongoing research on D2D communications and recent related projects for PSNs. Furthermore, emerging communication technologies to develop next-generation PSNs are discussed in this chapter. Finally, this chapter highlights the contributions of my research work to position this PhD thesis.

- Chapter 3: This chapter provides a description of the developed setup to perform D2D direct discovery for out-of-coverage scenarios. Different indoor and outdoor scenarios are discussed to carry out the measurement campaign. The empirical measurement results are presented to analyze the performance of ProSe direct discovery in real-time heterogeneous environments.

- Chapter 4: This chapter proposes a context-aware energy-efficient algorithm for sidelink direct discovery in emergency scenarios. The description of the proposed approach is given, and the performance of the proposed algorithm is evaluated and compared to the baseline discovery approach.

- Chapter 5: This chapter suggests a novel architecture, for PS communications in out-of-coverage emergency scenarios, as a possible solution to develop future PSNs. This chapter provides a description of a developed prototype to perform cooperative D2D communication in PS real-life scenarios and to share up-to-date important information with first responders. Furthermore, this chapter presents the empirical demonstration of cooperative D2D communication in PS real-life scenarios to share up-to-date important information with first responders. Finally, this chapter analyses the performance of implemented prototype in terms of reliable connectivity and latency.

- Chapter 6: Summary of this thesis, concluding remarks, and possible future directions are given in this chapter.

2 D2D Communication Overview, Evolution of D2D Communication in 3GPP and State-of-the-Art

This chapter is based on the following two publications:

- Ali Masood, Navuday Sharma, M Mahtab Alam, Yannick Le Moullec, Davide Scazzoli, Luca Reggiani, Maurizio Magarini, and Rizwan Ahmad. Device-to-device discovery and localization assisted by UAVs in pervasive public safety networks. In Proceedings of the ACM MobiHoc workshop on innovative aerial communication solutions for FIrst REsponders network in emergency scenarios, pages 6–11, 2019.

- Ali Masood, Davide Scazzoli, Navuday Sharma, Yannick Le Moullec, Rizwan Ahmad, Luca Reggiani, Maurizio Magarini, and Muhammad Mahtab Alam. Surveying pervasive public safety communication technologies in the context of terrorist attacks. Physical Communication, 41:101109, 2020.

2.1 D2D Overview

For the first time, the 3GPP proposed ProSe to enable D2D communication in Release-12 of LTE standardization. A new interface has been introduced for D2D communication, called sidelink (SL). In classical cellular networks, the BS uses two interfaces, uplink (UL) and downlink (DL), to communicate with a UE. This new additional interface, sidelink, enables direct communication between UEs with or without the help of BS, as illustrated in Fig. 3. Sidelink uses the resources allocated for uplink transmission. The reason to use the uplink spectrum is that most of the subframes on the DL are always occupied, and the subframes on the UL are generally available [33]. Only ProSe-enabled UEs can support the ProSe functionalities. ProSe provides two main functionalities: ProSe discovery and direct communication. ProSe discovery is a process that identifies services and detects other UEs in their proximity. Direct communication allows two devices to share data with each other in proximity [34].

Several new nodes and interfaces have been introduced in the network to enable D2D communication. The most important interfaces are PC5, which is between two UEs, and PC3, which connects the UEs with ProSe Function [35]. The basic architecture for sidelink-based D2D communication is shown in Fig. 5.

The ProSe function is a logical function, which provides information to UE to perform direct discovery and communications using the PC3 interface. A public land mobile network (PLMN) has only one ProSe Function. A UE could have the ID address of the ProSe Function as hard-coded. Otherwise, a UE uses a domain name system (DNS) to find the IP address of the ProSe Function. A UE has to establish an RRC connection (RRC_CONNECTED state) to communicate with ProSe Function. The ProSe Function shares the authorization policy and provisioning of PLMN information. A UE sends a request to ProSe Function in a local PLMN to provide an authorization policy. This authorization policy also has the information, whether the UE is allowed to perform D2D communication in the out-of-coverage scenario or not. Whereas, the provisioning of PLMN information contains the parameters like security guidelines, IP addresses, radio parameter configurations, etc. On the other hand, for public safety-enabled UEs, these parameters are preconfigured either in the UEs or universal integrated circuit card (UICC). If both have preconfigured information, then the information from the UICC has priority [35, 34].

Further, the ProSe application server distributes services to different ProSe applications and maps the UEs to individual functions. The ProSe application server is connected

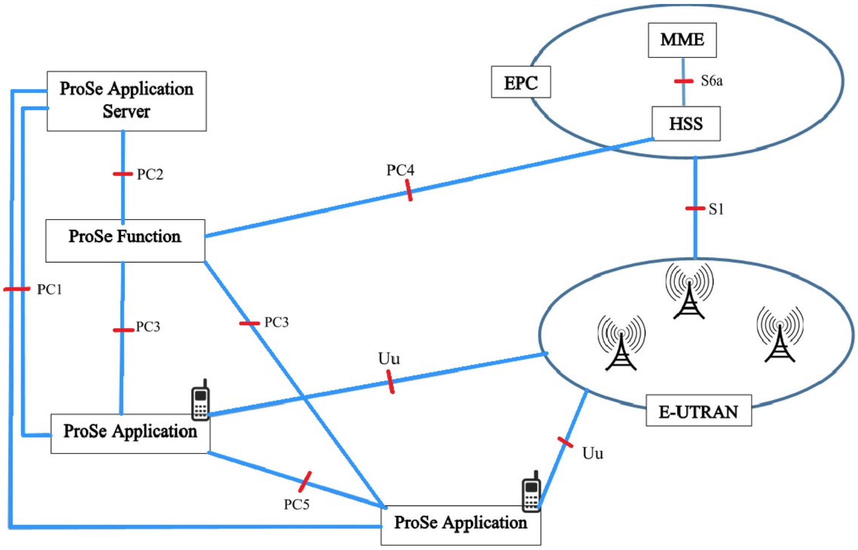

Figure 5: The basic architecture for sidelink-based D2D communication.

to the ProSe function via a PC2 interface, which is responsible for enabling interaction between the two entities, as given in [35, 34].

Besides new nodes, the home subscriber server (HSS) and mobility management entity (MME) should also be enhanced in order to authorize user information regarding ProSe services. To accomplish this, a new interface, PC4, has been introduced in [35, 34] and is shown in Fig. 5.

2.2 Evolution of D2D communication in 3GPP

The evolution of D2D communications in 3GPP is shown in Fig. 6. In cellular networks, the concept of D2D communication was initially introduced in Release12 of the 3GPP LTE standardization, referred to as ProSe [35]. D2D communications in Release 12 focus on PS. ProSe communications provide broadly two main features using sidelink interface: ProSe direct discovery and ProSe direct communication. To perform ProSe based communications, all the UEs have to follow the same timing reference to be synchronized. One UE has to transmit synchronization signals and other UEs will receive these signals. After synchronization, UEs can perform direct discovery or direct communication. Release 12 only allows D2D communication in out-of-coverage scenarios, which cannot be supported by BS. While it is highly desired and required for a UE to access the BS if it is available. To overcome these challenges, Release 13 enhanced ProSe services and introduced UE-to-network reply in the ProSe. This allows out-of-coverage UE to access the BS using the sidelink interface. The in-coverage UE assists the out-of-coverage UE located in its proximity and relays the information to the BS [34].

Starting from Release 14, the 3GPP platform further evolved for the automotive industry to support the basic road safety services, and such type of D2D communication is referred to as LTE-based vehicle-to-everything (V2X) services. In Phase 1 of the V2X services, vehicle-based UEs share cooperative awareness messages (CAM) and decentralized environmental notification messages (DENM) to share information about their status (such as speed, position, and heading) with other neighbouring vehicles, pedestrians, and

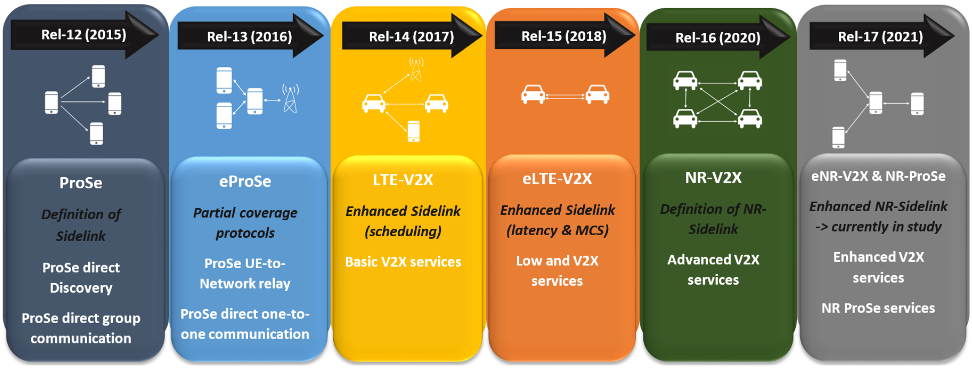

Figure 6: The evolution of D2D communication in 3GPP.

roadside units (RSUs) using the downlink, uplink, and sidelink interfaces [36, 37]. Phase 2 of the V2X services further expanded in Release 15 and enhanced sidelink communication by including new features such as sidelink carrier aggregation (CA), transmission diversity, and 64 quadrature amplitude modulation (QAM) to improve throughput and latency [38, 39].

In Releases 12-15, the D2D communications are based on the LTE network. Then Release 16 introduced the new radio (NR) sidelink to fulfil the requirements of the fifth-generation (5G) mobile network. Release 16 mainly targets V2X and standardises phase 3 of V2X services. Release 16 has defined the NR sidelink transmission and added new use cases for NR V2X services. The use cases are advanced driving, vehicle platooning, exchange of extended sensor information, and remote driving [40, 41, 42]. Phase 3 of V2X services demands high reliability, low latency, high throughput, and massive connectivity. To meet the requirements of Phase3, many new enhancements have been introduced to NR sidelink communication, for example, I) LTE V2X just supports broadcast transmission, whereas, NR sidelink supports broadcast, unicast and groupcast transmissions. II) A new feedback channel has been added in sidelink transmission that carries hybrid automatic repeat request (HARQ) feedback, named as physical sidelink feedback channel (PSFCH). The receiving UE shares the information about decoding status in form of acknowledgement (ACK) or negative-acknowledgement (NACK) on the PSFCH channel. III) Grant-free transmission protocol has been added in NR sidelink transmission to improve the latency and massive connectivity. IV) physical sidelink control channel has been modified in NR sidelink transmission to improve the channel sensing and resources allocation procedures.

Release 17 is expected to introduce several key features in V2X communication, e.g. extremely coverage enhancements, exceptionally energy efficient, highly intelligent, markedly context-aware and enormously reliable, and a new use case for ProSe services, i.e. UE-to-UE relay [43].

Release 12 and 13 enable ProSe based D2D communication to support mainly applications for PSNs. Whereas from Releases 14-16, the 3GPP provides communications for commercial cellular networks. Although, the main goal of this PhD thesis is to provide an innovative solution for PSNs to provide communications when BS are not available. Which will help the first responders to collect critical information from the affected zone, speed up the rescues process and reduce the response time. Therefore, this PhD thesis has emphasised the ProSe based D2D communication to address the challenges faced by first responders.

As mentioned earlier, ProSe provides two main functionalities: ProSe discovery and direct communication. Before performing ProSe based communications, all the UEs have to synchronize first.

2.2.1 Sidelink synchronization

Synchronization is essential in order to perform D2D communication over sidelink interface. All UEs have to synchronize to get the necessary timing and frequency information, and they must settle on the same system information utilized in the communication process such as subframe indication, bandwidth, etc. Therefore, the same synchronization reference (SyncRef) must be followed by UEs. For in-coverage scenarios, the BS provides the required information to start Synchronization. However, for out-of-coverage scenarios, the UEs use preconfigured parameters for synchronization [44, 45].

A SyncRef source transmits the sidelink synchronization signals (SLSS) periodically after every 40ms, and the synchronization subframe has six physical resource blocks (PRBs). A synchronization subframe has four types of synchronization signals: demodulation reference signals (DMRS), secondary sidelink synchronization signal (SSSS), primary sidelink synchronization signal (PSSS), master information block SL (MIB-SL) composed in the physical sidelink broadcast channel (PSBCH) [46], as shown in fig. 7.

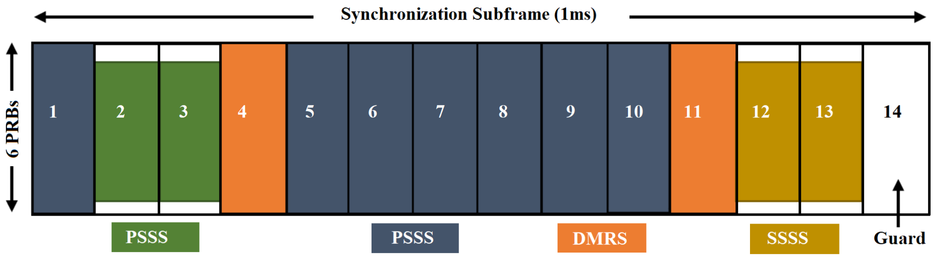

Figure 7: The sidelink synchronization subframe in ProSe services.

The PSSS and SSSS give the essential timing and frequency information for synchronization. Both PSSS and SSS have two adjacent single-carrier frequency division multiple access (SC-FDMA) symbols in the time domain and 62 resource elements in the frequency domain. The Zadoff–Chu sequences and m-sequences are used to generate PSSS and SSSS signals. The PSSS and SSSS also identify the SyncRef source by encoding the SLSS identification (SLSS ID). The SLSS ID may have a value between 0-335. If a value of SLSS ID is between 0-167, which means that the SyncRef source is inside the coverage range of a BS. Otherwise, the SyncRef source is in an out-of-coverage scenario. The PSBCH has the master information block-SL, which carries the systematic information required for synchronization at frame and subframe levels. MIB-SL provides information about carrier bandwidth, TDD configuration, frame number and subframe number. The DMRS signals measure demodulation of the PSBCH, channel estimation and sidelink reference signal received power (S-RSRP) at the receiving UE. The S-RSRP shows the received signal strength of a SyncRef source [46].

The general steps for sidelink synchronization are as follows, also illustrated in Fig. 8:

- A ProSe-enabled UE always tries to find a SyncRef source.
- If no SLSS signals are found from any SyncRef source, then the UE will become an independent SyncRef source. This SyncRef UE will use pre-configured parameters

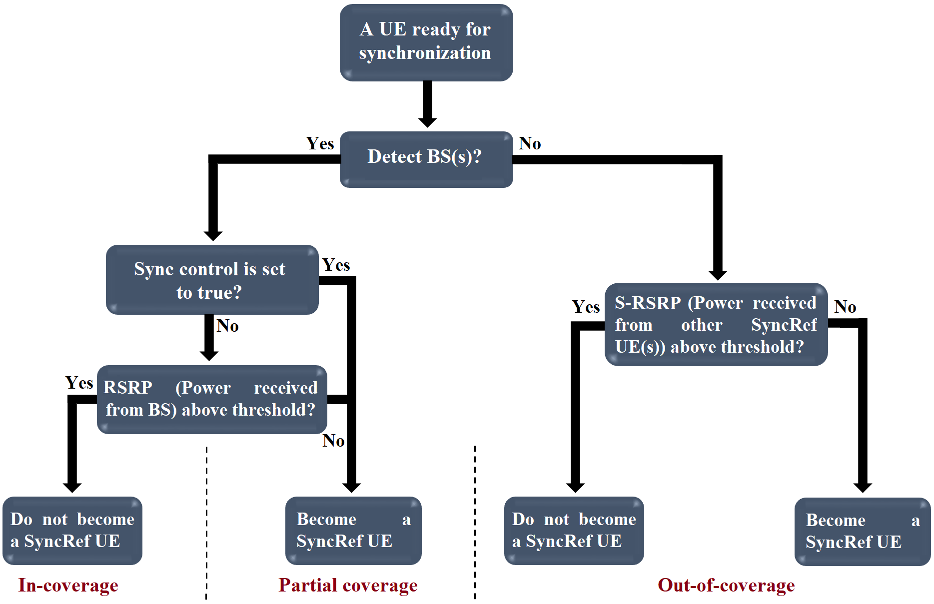

Figure 8: The general steps for sidelink synchronization.

to transmit the SLSS and establish a D2D network in the out-of-coverage scenario.

- If a UE detects SLSS signals sent by BS in the in-coverage scenario, then the BS will become SyncRef source and the UE will synchronize with BS to perform sidelink communication.

- If a UE detects SLSS signals from an in-coverage UE, then the out-of-coverage or remote UE will synchronize with in-coverage UE (SyncRef source). In partial coverage scenarios, a BS can also allow the in-coverage UE, who is at the edge of the BS coverage, to become a SyncRef source. The in-coverage UE acting as a SyncRef source relays the SLSS of the BS to out-of-coverage UE to connect it with the BS.

A ProSe-enabled UE may receive synchronization signals sent by multiple SyncRef sources. In such cases, a UE checks the priority level of the SyncRef sources. The synchronization signals sent by BS have a higher priority than the in-coverage UE acting as a SyncRef source. While SyncRef UE in the out-of-coverage scenario has the lowest priority. If a UE does not have any SyncRef source, then a UE will synchronize with the SyncRef source who has the highest priority. Whereas, if a UE already has a SyncRef source, a UE will follow the same priority criteria to reselect the SyncRef source. However, if both current and new SyncRef sources have the same priority level, then a UE will measure the signal strength of both SyncRef sources. Eventually, it will synchronize with the SyncRef source that has a strong signal level strength [47].

2.2.2 ProSe direct discovery

Direct discovery allows ProSe-enabled UEs to detect the services or detect the other ProSe-enabled UEs located in proximity. ProSe discovery is a broadcast service. A UE transmits the discovery messages periodically and the other UEs monitor the discovery messages to discover the announcing UE on the physical sidelink discovery channel (PSDCH). Periodicity could be up to 10.23 seconds, depending on the application. ProSe supports network-assisted discovery, partial network-assisted discovery and direct discovery. Both network-assisted discovery and partial network-assisted discovery get assistance from a BS to perform ProSe discovery, while UEs use preconfigured information to perform direct discovery in out-of-coverage PS scenarios [48].

Before starting ProSe discovery, UEs have to take authorization from ProSe Function. The ProSe Function informs whether the requested UE can transmit the discovery messages, receive the discovery messages, or both. Whereas, the out-of-coverage UEs in PS scenarios used pre-configured parameters stored either in the device or in UICC. After authorization, UEs can transmit and receive discovery messages.

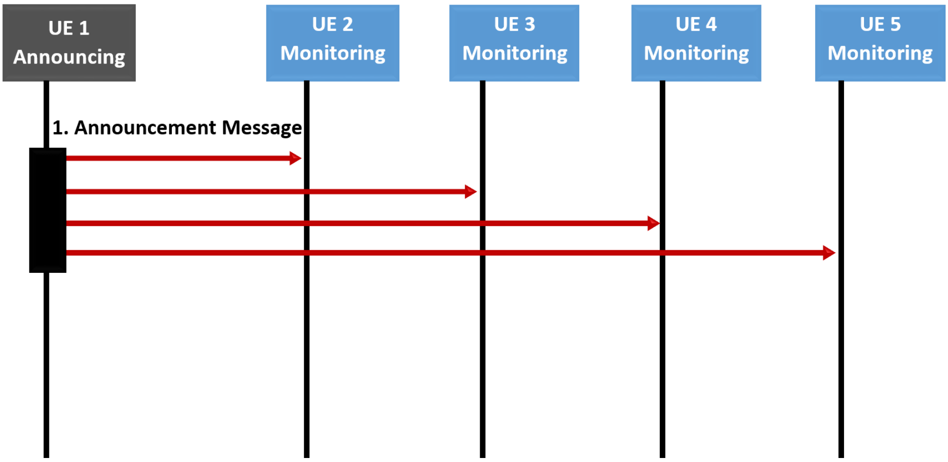

Figure 9: ProSe direct discovery with Model A.

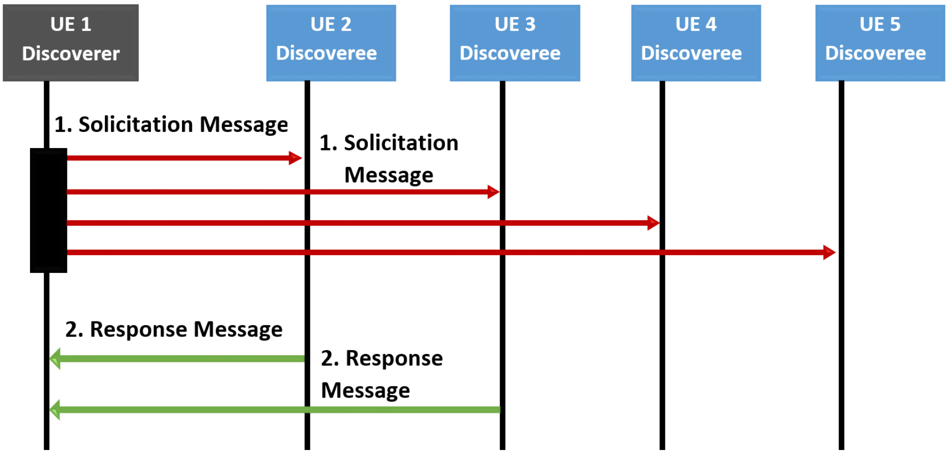

Figure 10: ProSe direct discovery with Model B.

Two models are introduced for ProSe discovery: Model A ("I am here") and Model B ("Who is there?") [34]. Model A uses only a single protocol message for discovery, i.e. a ProSe-enabled UE periodically transmits the discovery messages and the second

ProSe-enabled UE monitors the discovery messages, as shown in Fig. 9. On the other hand, Model B uses two protocol messages, i.e. a ProSe-enabled discoverer UE periodically transmits the solicitation messages and a discoveree UE sends back a response message to discoverer UE, as shown in Fig. 10. The discovery and response messages contain information such as message type, discovery group ID, announcer info, monitoring UE info, ProSe UE ID, etc., as shown in Fig. 11. More details about discovery and response messages can be found in [49]. In this thesis, I consider direct discovery with model A for the measurements in order to evaluate the performance of direct discovery in heterogeneous environments. Further, I examine both Model A and Model B when adding the coordinates of a UE in the discovery message as part of a suggested approach for improving the network lifetime of a UE, which will help first responders to locate and trace the affected UE in emergency scenarios.

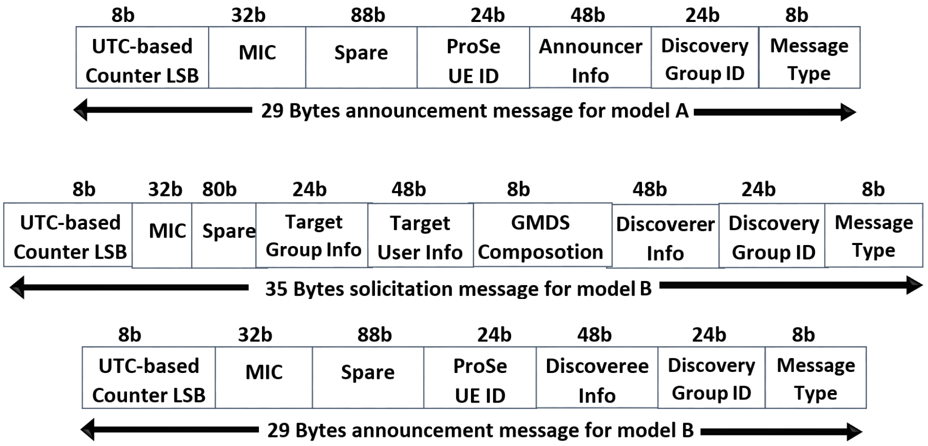

Figure 11: ProSe discovery messages for model A and model B.

2.2.3 ProSe direct communication

ProSe direct communication allows two UEs to communicate with each other in proximity. Just like ProSe direct discovery, ProSe direct communication can operate in three scenarios: in-coverage, partial coverage and out-of-coverage. ProSe direct communication is used two physical channels to establish a dedicated link between two UEs: physical sidelink control channel (PSCCH), and physical sidelink shared channel (PSSCH). The PSSCH channel carries the data of transmitting UE. The PSCCH carries the important information required by receiving UE to decode the PSSCH channel [50].

A transmitting UE needs permission from a BS to start ProSe direct communication. Thus, a transmitting UE sends a request to BS to get the required permission. The BS acquires about it from the higher layer of the network. The BS gives the permission to respond by the higher layer. After the permission, the BS assigns resource blocks to transmitting UE via the physical downlink control channel (PDCCH) for direct communication. The transmitting UE sends its data on the PSSCH channel and sidelink control information (SCI) on the PSCCH channel. The SCI message has important information such as source ID, destination ID, modulation and coding scheme (MCS), and the corresponding location of PSSCH resource blocks in the time domain and frequency domain, etc. A receiving ProSe-enabled UE reads the PSCCH channel to get the required information, which helps a receiving UE to retrieve data after decoding the PSSCH channel [35, 46].

However, in the out-of-coverages, ProSe-enabled UEs use preconfigured parameters to determine the resource blocks for both PSCCH and PSSCH channels independently [35, 46].

2.3 State-of-the-art and positioning of this PhD thesis

As previously indicated, D2D communication can be operated in two modes: centralized, which is controlled by the BS and decentralized mode, which is not assisted by the BS [51]. Contrary to the traditional cellular network, where cellular users (CU) communicate via BS, D2D provides direct communication between users regardless of the network status. Therefore, D2D communication can reduce the traffic load to the BS and provide better system throughput. However, D2D users can produce interference that can affect the cellular communications. In the literature, there are many studies focused on power allocation and efficient resource allocation schemes to reduce the interference level.

2.3.1 D2D Communication in centralized mode

Matching based scheme: In [52], a resource allocation technique is proposed to guarantee the QoS of D2D pairs and CUs at the same time, to improve the network throughput. The authors proposed a three-step scheme. The first step is to determine the D2D pair for each CU by ensuring the QoS by verifying the minimum SINR requirements. The second step determines the power allocation for CU and its D2D pair. The third, and last, step is the resource allocation for all D2D pairs, which consists of finding the best CU partner. The results show that the performance of D2D communications depends on the cell radius, location of D2D users, maximum power limitation for the D2D pair and, the numbers of active CUs and D2D pairs [53].

Mixed-integer nonlinear programming: During the downlink phase, CU could suffer from interference produced by the D2D transmitter. While during the uplink phase, the BS could face interference by the D2D transmitter when random allocation is used for radio resources [54]. In [55], the authors propose a mixed-integer-nonlinear programming (MINLP) scheme for D2D radio resource allocation, where the SINR values of CU and D2D pairs are found separately for UL and DL, and RBs are allocated with respect to SINR values. Numerical simulations show that D2D throughput, cellular throughput, and system throughput have improved significantly with the proposed algorithm compared to random allocation.

Proportional fair algorithm: In [56], the authors propose a proportional fair (PF) algorithm to allocate radio resources for CUs and a greedy heuristic algorithm for D2D users. The PF algorithm follows a greedy rule, wherein the CU with the minimum normalized transmission rate is selected as the best subcarrier. Further, the second heuristic algorithm first determines whether the D2D communication is suitable or not, by doing a path loss comparison. The resource will be allocated if the SINR values of both CU and the D2D pair meet the minimum requirement of the SINR. The results show that D2D and system throughput can improve with the increase in the number of D2D pairs.

Game theory framework: The work [57] proposes a joint scheduling method, power control, and channel allocation for D2D communication using a game theory approach. A technique named Stackelberg game framework is used, where cellular and D2D UE are grouped in a pair with a leader-follower combination. The CU acts as a leader while the follower is the D2D UE who purchases resources of the channel from the leader. The leader charges some dues from the follower for channel usage. So, the D2D user chooses the optimal power by utilizing the price given by CU. The results imply that the throughput performance for both the D2D and cellular UEs can be improved with the proposed method [58].

Water-filling algorithm: It allocates the power for the subcarriers assigned to each D2D pair. The water-filling method distributes the transmit power among all the assigned users [59]. The power allocation is proportional to the channel state information of the D2D link. This approach can improve the Spectral efficiency.

Distributed reinforcement learning: The work in [60] suggests two RL methods, team-Q and distributed-Q learning, to improve power control for D2D communication in cellular networks. In the team-Q learning algorithm where all agents keep the same Q-value table. The complexity level of this approach increases exponentially according to the increasing number of D2D UEs. A distributed Q-learning has been introduced to solve this problem. Distributed Q-learning breaks one big Q-value table in team-Q into several small tables. Now each agent has its own local Q-value table. Actions are sampled constantly during the learning process. So the Q-values in a table will only be updated once the next Q-value is greater than the existing Q-value. The agents, states, and actions also have been used for distributed-Q learning. Simulation results show that distributed-Q learning converges the Q-value faster than team-Q learning algorithm. It can also be seen that D2D throughout is more improved with distributed-Q learning than team-Q learning, with the increasing number of D2D UEs.

Cooperative reinforcement learning algorithm: In [61], the authors present a cooperative reinforcement learning (RL) algorithm for resource allocation for D2D communication to improve the system throughput, also called state action reward state action (SARSA). The cooperation is achieved by sharing the value function between UEs and a neighbouring factor. A set of actions is considered based on the transmission power level of a particular resource block. The reward function is defined by SINR and channel gains. The accuracy of the learning algorithm is increased by defining a set of states with a suitable number of system-defined variables. Simulation results show that the system throughput is improved with the proposed learning method as compared to the distributed reinforcement learning method. The shared learning policies between devices help to converge faster. D2D throughput is enhanced by around 7% compared with distributed reinforcement learning. A trade-off can be seen in D2D and CU throughput by changing the transmit power; higher transmit power will provide higher D2D throughput. It is also shown that D2D and the system throughput will improve by increasing the number of D2D UEs but cellular throughput decreases.

Deep Learning: The authors of [62] suggested a distributed transmit power allocation scheme using deep learning for every D2D UE. Each D2D transmitter can decide its transmit power considering both the D2D throughput and interference to the cellular system. D2D UE uses only its location to determine the transmit power to maximize the D2D throughput. Each D2D UE learns how to decide the transmit power to achieve the optimal system throughput based on locations considering the interference to BS. Deep learning has been applied for the learning process using a cost function to meet the constraints. The cost function can be considered as a linear function to decide the appropriateness of output. The results show that the proposed method is appropriate to cover the edge users. However, it provides almost the same throughout as compared to conventional methods by operating completely in a distributed manner.

Existing studies mainly focus on D2D sidelink communication in the in-coverage scenarios to reduce the network burden, improve the spectrum efficiency, and energy efficiency [53, 57, 63, 64, 65]. These studies propose different schemes for joint scheduling and resource allocation [53, 57, 63], interference-aware resource allocation [64], and distributed power control [65] for D2D sidelink communications. On the other hand, there is a relatively less number of studies on D2D communication for PS scenarios in the literature.

2.3.2 D2D Communication in decentralized mode

However, there is a relatively limited number of on studies on ProSe direct discovery for PSNs in the literature. Mostly studies propose different schemes for ProSe D2D discovery, like location based D2D discovery with the help of BS [65, 66], coordinated relay discovery approach [67]. In [68], the authors present the evaluation of network-assisted D2D discovery, in terms of number of discovered devices, through a mathematical analysis using stochastic geometry model in indoor and outdoor environments. It is concluded that the discovery performance can be improved by reducing the in-band emission.

An enhanced algorithm is proposed for the out-of-coverage scenarios in [69] to improve the discovery performance by detecting the presence and removal of UEs by using dynamic configuration instead of static configuration. In a static configuration, each UE will keep the same record of other discovered UEs at the time they were discovered. Furthermore, all the UEs use the initial transmission probability, and they will not update it according to the current situation during the whole discovery process. The proposed algorithm uses a dynamic configuration where each UE processes the received announcements to check different transmission probabilities and computes its own transmission probability, after the addition or removal of UEs in the discovery group. The approach is known as dynamic configuration due to the continuous upgrading of transmission probabilities. Presented results show that the proposed algorithm can improve the accuracy and required time for the discovery up to 15%.

In [70], ProSe direct discovery mechanisms have been investigated, in particular, w.r.t. energy consumption. In addition, it is also suggested that UEs should perform ProSe direct discovery only when there is a high probability to find other UEs or services. The authors proposed a neighbour discovery scheme through demodulation reference signals based on a power normalized correlation process [71, 72]. Discovery re-transmission scheme with different discovery periods can help to discover more devices in proximity, improve discovery accuracy and energy efficiency [73].

Emerging technologies for PSNs

Emerging communication technologies such as FirstNet, MUrgency [74], push-to-talk [75], etc., are being used for PS communications. These technologies provide features like sharing data, voice communication, or live video streaming during disaster scenarios. However, proper network infrastructure is required for most of them to operate. WiFi-Direct is an established technology that brings a solution to overcome such challenges by creating ad-hoc communication. However, WiFi-Direct faces connectivity problems when communicating with more than two devices [76]. During emergency scenarios, common social media websites like Facebook and Twitter become flooded with messages for help requests [19]. Such scattered information and massive numbers of requests not only degrade the quality of service of the existing network but also do not help the first responder to reduce the response time.

Whereas, D2D communication is a promising paradigm to design future PSNs in 5G and beyond. D2D communication can reduce network load, improve capacity per area, enhance spectral efficiency, increase energy efficiency, and reduce latency in a cellular network [77]. On the other hand, D2D communication can also extend cellular coverage of a BS using relaying [78], multi-hop [29], UAVs [79, 80], and clustering [81] techniques.

These emerging technologies could have a significant impact in PS scenarios.

When BSs are switched off or non-functional, UEs are not able to connect with BS. A feasible solution to overcome this problem is to relay the signals via other devices that act as a link between users and operational BSs using D2D communication. In particular, the UEs that are not in the coverage area of the cellular BS can use the UEs that are in the coverage area as relays, thus accomplishing a multi-hop D2D connection with the cellular network [82]. Under exceptional circumstances, these D2D links, standardized in the 3GPP Release 13, play an important role in filling coverage holes and providing seamless coverage.

It is worth observing that relaying of signals can also be done through moving relays e.g. devices that are installed on moving vehicles such as UAVs or trucks. In recent times, UAVs have been proposed for PS scenarios [83]. The UAVs have been used as a relay to connect the emergency zone with the nearest BS [79]. Recently, UAVs have been deployed as portable BS to provide cellular connectivity to crowded events. The expected time to deploy a fixed BS is up to 90 days whereas setting up a portable BS on a UAV platform reduces this time to approximately 90 minutes. Moreover, unlike a fixed BS, the UAV provides the freedom to move the deployed BS and change its position according to the requirements [84]. The use of drones is more feasible when the risk factor is high. This allows public safety agents to deploy relays in some areas such as earthquakes, terrorist attacks, etc.

2.3.3 Ongoing and completed research projects

Some ongoing and completed research projects are discussed below.

- BSA-D2D: Base Station Aided D2D communication is an initiative of the European Commission (EC) [85]. The main aim of this project was to increase the system capacity by exploring network coding, interference alignment, regenerative storage codes, multiple description source coding and joint source-channel coding.

- MCN: Multilayered Communication Network is an initiative of the Japanese government for research in disaster management [86]. The objective of this project was to establish an alternative communication route and technologies when the 3G network is not available.

- ABSOLUTE: Aerial BSs with Opportunistic Links For Unexpected and Temporary Events (ABSOLUTE) project is a Framework Programme 7 (FP7) initiative that aims to design and validate innovative rapidly deployable networks [87].

- CODEC: The Cellular Network based D2D Wireless Communication (CODEC) project is funded under FP7 framework [88]. It focuses on achieving QoS, energy and spectral efficiency through efficient resource management in D2D Cellular communications.

- D2D-LTE: Device-to-Device Communication: Fundamentals with Applications to LTE (D2D-LTE) is a project funded by the National Science Foundation (NSF), USA [89]. The key idea is to exploit direct communication between nearby devices to achieve throughout, improved spectrum utilization and energy efficiency. In addition, this project explores new peer-to-peer and location-based applications and services.

- PSS: Pervasive Spectrum Sharing (PSS) for public safety communications is an NSF funded project [90]. The main aim of the project is to improve spectral efficiency. The main idea is to provide incentives to users that opportunistically share their spectrum as substrates (e.g., 3G data and WiFi connectivity), and open D2D protocols.

- COHERENT: The coordinated control and spectrum management for 5G heterogeneous radio access networks (COHERENT) framework aims at improving the existing control solutions for inter-network coordination [91]. The project is funded by Horizon 2020 (H2020) programme. It devises theories and methods to abstract network states and behaviors.

- METIS: Mobile and wireless communications Enablers for Twenty-twenty Information Society (METIS) is a research project funded by FP7 [92]. The objective of the project is to design a system concept that delivers the necessary scalability, efficiency, and versatility for a 5G wireless communications system. Direct D2D communication is one potential technology and is used to improve coverage in terms of availability, reliability and cost efficiency.

- UAV4PSC: CAREER: Towards Broadband and UAV-Assisted Heterogeneous Networks for Public Safety Communications (UAV4PSC) is an NSF funded project [93]. The main idea of this project is to use UAVs along with cellular technologies to ensure connectivity with potentially damaged network infrastructures, dynamically manage interference between UAV, BS, UE, and allow smooth handovers.

- NICER: Networked Infrastructure-less Cooperation for Emergency Response (NICER) is a LOEWE funded project [94]. It explores how infrastructure-less information and communications technology that can establish links between people in the event of a crisis, thus enabling them to work together to overcome the crisis.

- BROADMAP: BROADMAP is another H2020 funded project [95]. The project aims to develop next generation broadband inter-operable radio communication systems for public safety and security in the EU. BROADWAY [96] is a new project working on carrying forward BROADMAP initiatives.

- LCMSSER: Location-based Control and Management System for Safety and Emergency Rescuing Services using LTE D2D (LCMSSER) is a British Council funded project through its Newton Fund initiative [97]. The aim of the project is to support mobile users through the location-based system that provides emergency services in the event of disasters.

- DDPS: The DDPS project aims at providing mission-critical voice, 3GPP ProSe, one to one and one to many group communication as key services [98]. The project is funded by the National Institute of Standards and Technology (NIST) and the main partners are US Army Vencore Laboratory and Eurecom. The project involves building a complete ProSe stack for mission-critical voice based on 3GPP standard and open source OpenAirInterface (OAI) and demonstrate in a hardware test-bed.

- COUNTER-TERROR: COmmUNication in conTExt Related to Terror Attacks (COUNTER-TERROR) is a new project that has been recently funded by the North Atlantic Treaty Organization (NATO) within the science for peace and security (SPS) programme [99]. The project aims to establish and maintain connectivity in the case of terrorist attacks, which cause partial or total network failure, exploiting multi-hope D2D communication, beamforming and localization, and jamming and anti-jamming techniques for reliable PSN.

However, most of the available information is about their use-cases and does not give full descriptions of their implementations. Furthermore, the performance evaluation of the direct discovery in heterogeneous out-of-coverage scenarios is still missing in the literature.

2.3.4 Positioning of this PhD thesis

In simulation frameworks, an enormous number of schemes have been proposed for D2D communications. A majority of existing studies cover many details about D2D communications in the centralized mode when the cellular infrastructures work properly. However, there are relatively limited number of studies on direct discovery in out-of-coverage networks.

Whereas, to my best knowledge, this is the first experimental study on direct discovery for out-of-coverage PS communication. Hence, this PhD thesis suggests a novel architecture, based on context-aware ProSe D2D discovery along with the technologies such as UAVs, clustering and UE-UE-relay communications, as a possible solution to design future PSN, as shown in Fig. 4. It is envisioned that smartphones, and/or OS-A devices, which have enabled ProSe features in emergency scenarios (such as earthquakes, floods, terrorist attacks), can be exploited to get critical information from the affected zone. The first responder will deploy multiple UAVs to cover the affected area and an external command center near the affected zone. The OS-A devices will share information with UAVs and UAVs will relay this information to deployed command center over sidelink. Especially when the BSs are not available and the signal power is too weak to propagate. The proposed architecture can establish reliable communication, disseminate the important information from the affected zone to the external deployed command center, speed up the rescue process and reduce the response time in PS scenarios [2, 1].

The PS communication generally operates at a sub-1 GHz band. However, existing studies lack in understanding the D2D communication at such frequencies e.g., realistic communication ranges under various conditions, packet losses, and baseline network lifetime in real-time scenarios. This thesis work addresses these gays by implementing a testbed to perform ProSe direct discovery-based D2D communication in the absence of BS; analysing the performance of ProSe direct discovery in terms of reliability of successful discovery message reception and maximum discovery range in real-time heterogeneous environments; proposing an energy-efficient and context-aware algorithm for ProSe-enabled UEs to enhance their lifetime and prolong network connectivity. Finally, this PhD thesis presents an empirical demonstration of cooperative D2D communication in PS real-life scenario to disseminate the important information (e.g., the number of people, their IDs and current locations) from an affected zone to the external command center.

Chapter summary

This chapter provides an overview of D2D communication, evaluation of D2D communication in 3GPP standards, ongoing research on D2D communication, recent projects related to PSNs, emerging technologies for PSNs, and discusses the key contractions to position this PhD thesis. Whereas, the next chapter gives a description of the developed setup and presents the empirical results to analyze the performance of direct discovery-based D2D communication in out-of-coverage scenarios.

3 Direct Discovery-Based a Reliable D2D Communication for PS Scenarios

This chapter covers the development of the open-source software and USRP-based hardware testbed. The developed testbed allows out-of-coverage UEs to create a dedicated D2D network and perform ProSe direct discovery over sidelink when BSs are not available. Using this testbed, experimental measurements have been carried out to characterize the performance of ProSe direct discovery in three different scenarios: i) indoor LoS, ii) indoor NLoS, and iii) outdoor (LoS). The performance of baseline direct discovery has been evaluated in terms of reliability of successful discovery message reception and maximum discovery range in heterogeneous real-time environments. The experimental results highlight the suitable parameters to perform reliable direct discovery in out-of-coverage scenarios. This chapter is based on the following publication:

- Ali Masood, Muhammad Mahtab Alam, and Yannick Le Moullec. Experimental characterization of ProSe direct discovery for emergency scenarios. In 2021 IEEE 7th World Forum on Internet of Things (WF-IoT), pages 891–896. IEEE, 2021.

Before performing ProSe direct discovery, all UEs have to synchronize to get the necessary timing and frequency information in order to perform successful transmission and/or reception. In an out-of-coverage scenario, when BSs are unavailable, a UE which is called SyncRef periodically transmits the SLSS after every 40 ms. The other UEs, which are called remote UEs, receive these SLSS signals to get synchronized with the SyncRef UE in order to start the direct discovery and direct communication. The synchronization subframe has six PRBs and four types of synchronization signals: DMRS, SSSS, PSSS, MIB-SL composed in the PSBCH more details can be found in [34].

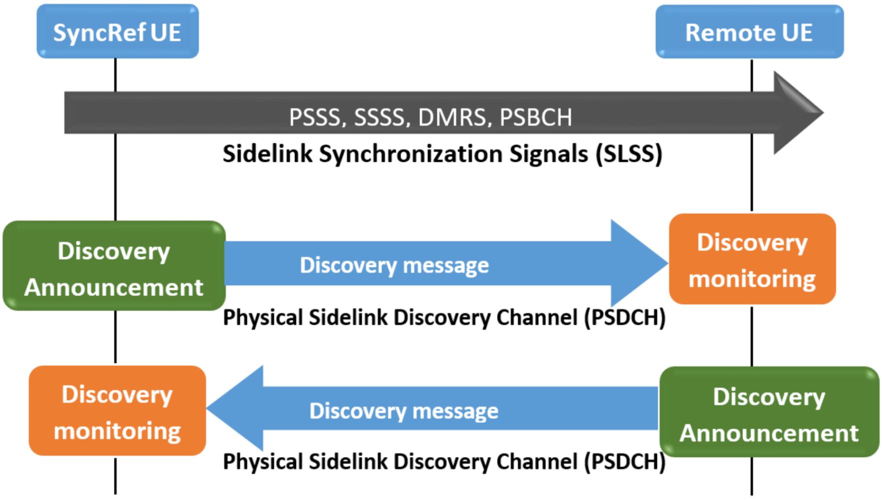

Figure 12: Overall procedure for the ProSE direct discovery.

After synchronization, the UE starts to announce the discovery message periodically and the other UE(s) will monitor the discovery message to discover the announcing UE on the PSDCH [49], as depicted in Fig. 12.

3.1 Development of direct discovery-based experimental testbed

The OpenAirInterface (OAI) open-source software and USRP hardware platform have been used to perform the experiments and collect empirical data. In brief, the OAI Software Alliance (OSA) is a non-profit association that encourages the research and industrial contributors for open source software and hardware development for the core network (EPC), access network, and UEs of 3GPP cellular networks. The OSA is an initial work of Eurecom that creates OAI towards the development of 5G cellular stack on commercial-off-the-shelf (COTS) hardware.

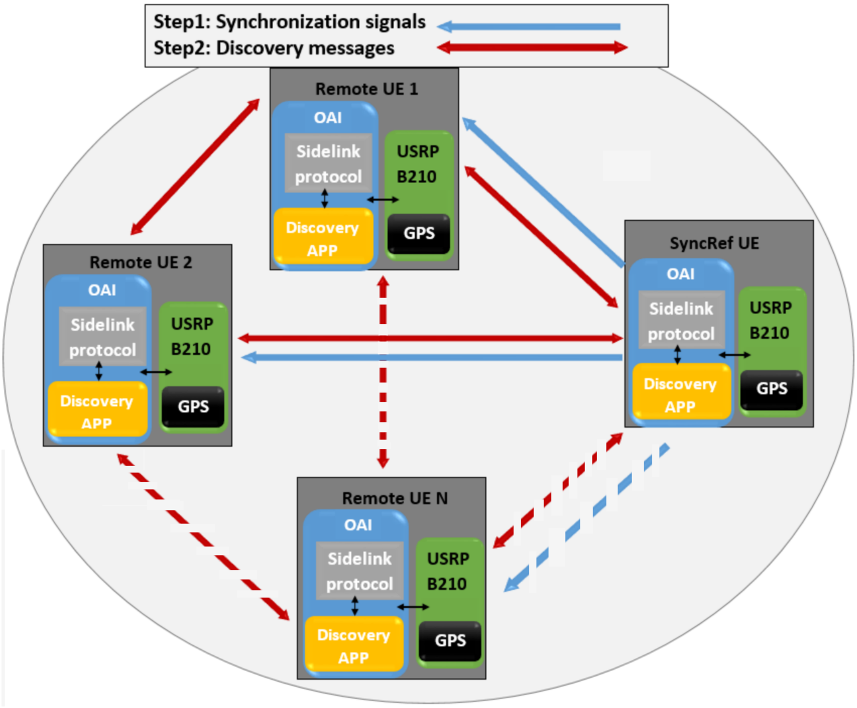

Figure 13: Components and architecture for the ProSe direct discovery.

Our OAI/USRP based testbed consists of the following equipment.
Each UE is composed of:

- USRP B210 board used as the radio front-end hardware part of a UE. The main components of the USRP B210 are a Xilinx Spartan 6 XC6SLX150 FPGA, Analog Devices AD9361 RFIC direct-conversion transceiver, Cypress Semiconductor CYUSB3014 USB 3.0 interface, four connectors for the antennas (Rx and Tx, two channels each). The radio frequency (RF) part is based on the AD9361 chip, whose maximum output power is 8 dBm. After the AD9361, there is a PGA-102+ output amplifier (15.9 dB gain at 800 MHz), which makes that the maximum Tx power of the USRP B210 board can be up to 24 dBm. The available Tx gain and Rx gain are 89.8 dB and 76 dB, respectively and the maximum noise figure of the receiver is 8 dB max [100].

- Board Mounted GPSDO (TCXO) module that provides a high-accuracy 10 MHz reference. All UEs in the network use the same reference clock for synchronization.

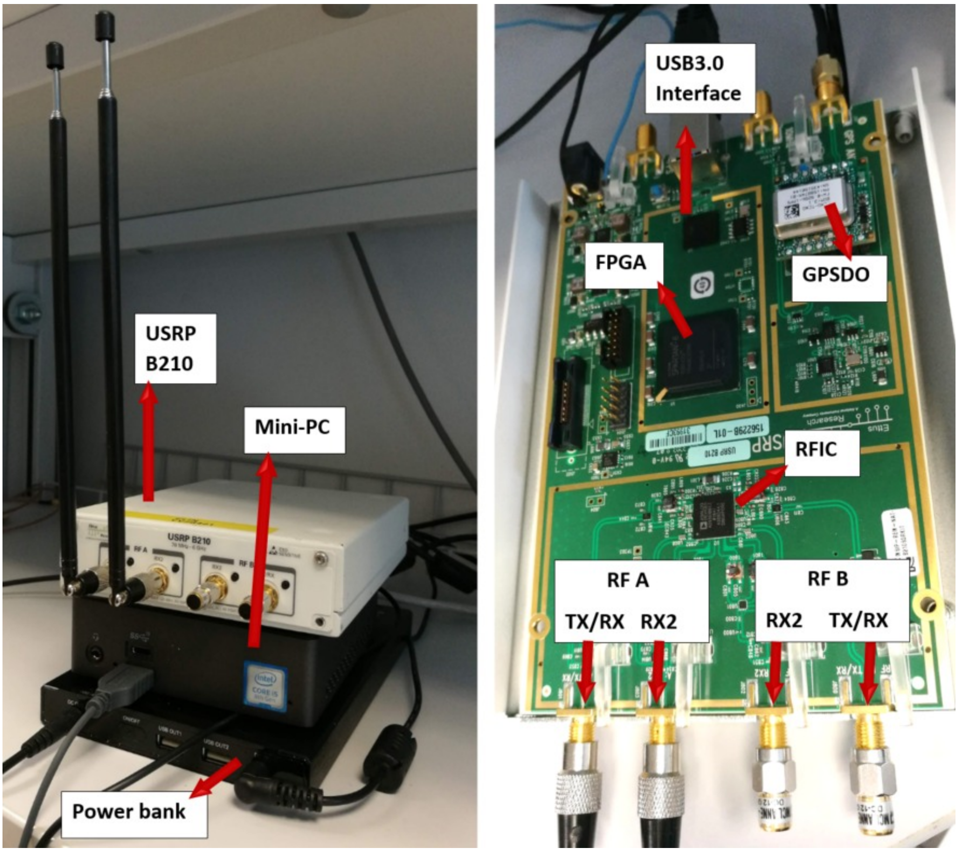

Figure 14: Photos of a developed ProSe-enabled UE. Left (from top to bottom): USRP B210 radio front-end including GPSDO, Gigabyte Brix GB-BRi5-8250 mini-PC, Sandberg 420-23 power bank. Right: close-up of the USRP B210 board.

- Two telescopic antennas to transmit and receive the signals (one-channel configuration on RF A).

- Mini PC used to run the software part of OAI. It runs the Linux Ubuntu operating system and the OAI protocol stack of 3GPP standard (Starting at LTE (Rel 8), including features from LTE-Advanced (Rel 10/11/12), LTE-Advanced-Pro (Rel 13/14), going on to 5G Rel (15/16)). Each mini PC is linked with one USRP to configure it as one OAI-based UE. The implemented D2D application for the direct discovery, based on sidelink protocol, runs on top of the 3GPP protocol stack.

For convenience, each UE (composed of the above elements) can be powered by a Sandberg 420-23 20000 mAh/74Wh power bank. A diagram of the architecture and components (except power bank) of the OAI-based UE are shown in Fig. 13; corresponding hardware photos are shown in Fig. 14.

The OSA provides an open-source OAI Software for ProSe communication, publicly available at Eurecom's website[1]. Out-of-the-box, the above-mentioned setup has limitations. Each USRP board has to connect with one OctoClock (CDA- 2990) through SMA

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[1] https://gitlab.eurecom.fr/oai/openairinterface5g/-/tree/LTE-sidelink/

cables to get synchronized with the same reference clock. Therefore mobility of UEs is a major issue. Moreover, the above setup has two UEs in the network who transmit one random discovery message over sidelink. As a starting point, I have used the same setup and introduced new enhancements. In expanded setup, I have solved the mobility issue by installing a GPSDO module on each USRP board to remove the need for the OctoClock. Furthermore, I have developed an application for self-aware ProSe direct discovery which provides reliable, context-aware and energy-efficient communication in public safety scenarios; more details can be found here [4] or in Chapter 4.

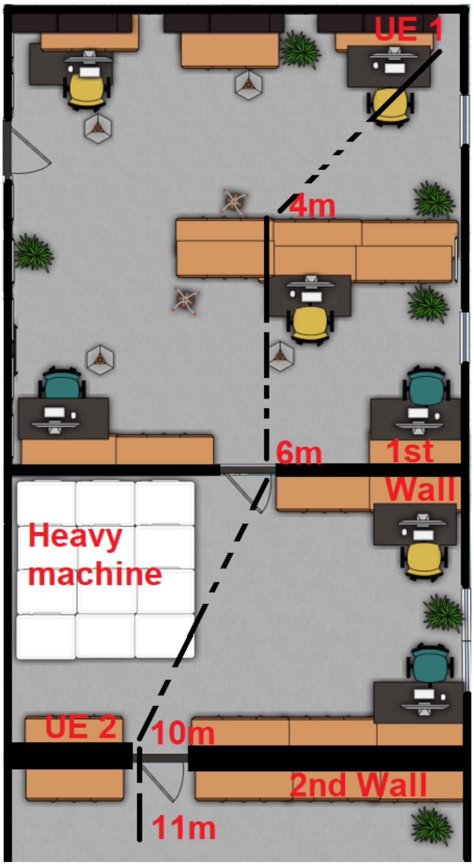


Figure 15: UEs perform direct discovery in an indoor NLoS transmission path (laboratories).

3.2 Measurement Campaign

In this work, all the experiments were performed at Tallinn University of Technology after obtaining the required permission (RF test license) for the measurement campaign. Up to eight OAI-based UEs are used in this measurement campaign. The UEs are deployed in outdoor and indoor scenarios to analyze the performance of the direct discovery.

1. Indoor (NLoS): in the indoor NLoS scenario, UEs have not a direct transmission path. Experiments are carried out up-to three different labs where UEs have different obstacles between them, shown in Fig. 15.

2. Indoor (LoS): in the indoor LoS, UEs have a direct transmission path between them without any obstacle. Experiments are performed in a long and straight corridor of the university building, as shown in Fig. 16.

Figure 16: UEs perform ProSe direct discovery in an indoor LoS transmission path (corridor).

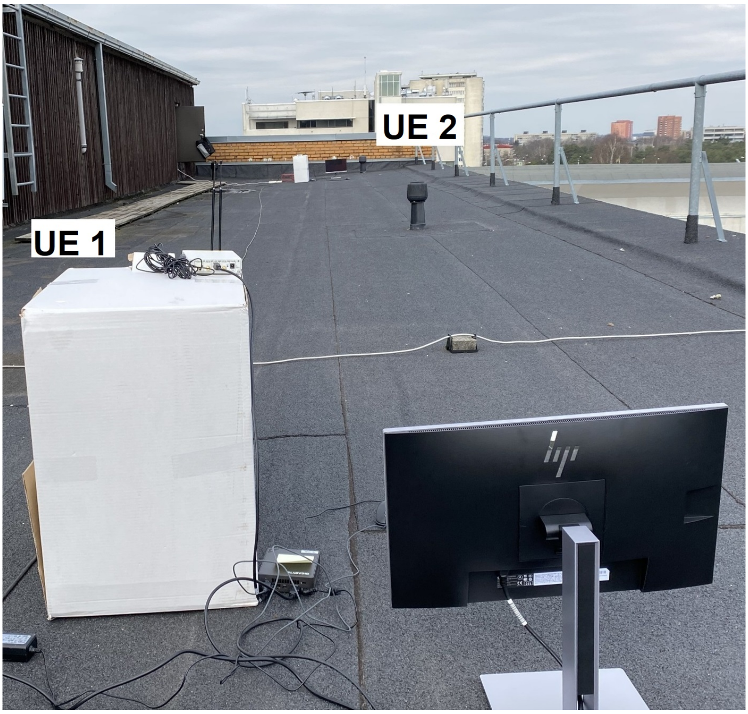


Figure 17: UEs perform direct discovery in an outdoor LoS transmission path (rooftop).

3. Outdoor (LoS): outdoor LoS experiments are carried out on the rooftop of the university building where UEs have a direct transmission path between them, as shown in Fig. 17.

3.3 Empirical Measurement Results

This section presents the empirical measurement results to examine the direct discovery in the three different scenarios. The main goal of this analysis is to provide recommended values for sidelink direct discovery in critical scenarios when the BS becomes non-functional.

First, the impact of the carrier frequency and of the Tx and Rx gains on direct discovery have been investigated in the indoor NLoS scenario. After observing the performance of ProSe direct discovery in terms of discovery reliability, the maximum discovery range is examined in the three described scenarios.

For the empirical results, the 700 MHz and 800 MHz bands have been examined as the spectrum within the 694-894 MHz allocated for PS communication in Europe, North America, and in many other countries [101]. A total number of 600 discovery messages are transmitted by two UEs to evaluate the performance of direct discovery as a reference. The first UE periodically transmits a discovery message each 500 ms and the second UE monitors it. After transmitting eight messages in one cycle, the second UE starts transmitting, and then the first UE monitors the discovery messages. Again after transmitting eight messages in the next cycle, the first UE starts transmitting without changing any parameter, and so on. Overall, 300 discovery messages are transmitted by each UE and eight discovery messages are transmitted in each cycle as a reference. To evaluate the performance of direct discovery in terms of reliability, I calculated the following three key performance indicators (KPIs): average discovery ratio, maximum discovery ratio, and minimum discovery ratio.

The average discovery ratio, DR_{-mean}, is defined as the total number of successful discovery messages received, $N_{-received}$, by the monitoring UE over the total number of transmissions $N_{-transmitted}$. (600 discovery messages are transmitted in total.) It is expressed as:

$$DR_{-mean} = 100\frac{N_{-received}}{N_{-transmitted}} \tag{1}$$

The maximum discovery ratio, DR_{-max}, shows the maximum of the total number of successful discovery messages received by the monitoring UE in any cycle, $N_{-received\,per\,cycle}$. The total number of transmitted discovery messages in a cycle, $N_{-transmitted\,per\,cycle}$, is set to eight discovery messages per cycle. It is expressed as:

$$DR_{-max} = 100\frac{max(N_{-received\,per\,cycle})}{N_{-transmitted\,per\,cycle}} \tag{2}$$

The minimum discovery ratio, DR_{-min}, shows the minimum number of successful discovery messages received by the monitoring UE in any cycle. It is expressed as:

$$DR_{-min} = 100\frac{min(N_{-received\,per\,cycle})}{N_{-transmitted\,per\,cycle}} \tag{3}$$

The average discovery ratio is directly proportional to the reliability of the direct discovery. A 100% discovery ratio signifies the best transmission conditions for direct discovery; the reliability of direct discovery decreases with a decreasing average discovery ratio. On the other hand, the minimum and maximum discovery ratios are indicated by the vertical short lines in the figures, which show the minimum and maximum value at each point. The higher difference between the minimum and maximum values mean denser multi-path and consequently less reliable connection. In the next subsections, I discuss the impact of frequency, amplification, distance, and number of UEs on the discovery ratio.

3.3.1 Discovery ratio as a function of the carrier frequency

Figure 18 shows the impact of the carrier frequency on direct discovery in an indoor NLoS scenario. It can be noticed that as the carrier frequency increases, the discovery ratio improves as well (see, for example, the curve associated with D = 8 m, Rx gain = 45 dB and Tx gain = 50 dB, shown as a magenta dotted line with '*' marker, in Fig. 18.

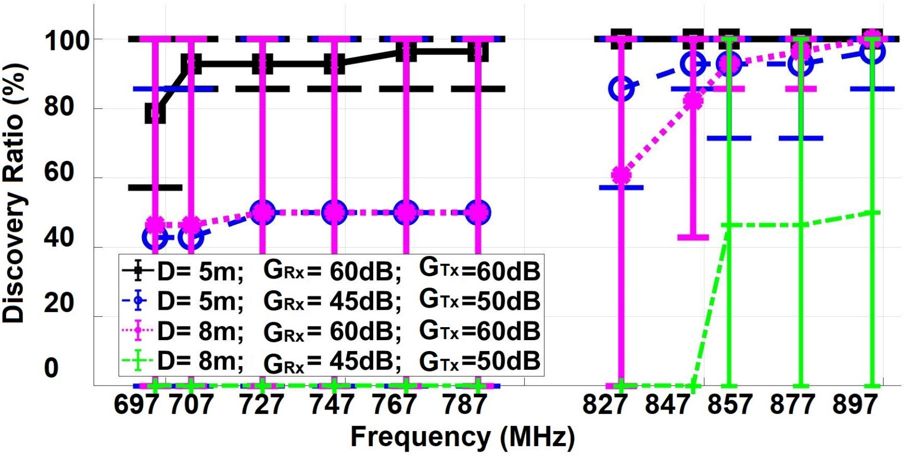


Figure 18: Impact on the direct discovery due to frequency in an indoor NLoS scenario.

For the carrier frequency of 697 MHz, the average discovery ratio is 46%, and the maximum and minimum discovery ratios are 100% and 0%, respectively. The 46% average discovery ratio value indicates that 46 discovery messages are received by the monitoring UE out of 100 transmitted messages. The 100% maximum and 0% minimum discovery ratios indicate that a monitoring UE could receive all the transmissions or it could also miss all the transmissions from the announcing UE. This shows very poor settings for the direct discovery.

Next, the average discovery ratio increases by increasing the carrier frequency and it reaches 100%. The carrier frequency of 897 MHz yields a 100% average discovery ratio and provides a very reliable and stable connection for direct discovery. It is also observed that carrier frequencies set in the spectrum from 857 to 897 MHz provide reliable connectivity for direct discovery in all the considered cases, even with low Rx and Tx gains.

These results can be explained looking at the specific characteristics of the selected NLoS propagation environment; nevertheless, the most interesting aspect revealed by the experimentation is that carrier frequency can have a remarkable impact on discovery performance even in the most favorable range of frequency carriers for mobile systems, i.e. below 1 GHz.

Note that the selected frequencies were not being used for the other purposes as also checked by a portable FSH4 spectrum analyzer. Furthermore, the spectrum from 790 to 820 MHz has not been evaluated because it is occupied by mobile operators in Tallinn, Estonia.

3.3.2 Discovery ratio as a function of the Tx and Rx amplifier gains

As can be observed from Fig. 18, the Tx and Rx amplifier gains have an impact on the performance of direct discovery. In order to have a better understanding of this impact, Fig. 19 represents the effect of the Tx and Rx gains on the performance of direct discovery in the indoor scenario: here UEs are placed 6 m apart to announce discovery messages at 857 MHz. In fact, as can be seen in Fig. 18, carrier frequency from 857 MHz provides reliable connectivity for all the considered cases.

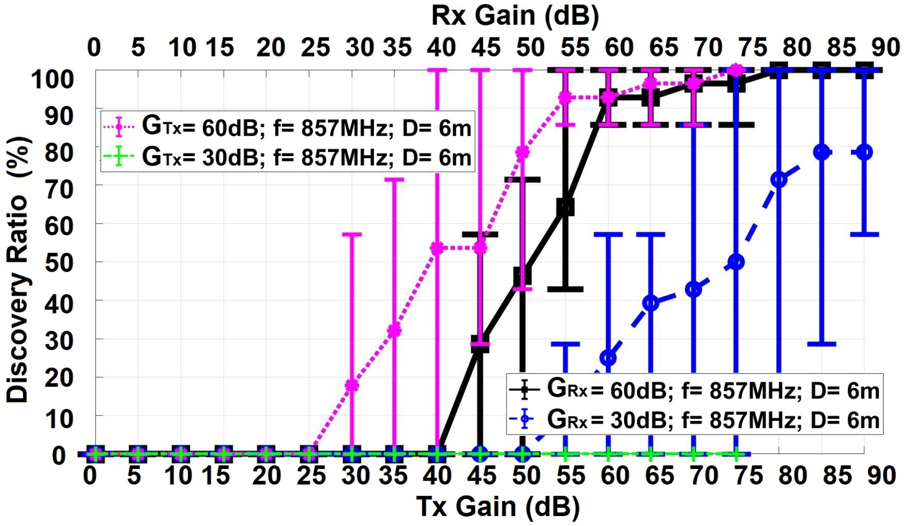


Figure 19: The impact of Tx and Rx gains on the direct discovery in an indoor NLoS scenario.

It can be observed that by increasing the Tx gain, the reliability of the direct discovery improves. When the Rx gain is set to 60 dB, shown as a black solid line with a square marker in Fig. 19, the average discovery ratio remains zero for Tx gains ranging from 0 to 40 dB. This shows that no discovery message is received by the monitoring UE.

The average discovery ratio increases from 0 to 65% for Tx gains ranging from 40 to 55 dB. However, there is a large difference between the maximum and minimum discovery ratios that indicate poor connectivity. After that, the average discovery ratio increases very gradually from 93 to 100% for Tx gains ranging from 60 to 80 dB, and connectivity becomes stable and reliable for direct discovery. If instead of 60 dB, I set the Rx gain to 30 dB, even higher Tx gains do not provide a reliable discovery, as shown with a blue dotted line.

The effects of Tx Gains on ProSe discovery can be better understood from Table 1 (measured by means of a portable FSH4 spectrum analyzer. As it is explained in Chapter 2.1, the UEs have to synchronize using SLSS signals before transmitting the discovery messages. Otherwise, UEs will not able to discover each other. Therefore, output transmitted power and signal-to-noise ratio (SNR) values of both SLSS signals and PSDCH channel against Tx gains are presented in the table. An FSH4 spectrum analyzer is used to measure the output power and SNR values. It can be seen from the table that the output power of both SLSS and PSDCH remains approximately -92 dBm for Tx gains ranging from 0 to 34.75 dB. After that, the output power increases gradually from -89,8 to -42 dBm for Tx gains ranging from 39.75 to 89.75 dB.

On the other side, the SNR value remains less than 10 dB for the TX gains of less than

Table 1: The effect of Tx gains on the output power and SNR values of transmitted signals.

	SLSS		**PSDCH**	
Tx Gain (dB)	**Output power (dBm)**	**SNR (dB)**	**Output power (dBm)**	**SNR (dB)**
89,75	-42,4	23	-42,6	22
84,75	-47,3	23	-47	22
79,75	-51,9	23	-51	21,7
74,75	-58,1	22,5	-60,7	21,7
69,75	-62,4	21,5	-61,6	20,8
64,75	-68	21	-69,2	20,8
59,75	-72,4	20,4	-71,4	19,6
54,75	-79,8	12,5	-78,3	10,6
49,75	-83,7	8,2	-83,9	9,8
44,75	-86,7	4,4	-88,1	5,6
39,75	-89,8	1,1	-91,5	2,2
34,75	-92	0,5	-92,4	1,7
29,75	-92	0,5	-92,4	1,7
24,75	-92,6	0,2	-95,2	0,3
19,75	-92,6	0,2	-95,2	0,3
14,75	-92,6	0,2	-95,2	0,3
9,75	-92,6	0,2	-95,2	0,3
4,75	-92,6	0,2	-95,2	0,3
0	-92,6	0,2	-95,2	0,3

50 dB for both SLSS and PSDCH. Such low SNR values give very poor discovery ratios, as shown in Fig. 19, 46% average discovery ratio with 60 dB Rx gain and 0% with 30 dB Rx gain. The SNR improves significantly around 10 dB to 20 dB for Tx gains ranging from 49.75 to 59.75 dB. The discovery ratio also improves to 93% with 20 dB SNR. Then SNR improves gradually up to 23 with maximum Tx gain and the direct discovery becomes very reliable with a 100% discovery ratio. A similar behavior is observed when Tx has a fixed value. By increasing the Rx gain, the performance of direct discovery improves. For example, when the Tx gain is set to 60 dB, shown as a magenta dotted line with '*' marker in Fig. 19, the average discovery ratio is 93% when Rx gain is set to 55 dB. For Rx gain equal to or larger than 70 dB, the discovery ratio reaches 100% and provides a very stable and reliable direct discovery. Whereas, when the Tx gain is set to 30 dB, the discovery ratio remains 0% regardless of the Rx gain, shown as green dashed line.

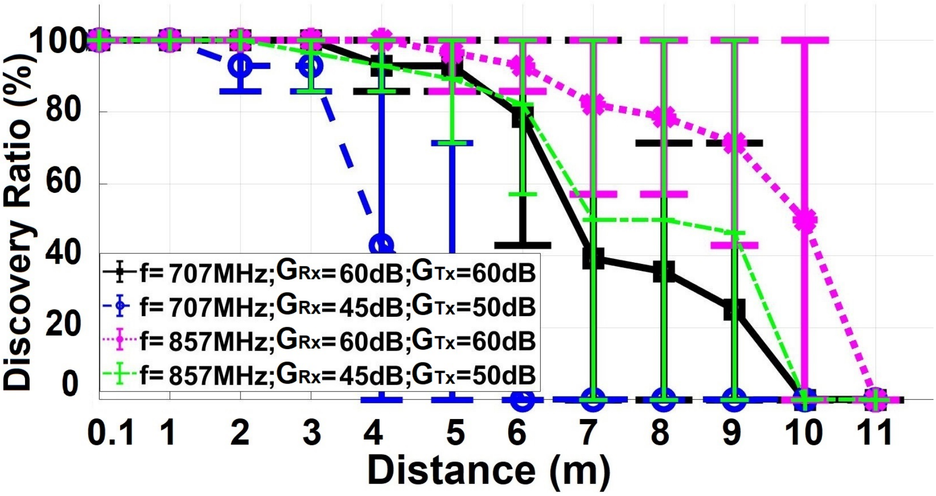


Figure 20: The impact on the direct discovery due to the distance between two UEs in the indoor-NLoS scenario (labs).

It can be seen from Fig. 18 and Fig. 19 that the reliable connectivity for direct discovery also depends on the distance between announcing and monitoring UEs along with carrier frequency, and Tx and Rx gains. It can be also observed that the average discovery ratio is more than 90% when $f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB, and the average discovery ratio is around 50% when $f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB in most of the considered cases. Therefore, I used these moderate gains and carrier frequencies and considered the following four cases to analyze maximum discovery range for direct discovery in three different scenarios: case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), case 2 ($f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB), case 3 ($f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB).

3.3.3 Discovery ratio as a function of a distance between two UEs in the indoor-NLoS

Figure 20 shows the impact of the distance between announcing and monitoring UEs on the direct discovery in the indoor NLoS scenario. The case, referred to as case 3, that provides the best connectivity and maximum distance for the direct discovery as compared to the other three cases is with both Rx and Tx gains set to 60 dB and the carrier frequency set to 857 MHz ($f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), shown as a magenta dotted line with '*' marker in Fig 20. It can be seen that the average discovery ratio remains 100% when the distance is up to 4 m between two UEs. The discovery ratio decreases gradually to 84% with increasing distance up to 7 m regardless of the first concrete wall at 6 m (Fig 15).

It is also interesting to observe the behavior with the case 1 ($f = 707$ MHz, Rx gain = Tx gain = 60 dB) and case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB) after the first concrete wall (i.e. after 6 m). The average discovery ratio decreases swiftly, and reaches 0% after the radio signal meets an obstacle (a heavy machine) at 10 meters. Whereas the average discovery ratio decreases gradually regardless of the obstacles until 10 meters in case 3, but it decreases swiftly after the second concrete wall and becomes zero at 11 meters.

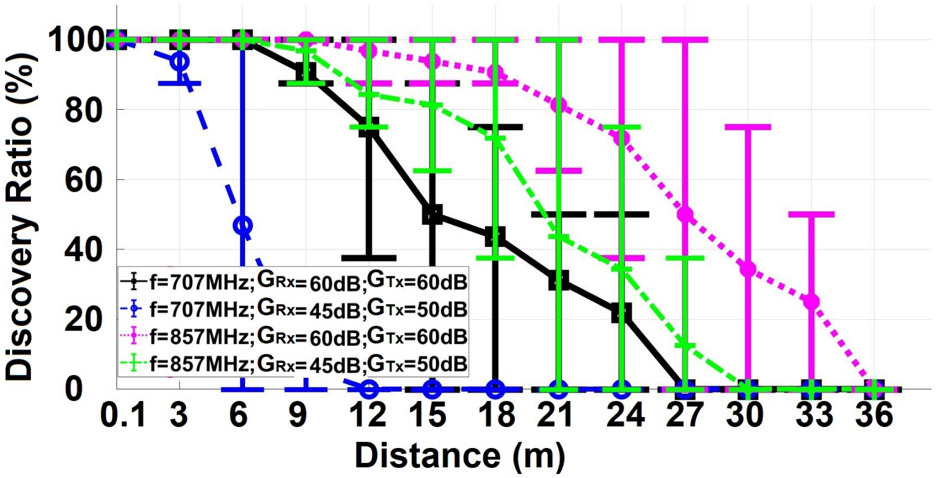


Figure 21: The impact on the direct discovery due to the distance between two UEs in the indoor-LoS scenario (corridor).

Finally, for case 2 with low gains and carrier frequency ($f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB), the average discovery ratio reaches 0% at 6 meters, as shown with the blue dashed line in the Fig. 20.

3.3.4 Discovery ratio as a function of a distance between two UEs in the indoor-LoS

Figure 21 shows the impact of the distance between two UEs on the direct discovery in the indoor LoS scenario. Case 3 ($f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB) shown as a magenta dashed line in Fig. 21 provides the best connectivity and maximum range for direct discovery with the highest discovery ratio. It can be observed that the average discovery ratio remains 100% when the distance is up to 9 meters between two UEs. The discovery ratio decreases gradually and reaches 0% at 36 meters. A similar trend can be seen in case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB) and case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), where the average discovery ratio remains 100% until 6 meters in both cases, and the maximum discovery range is 24 and 27 meters respectively. On the other hand, in Case 2, the UEs could not discover each other after only 9 m with low gains and carrier frequency ($f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB), as shown with the blue dashed line in the Fig. 21.

3.3.5 Discovery ratio as a function of a distance between two UEs in the outdoor (LoS)

Figure 22 shows the measurements for the outdoor scenario. A similar behavior can be observed in Fig. 22 as compared to the indoor LoS (Fig. 21). Once again, Case 3 ($f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB) provides the highest discovery ratio, reliable connectivity, and maximum distance for direct discovery as compared to the other three cases. It can be observed that the average discovery ratio remains 100% when the distance is up to 20 meters between two UEs, and it decreases gradually and reaches 0% when the distance is 70 meters. However, the maximum discovery ranges are 35 and 45 meters in case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB) and case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB) respectively.

On the other hand, in Case 2 ($f = 707$ MHz, Rx gain = 45 dB, Rx gain = 50 dB), the UEs configured with low gains and frequency could not discover each other after 15 meters.

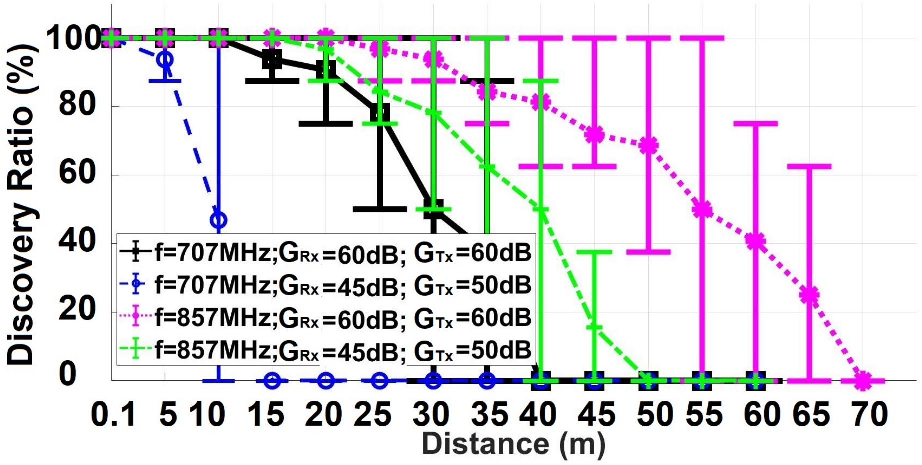


Figure 22: The impact on the direct discovery due to the distance between two UEs in the outdoor scenario (rooftop).

It can be confirmed that case 3 with maximum amplification and frequency ($f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB) provides the best connectivity and maximum range for a reliable direct discovery as compared to the other three cases.The impact on the direct discovery due to the distance between two UEs in all three scenarios is shown in Fig. 23.

It is important to appreciate the performance gap between the three significant propagation scenarios, which can be measured numerically by the different slopes of the curves as a function of the distance.

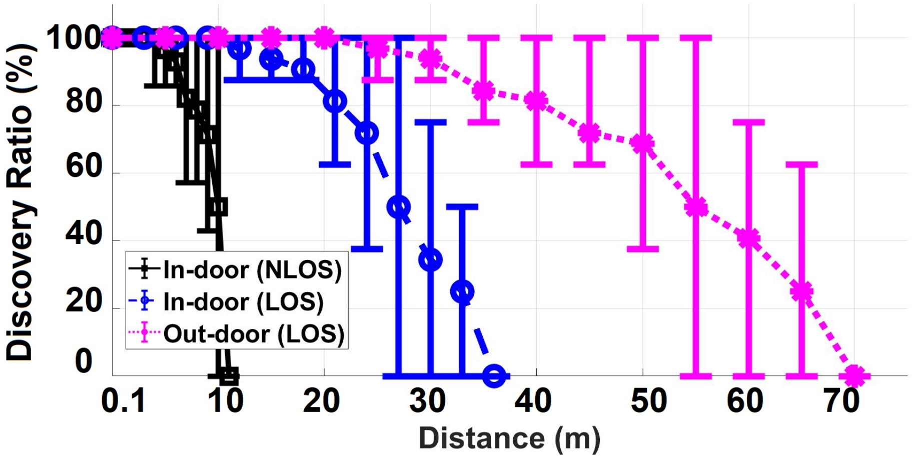


Figure 23: The impact on the direct discovery due to the distance between two UEs in all three scenarios where $f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB.

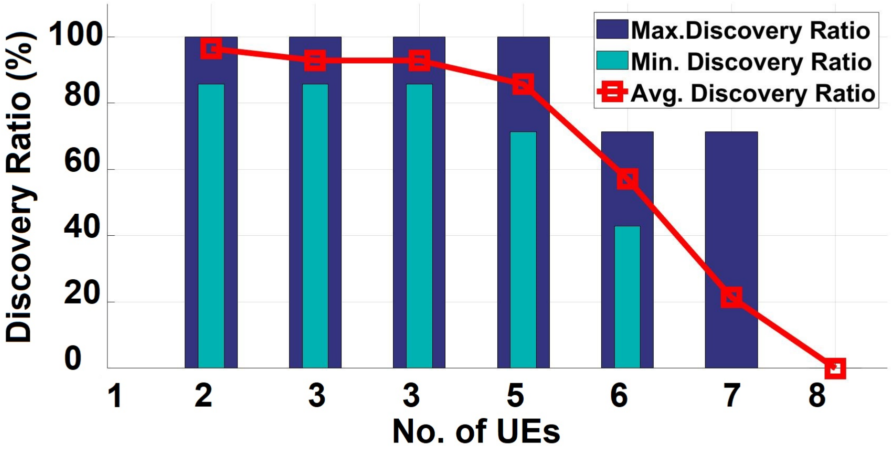


Figure 24: The Impact on direct discovery due to Increase in number of UEs in the indoor-NLoS scenario where D = 5 m, $f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB.

3.3.6 Discovery ratio as a function of the number of UEs

Finally, Fig. 24 shows the impact on the number of UEs in a group on the performance of direct discovery in the indoor-NLoS scenario, where D = 5 m, $f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB. It can be seen that the discovery ratio decreases gradually when increasing the number of UEs in the network. OAI-based direct discovery can support up to 5 UEs in a group with up to 90% discovery ratio. After adding the sixth UE in the group, the average discovery ratio decreases swiftly (down to 60%). It can be seen that a maximum of 7 UEs can be discovered in one group but with a low average discovery ratio of only 20%. According to the 3GPP system, sidelink communication shall be able to support up to 5 UEs in a group, and NR sidelink communication shall be able to support up to 19 UEs in a group [102].

Chapter summary

In this chapter, the performance of direct discovery has been evaluated in terms of discovery reliability and the maximum range of discovery in three different environments. The experimental results suggest suitable parameters that are required for a reliable direct discovery in out-of-coverage heterogeneous environments. In the next chapter, I propose an algorithm for direct discovery to improve the lifetime of UEs and the network in critical situations.

4 ProSe D2D Application: A Novel Energy-Efficient Context and Self-Aware Intelligent Algorithm for Direct Discovery to Extend Public Safety Networks Lifetime

In a decentralized case when the BS is not available, a ProSe-enabled UE transmits the discovery messages with a fixed period. Periodicity could be up to 10 seconds [103]. A UE keeps transmitting discovery messages although it has already been discovered by the neighboring UEs, first responder, or UE does not have new information to transmit. For instance, when a discovery message has been received by the first responder and the UE is not changing its position then there is no need to re-transmit the discovery message. However, if a UE transmits redundantly it will consume more energy, and eventually, it will die out swiftly in the network. As a dead node, a UE could increase the delay to obtain the rescue services. In a critical situation, it is very important to stop redundant transmissions of discovery messages in order to keep the UE alive in the network for a longer time and increase the probability to get relief from the first responders.

This Chapter suggests a self-aware D2D discovery approach based on the current position and battery level of a UE in emergency scenarios (Algorithm 1). The proposed approach aims to improve significantly the lifetime of UEs by decreasing their number of redundant discovery messages transmissions. This chapter is based on the following publications:

- Ali Masood, Muhammad Mahtab Alam, Yannick Le Moullec, Luca Reggiani, Davide Scazzoli, Maurizio Magarini, and Rizwan Ahmad. ProSe direct discovery: Experimental characterization and context-aware heuristic approach to extend public safety networks lifetime. IEEE Access, 9:130055–130071, 2021.

4.1 Description of the proposed energy-efficient context and self-aware intelligent algorithm

The proposed approach has two main phases. The first phase defines the periodicity for discovery transmissions; there are two stages in each periodicity: transmission stage and idle stage. In the transmission stage, a UE can transmit N (up to eight) discovery messages in a time t_{TX}, and in the idle stage, a UE remains idle for a time t_{IDL}. The second phase determines either to transmit the optimal number of discovery messages in the transmission stage, or to remain idle for time t_{TX}. The steps involved in the proposed approach are shown in Fig. 25.

4.1.1 First phase of the proposed algorithm

The first phase defines the periodicity for discovery transmissions according to the current battery level of a UE. Therefore, I consider battery capacity of a UE in the application for simulation purposes. Modern smartphones have 15.04 Wh battery capacity (i.e. 3957.9 mAh at 3.8 V) on average [104]. As a reference, I consider one half of this capacity, i.e. 7.52 Wh or 27072 Ws, as the total battery capacity of a single UE in the application. Further, I divide the battery capacity into seven levels, denoted from one to seven, to indicate the status of the battery. The one to seven battery levels indicate when the remaining battery is between 100-97%, 96-88%, 87-75%, 74-50%, 49-25 24-10%, and 9-0%, respectively. Each battery level has a different but fixed periodicity to transmit the discovery messages. In this work, time t_{TX} for the transmission stage remains fixed for all battery levels (1 s).

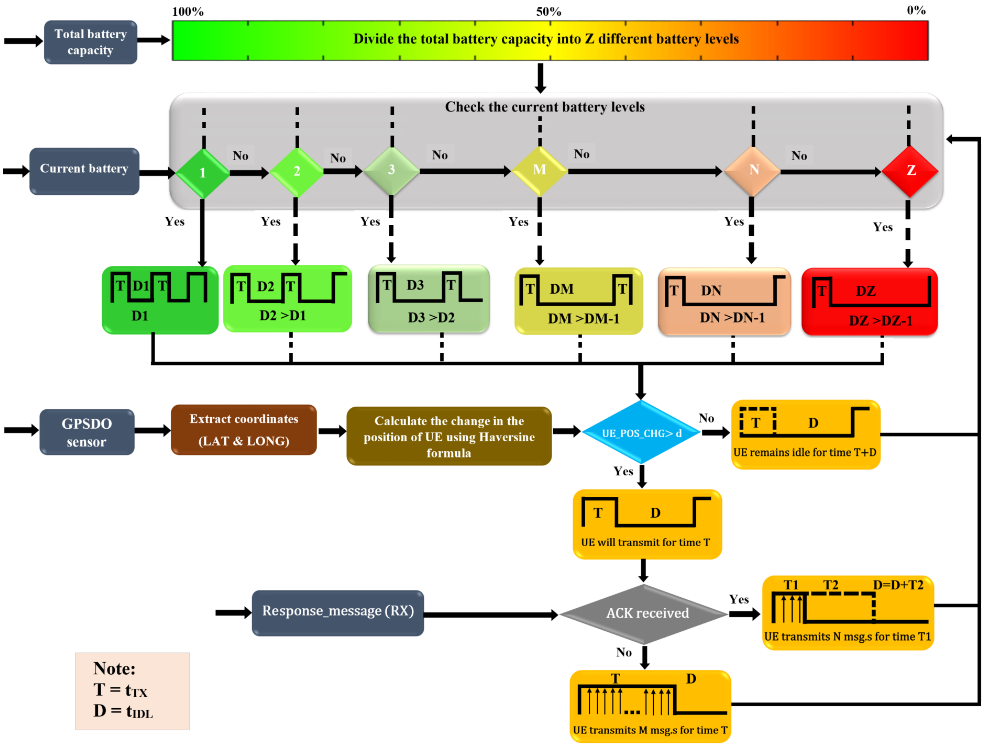
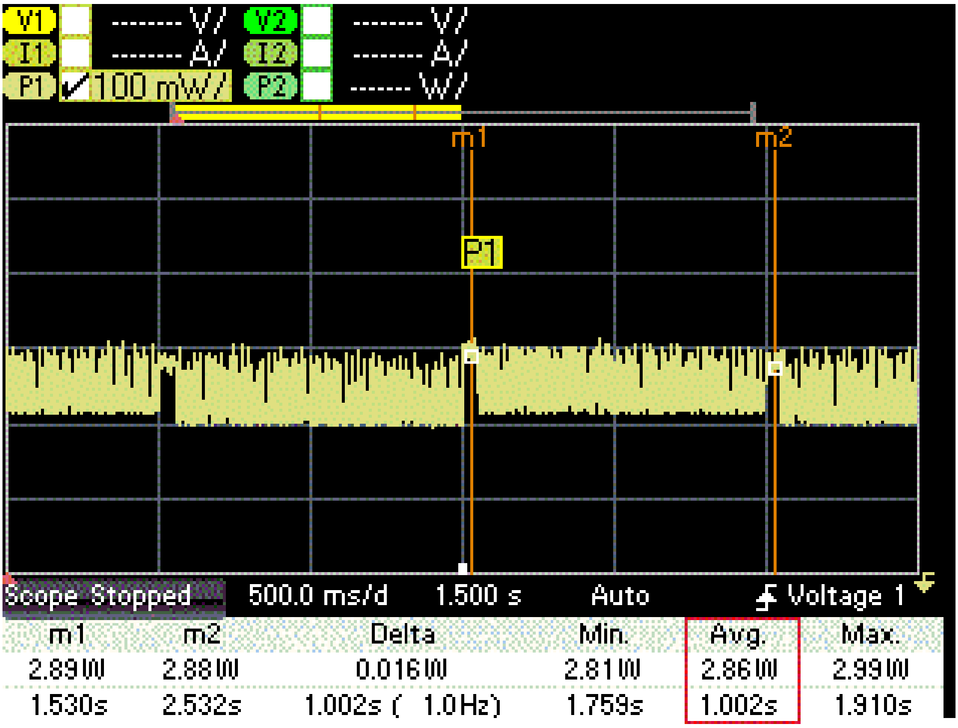


Figure 25: Steps involved in the proposed algorithm.

Time t_{IDL} for the idle stage increases with decreasing battery values over time, as shown in Fig. 25. I assign different periods for the idle stage i.e. t_{IDL} = 2 s, 3 s, 9 s, 29 s, 59 s, and 299 s for battery levels one to six, respectively. In the last battery level (less than 10%), a UE will remain idle and can transmit up to eight messages before dying.



Scope Stopped 500.0 ms/d 1.500 s Auto Voltage 1

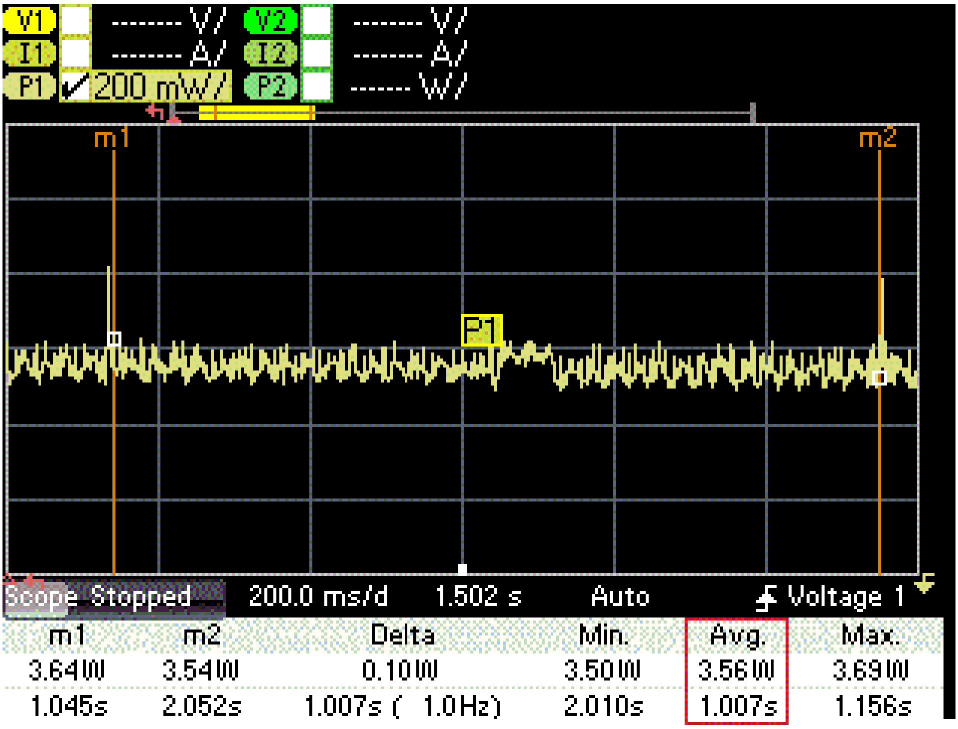
m1	m2	Delta	Min.	Avg.	Max.
2.89 W	2.88 W	0.016 W	2.81 W	2.86 W	2.99 W
1.530s	2.532s	1.002s (1.0Hz)	1.759s	1.002s	1.910s

Figure 26: Baseline power consumption of a ProSE UE implemented with OAI/USRP.

This heuristic approach saves a substantial amount of energy consumption by reducing the redundant transmissions of discovery messages. A UE in a decentralized case consumes energy in both idle and transmission stages. In this work, I also provide energy consumption values of a UE in both stages using the keysight N6705C power analyzer. the main objective was to measure the energy consumption by a UE in the transmission and idle stages. Therefore, the power consumed by the USRP board and Mini PCs is considered as the baseline power (2.86 W), as shown in Fig. 26. A UE consumes 0.7 W $(3.56 - 2.86)$ for one second in the idle stage as shown in Fig. 27. A discovery transmission consumes an additional 0.1 W. A UE consumes 0.8 W if it transmits a single discovery message in one second. The energy comparison is shown in Fig. 28 when a UE transmits up to eight discovery messages or remains idle for one second.

4.1.2 Second phase of the proposed algorithm

The second phase has two further steps to determine the optimal number of discovery messages for the transmission stage. In the first step, a UE will take a decision based on its mobility, i.e. either it will transmit for time t_{TX} or remain idle. Once an announcing or affected UE in emergency situations is already discovered by the first responders and this UE does not change its position, there is no need to keep transmitting the discovery messages because the first responder already received the updated information. However,



m1	m2	Delta	Min.	Avg.	Max.
3.64W	3.54W	0.10W	3.50W	3.56W	3.69W
1.045s	2.052s	1.007s (1.0Hz)	2.010s	1.007s	1.156s

Figure 27: Power consumption in the idle stage of a ProSE UE implemented with OAI/USRP.

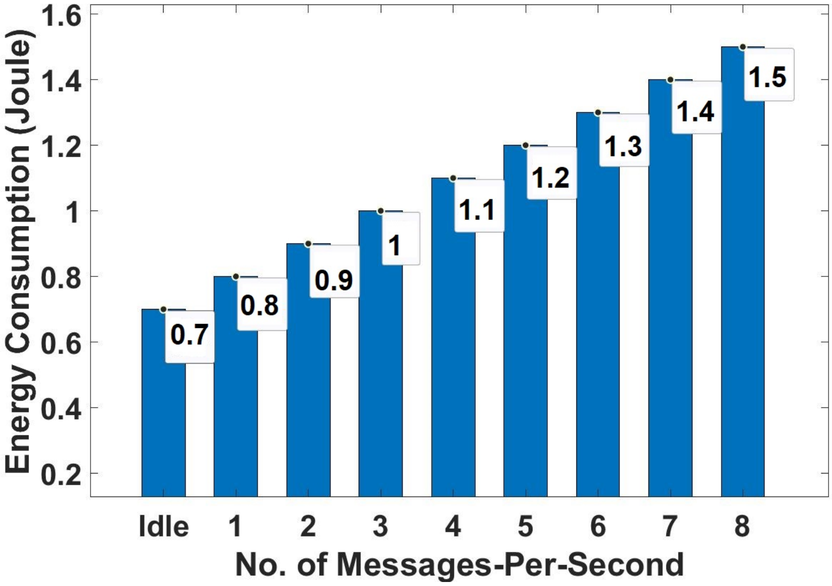


Figure 28: Energy consumption comparison of a UE implemented with OAI/USRP when it transmits N number of discovery messages or it remains idle.

whenever a UE changes its position it is important to transmit the discovery messages. This will benefit the first responder to keep track of the updated information and to keep tracking the affected UE. Given that a UE can move continuously, I set a threshold on the position change equal to 5 m based on application requirements. Thus, a UE can only transmit the discovery messages in the transmission stage when a change in the position of a UE is more than 5 m. A GPSDO module is used to get the coordinates of a UE in real-time. A distance covered by a UE is calculated from the haversine formula using the current coordinates (point A) and the coordinates of a UE at the previous transmission (point B), as explained in the proposed algorithm (Algorithm 1), where ϕ_1, ϕ_2 are the latitude of point A and latitude of point B, respectively and λ_1, λ_2 are the longitude of point A and longitude of point B, respectively. All the angles are in radians and R is the radius of earth in meters. If an affected UE initiates the discovery transmission, for the first time, it will not follow this step and directly goes to the second step of the second phase.

The second and last step of the second phase is to determine the optimal number of re-transmission of discovery messages in the transmission stage. A UE can re-transmit up to eight discovery messages per second in the transmission stage. It was observed after the measurement campaign in different scenarios that the reliability of network connectivity depends on the channel conditions and distance between two UEs. It is further shown in Sect. 4.2 that when the channel condition is good, a monitoring UE or the first responder can discover the announcing or affected UE with a single transmission. On the other hand, in poor channel conditions, an affected UE has to re-transmit multiple discovery messages to be discovered. Therefore, I add a response message in proposed approach, so that an affected UE will keep re-transmitting the discovery messages until it receives a response message from the first responder. The proposed heuristic approach provides a reliable D2D discovery and significantly improves the UE lifetime in a critical scenario.

4.2 Performance evaluation of the proposed algorithm

After evaluating the performance of direct discovery in terms of reliability and maximum range of direct discovery in heterogeneous environments (see Section **??**), I proposed the above-described heuristic approach to improve the UE lifetime in a network by stopping the redundant discovery transmissions and to provide a reliable direct discovery in critical situations. When a BS is unavailable, a UE will redundantly transmit discovery messages with a fixed period even although it is discovered by the rescue services and not changing its position. Normally, the periodicity could be up to 10 seconds [103]. As a baseline, I consider different periodicity periods (P) for discovery transmission, i.e. $P = 125$ ms, 160 ms, 250 ms, 500 ms, in other words, a UE transmits 8, 6, 4, 2 messages-per-second (MPS), respectively. With the proposed approach, a UE considers two factors before performing discovery transmission: the current battery level of a UE and the distance covered by a UE. The current battery level of a UE defines the periodicity period for discovery transmission, whereas the distance covered by a UE determines to either transmit the optimal number of discovery messages in the transmission stage or remain idle, as fully explained in Section 4.1.

It can be seen from Fig. 29 that the proposed approach significantly improves the UE lifetime in the network compared to baseline discovery transmissions. A UE lifetime has been prolonged by 128, 219, and 329 minutes when compared to fixed periodicity periods for discovery transmission where $P = 2$, 4, and 8 MPS, respectively. The proposed approach also stops the redundant transmissions and only transmits 1.72%, 1.05%, and 0.72% of discovery messages compared to fixed periodicity periods where $P = 2$, 4, and 8 MPS, respectively. A 100% fully charged battery is considered for this result. However,

Algorithm 1 Proposed heuristic algorithm

```
Input: Tot_battery_cap, Curr_battery_cap, UE_coordinates, response_message (Rx)
Output: Transmit a discovery message (TX)

Divide the Tot_battery_cap into Z different battery levels
while $(Curr\_battery\_cap \neq 0)$ do
    Check the Curr_battery_level
    i = {1,2,3,...,Z}$\leftarrow$ depends on Curr_battery_level
    for $(i; i \leqslant Z; ++i)$ do
        Calculate a distance coved by a UE using Haversine formula:
        a = $\sin^2(\frac{\phi_2-\phi_1}{2}) + \cos(\phi_1)\cos(\phi_2)\sin^2(\frac{\lambda_2-\lambda_1}{2})$
        c = $2\arctan 2(\sqrt{a}, \sqrt{1-a})$
        $UE\_POS\_CHG$ = R * c
        if $(UE\_POS\_CHG > Threshold)$ then
            if $(Response == 1)$ then
                while $(ACK \neq True)$ do
                    Transmit a discovery message in time $t_{TX}$
                    TX_counter += 1
                end
            else
                UE Transmits N no. of discovery messages for time $t_{TX}$
                TX_counter += N
            end
        else
            UE will remain idle for time $t_{TX}$
        end
        UE remains idle for $t_{IDL} \leftarrow t_{IDL}$ = {$t_{IDL}$1, $t_{IDL}$2, ... , $t_{IDL}$Z} & $(t_{IDL}1 < t_{IDL}2, .., < t_{IDL}Z)$ }
        $NW\_lifetime += $t$_{TX}$ + $t_{IDL}$
    end
end
```

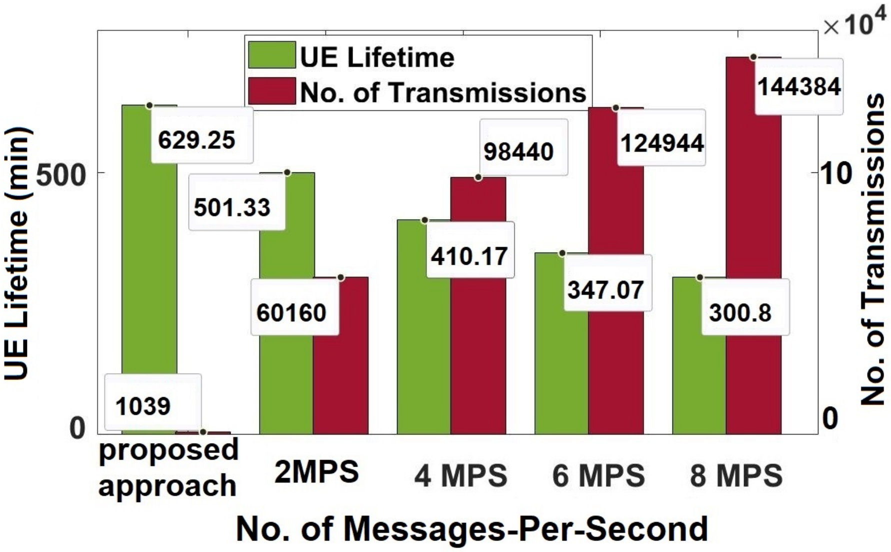


Figure 29: Comparison of the lifetime of a UE in the NW between proposed approach (without response message) and fixed numbers of messages per second.

on-scene available devices have different charging levels in real-life scenarios. Therefore, in what follows, I consider 30 UEs with different charging levels to analyze the average network lifetime, as shown in Fig. 30. A similar behavior is observed in network lifetime and number of transmissions of discovery messages. The proposed approach outperforms baseline transmission for direct discovery thanks to the self-awareness strategy of a UE, based on its current battery level indication and context-awareness, before transmitting the discovery message. For the results shown in Figs. 29 and 30, I consider a very good channel condition with a 100% reliable connection; therefore, a UE transmits a single discovery message in the transmission stage to be discovered.

However, it is not feasible to always have a 100% reliable connection in critical situations. This depends on the channel conditions between the announcer and the monitoring devices. As it has been observed from the experimental results, a reliable direct discovery depends on the operating frequency, RX and TX gains, distance between transmitter and receiver, and different environments. Fig. 31 shows a very revealing result where I use the number of messages transmitted in Fig. 29 and average discovery ratio in the indoor-NLoS scenario to show the comparison between transmitted versus received number of discovery messages.

It can be seen that all the transmitted messages are received when the distance is up to 4 m between two devices and a 100% reliable direct discovery is achieved. The number of received messages or discovery ratio decreases with increasing the distance. It is important to note that when the discovery ratio is low, there is a higher probability that a monitoring device can receive a discovery message with more re-transmissions. However, the challenge is “what could be an optimal number for re-transmitting the discovery messages in the transmission stage?". Thus, the proposed approach suggests that an announcing device should keep transmitting the discovery messages until a response message is not received from the monitoring device. This approach provides a highly reliable direct discovery and improves the UE lifetime in heterogeneous environments, as shown in Fig. 32. A UE lifetime is just 4 minutes shorter as compared to a fixed single transmis-

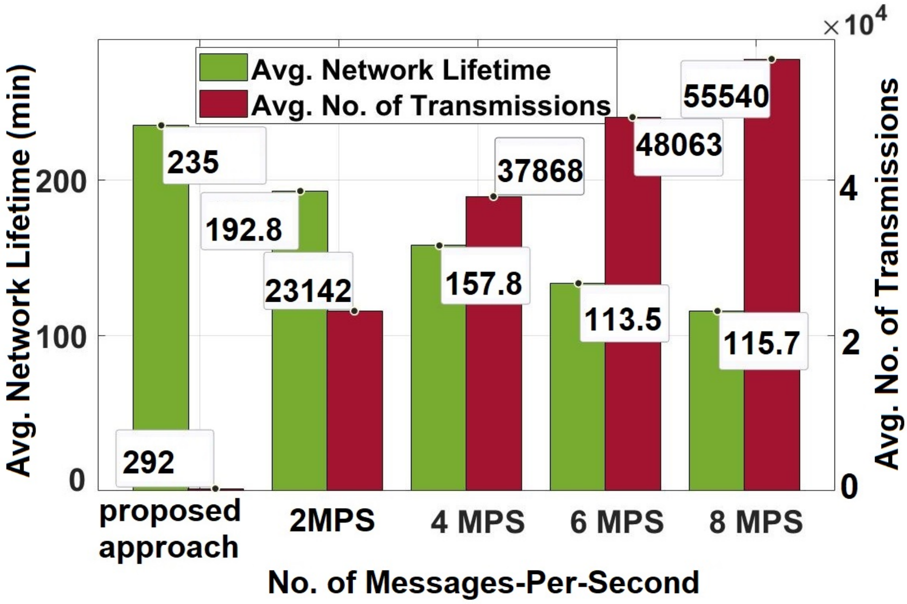


Figure 30: Comparison of the Avg. NW lifetime with 30 UEs between proposed approach (without response message) and fixed numbers of messages per second.

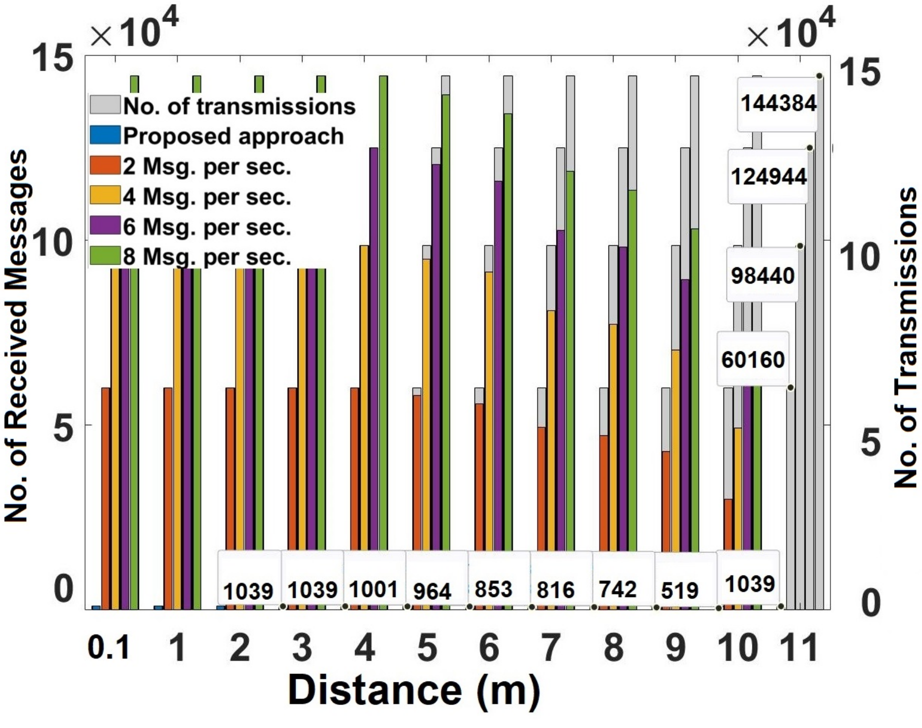


Figure 31: Comparison of the discovery ratio in the indoor-NLoS scenario between proposed approach and fixed numbers of messages per second.

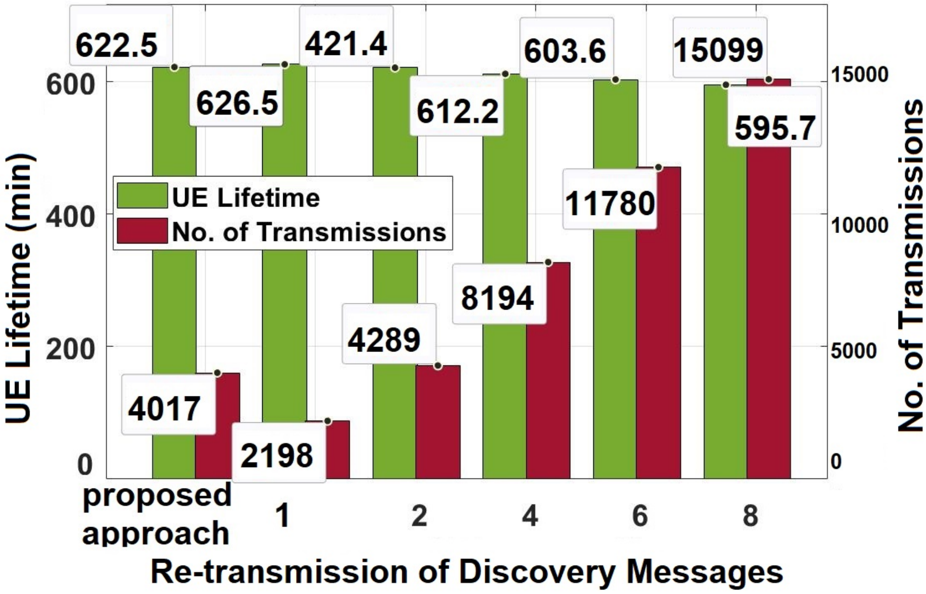


Figure 32: Comparison of the number of re-transmissions between proposed approach (with response message) and fixed numbers of messages per second.

sion in the transmission stage. The proposed approach outperforms all fixed numbers of discovery re-transmissions in the transmission stage except a single transmission. However, a fixed number of discovery re-transmission is not a reliable solution in critical and heterogeneous environments.

Chapter summary

This chapter suggests a self-aware D2D discovery algorithm based on the current position and battery level of a UE in emergency scenarios. The proposed algorithm improves the lifetime of UEs (20-52%) and avoids redundant transmissions of discovery messages without compromising the transmission of critical information. Next chapter presents the empirical demonstration of energy-efficient and context-aware D2D communication in PS real-time scenarios.

5 Direct Discovery-based Cooperative Device-to-Device Communication for Emergency Scenarios in 6G: A Demonstration

This chapter presents a demonstration of a cooperative D2D communication system in an emergency scenario to disseminate important information (e.g., the number of people, their IDs and current location) from an affected zone to a deployed command centre in the absence of cellular infrastructure. The proposed architecture exploits technologies such as clustering, UE-UE-relay, UAVs and context-aware D2D communication to implement the future PSN, as shown in Fig. 33. Further, this chapter covers the implementation of a cooperative D2D communication system and deployment of the implemented prototype in real-time scenarios. The performance of the implemented prototype is also analysed in terms of reliable connectivity and latency. This chapter is based on the following publications:

- Ali Masood, Navuday Sharma, M Mahtab Alam, Yannick Le Moullec, Davide Scazzoli, Luca Reggiani, Maurizio Magarini, and Rizwan Ahmad. Device-to-device discovery and localization assisted by UAVs in pervasive public safety networks. In Proceedings of the ACM MobiHoc workshop on innovative aerial communication solutions for FIrst REsponders network in emergency scenarios, pages 6–11, 2019
- Ali Masood, M Mahtab Alam, Yannick Le Moullec. Direct Discovery-based Cooperative Device-to-Device Communication for Emergency Scenarios in 6G. In 2022 European Conference on Networks (EuCNC) and Communications 6G Summit (Accepted). IEEE, 2022.

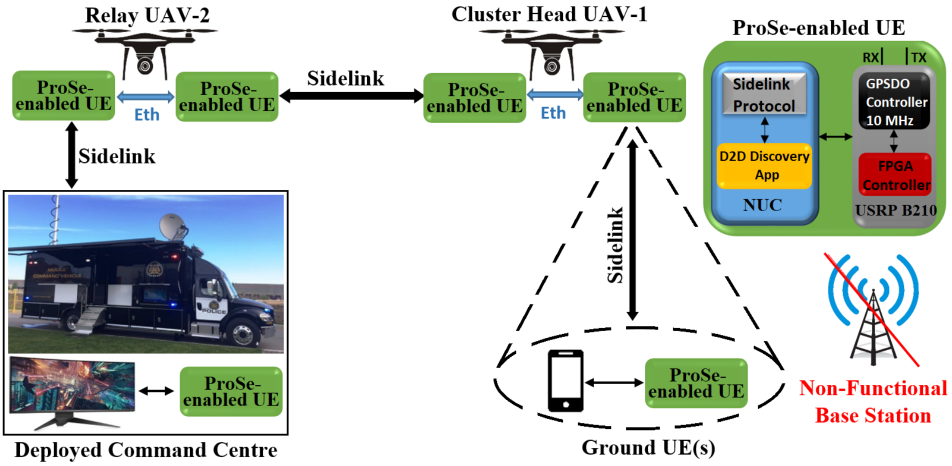


Figure 33: Suggested novel architecture for UAV and D2D communication assisted public safety network for emergency scenarios wherein cellular BSs are non-functional. The ProSe-enabled UEs are able to communicate with the deployed command centre via the multi-hop sidelink connectivity over UAVs.

5.1 Architecture

An emergency scenario has been considered for demonstration where the BS is non-functional. UAVs with ProSe direct discovery features have been deployed to cover the emergency zone and provide connectivity to the ground or remote UEs. UAVs operate as SyncRef UEs and transmit the synchronization signals. PS-enabled UEs with ProSe direct discovery features receive those signals and establish connectivity. A UE shares its important information, such as ID and current location, with the UAV. A UAV sends back an acknowledgement to the announcing UE. UEs use the direct discovery protocol to send this information over sidelink interface. The payload frame format of direct discovery with all the information can be seen in Fig. 34.

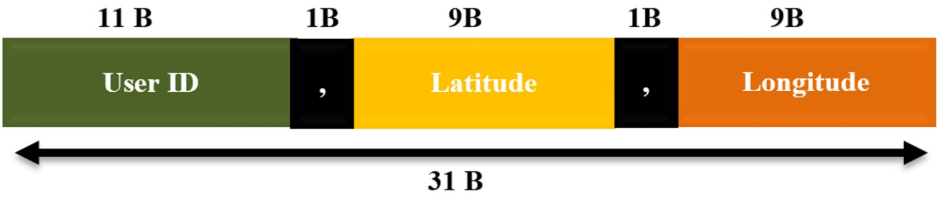


Figure 34: The discovery payload contains information about user ID and current location.

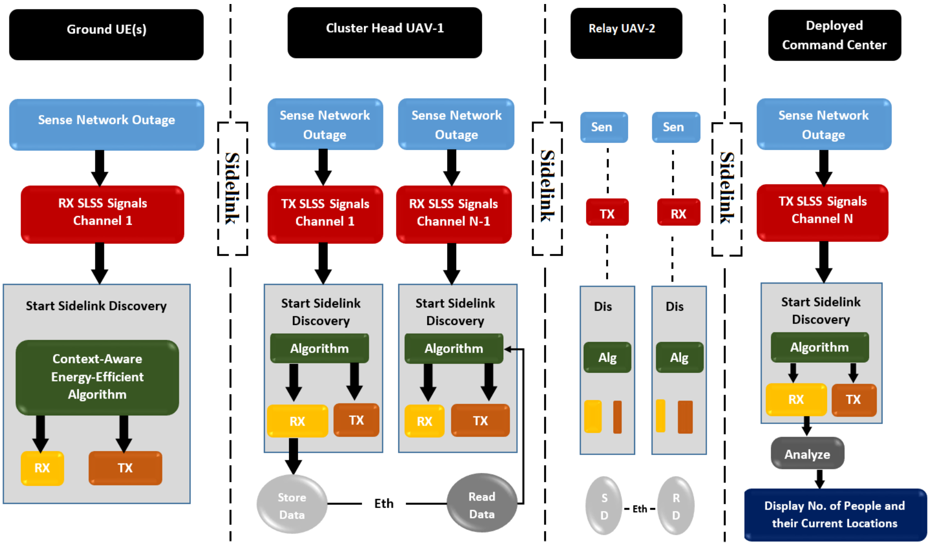
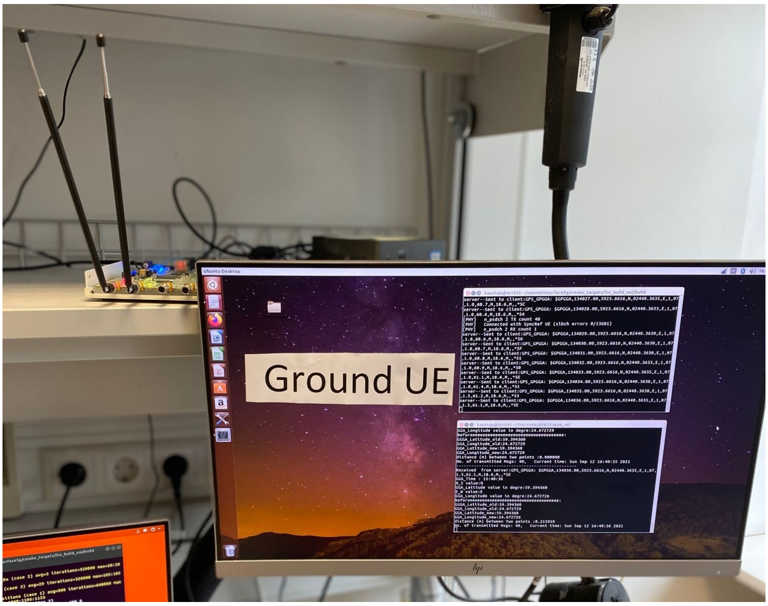


Figure 35: High-level process flow diagram of the implemented prototype. The green boxes depict the implemented contextaware and self-aware intelligent algorithm for minimizing energy consumption while maintaining the necessary information transmission

The implemented context-aware and self-aware intelligent algorithm minimize energy consumption while maintaining the necessary information transmission. When a UE changes its current position, it transmits N number of discovery messages depending on the channel conditions. This approach does not only avoid redundant transmissions and improve the lifetime of a UE but also provides updated information to the first responders. The UAV acts as a cluster head and gathers information from all the UEs inside the coverage area. The UAV passes this information to the next UAV. The second UAV sends this received information to the external deployed command center (as shown in Fig. 35). Both UAVs and the deployed command center use the same discovery protocol to transmit and receive information over the sidelink interface. The second UAV also has both functionalities; it acts as a cluster head to provide connectivity to ground UEs, and as a relay node to pass information to the command center. In demonstrator, the second UAV is used only as a relay node. Thanks to the developed system, the external deployed command center collects all the important information (number of affected people, their identities, and current locations inside the emergency zone). This information at the deployed command center can help first responders to plan their strategies and speed up the rescue process.



```
server--Sent to client:GPS_GPGGA: $GPGGA,134027.00,5923.6616,N,02440.3635,E,1,07
,1.0,60.7,M,18.6,M,,*5C
server--Sent to client:GPS_GPGGA: $GPGGA,134028.00,5923.6616,N,02440.3633,E,1,07
,1.0,60.6,M,18.6,M,,*54
[PHY]   n_psdch 2 TX count 40
[PHY]   Connected with SyncRef UE (slbch errors 0/13681)
[PHY]   n_psdch 2 RX count 1
server--Sent to client:GPS_GPGGA: $GPGGA,134029.00,5923.6616,N,02440.3630,E,1,07
,1.0,60.6,M,18.6,M,,*56
server--Sent to client:GPS_GPGGA: $GPGGA,134030.00,5923.6616,N,02440.3630,E,1,07
,1.0,60.7,M,18.6,M,,*5F
server--Sent to client:GPS_GPGGA: $GPGGA,134031.00,5923.6616,N,02440.3630,E,1,07
,1.0,60.8,M,18.6,M,,*51
server--Sent to client:GPS_GPGGA: $GPGGA,134032.00,5923.6616,N,02440.3633,E,1,07
,1.0,60.9,M,18.6,M,,*50
server--Sent to client:GPS_GPGGA: $GPGGA,134033.00,5923.6616,N,02440.3635,E,1,07
,1.0,61.1,M,18.6,M,,*5E
server--Sent to client:GPS_GPGGA: $GPGGA,134034.00,5923.6616,N,02440.3638,E,1,07
,1.0,61.4,M,18.6,M,,*51
server--Sent to client:GPS_GPGGA: $GPGGA,134035.00,5923.6616,N,02440.3638,E,1,07
,1.5,61.2,M,18.6,M,,*53
server--Sent to client:GPS_GPGGA: $GPGGA,134036.00,5923.6616,N,02440.3635,E,1,07
,1.5,61.1,M,18.6,M,,*5E
```

```
GGA_Longitude value in degre:24.672729
beforeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeee:
GGGA_Latitude_old:59.394360
GGA_Longitude_old:24.672729
GGA_Latitude_new:59.394360
GGA_Longitude_new:24.672729
distance (m) between two points :0.000000
No. of transmitted Msgs: 40,   Current time: Sun Sep 12 16:40:35 2021
---------------------------------------------
Received  from server:GPS_GPGGA: $GPGGA,134036.00,5923.6616,N,02440.3635,E,1,07,
1.5,61.1,M,18.6,M,,*5E
GGA_Time : 15:40:36
N_S value:N
GGA_Latitude value in degre:59.394360
E_W value:E
GGA_Longitude value in degre:24.672726
beforeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeee:
GGGA_Latitude_old:59.394360
GGA_Longitude_old:24.672729
GGA_Latitude_new:59.394360
GGA_Longitude_new:24.672726
distance (m) between two points :0.215959
No. of transmitted Msgs: 40,   Current time: Sun Sep 12 16:40:36 2021
```

Figure 36: Deployed ground (or remote) UE in indoor lab environment.

5.2 Experimental Setup

The OpenAirInterface software (OAI) and USRP-based hardware platforms are used to develop the prototype. An out-of-coverage emergency scenario has been considered when the BS is not available; therefore, all devices are configured as UEs. Each UE has the same components. The following types of equipment are used in OAI/USRP-based prototype.

- USRP B210: The USRP board has been used as the radio front-end hardware part of a UE. Each USRP has two telescopic antennas to transmit and receive the signals.
- Board Mounted GPSDO (TCXO): Each USRP board has a GPSDO module to get a high-accuracy 10 MHz reference clock; all UEs are synchronized with the same reference clock.
- 5-Volt Active GPS Antenna: A GPS antenna has been used with the GPSDO module to obtain the satellite's information to calculate the coordinates of a UE.
- Mini PC: The next unit of computing (NUC) (or "mini PC") has been used for running the software part of a UE. It operates the OAI software having a 3GPP protocol stack, starting from LTE (Rel 8) and going up to 5G (Rel 16). Furthermore, it runs implemented application for direct discovery which is context-aware and energy-efficient. Each OAI-based UE has both mini PC and USRP board connected over USB 3.0 (see Fig. 14).
- Unmanned aerial vehicles: Two UAVs (DJI Matrice 600 Pro) have been used to carry on implemented OAI-based UEs. Each UAV can provide connectivity to ground UE as a SyncRef UE, and gather information from ground UEs as a cluster head. After receiving

information from the ground UEs, the UAV sends it to the next UAV or external deployed command center. A system-level architecture of the prototype can be seen in Fig. 35).

5.3 Deployment in Real-life scenarios

The demonstration has been prepared at Tallinn University of Technology. All the required permissions have been obtained to carry out these activities, for example, RF test license, permit to fly drones, etc. Six OAI-based UEs and two UAVs have been used in the real-life demonstration.

1) Ground UE: One ProSe-enabled UE gas has been deployed as a ground UE in the indoor lab environment on the second floor at an altitude of 6 m. A ground UE searches for the synchronization signals from an external deployed UAV to start communication. A ground UE has a NLoS transmission path with a UAV, which can be seen in Fig. 36.

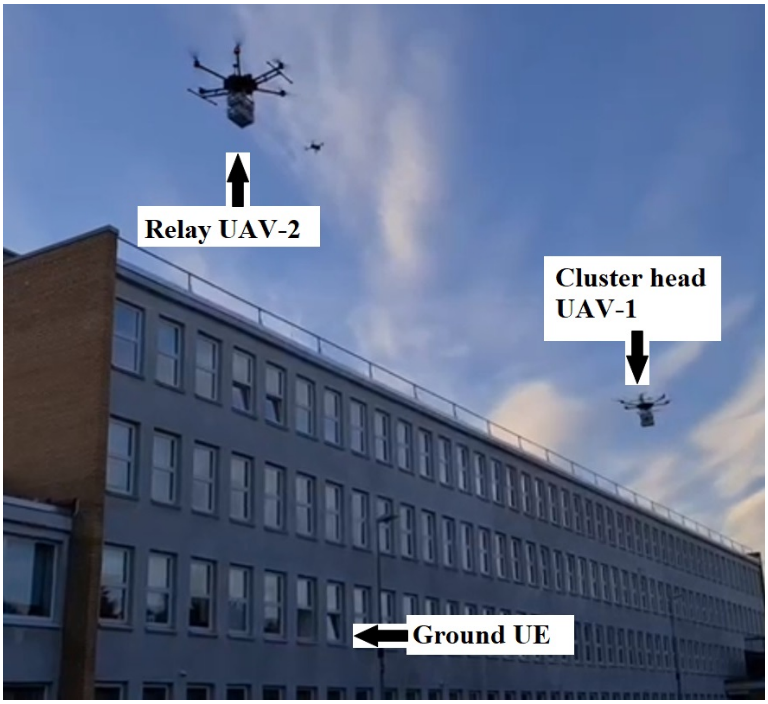


Figure 37: Deployed UAVs in outdoor environment provide connectivity, collect and pass information to the command centre.

2) UAVs: Two UAVs have been deployed in the outdoor environment to provide connectivity to ground UE(s) and relay the information to the deployed command center. Both UAVs have a direct transmission path between them, as shown in Fig. 37. The first UAV has been configured as a cluster head to provide connectivity to ground UE(s), discover the ground UE(s), and send data to the next UAV. The first UAV has two ProSe-enabled UEs (i.e. two mini-PCs and two USRP boards). The first UE communicates with ground UE(s) and collects information using one channel. The second UE has been used to enable communication between UAVs and transmit the received information to the next UAV using another channel to extend the range. Both UEs have mounted on a UAV communicate with each other over an Ethernet cable. The second UAV has the same functionalities. Which receives data from the first UAV and relays it to the external deployed command

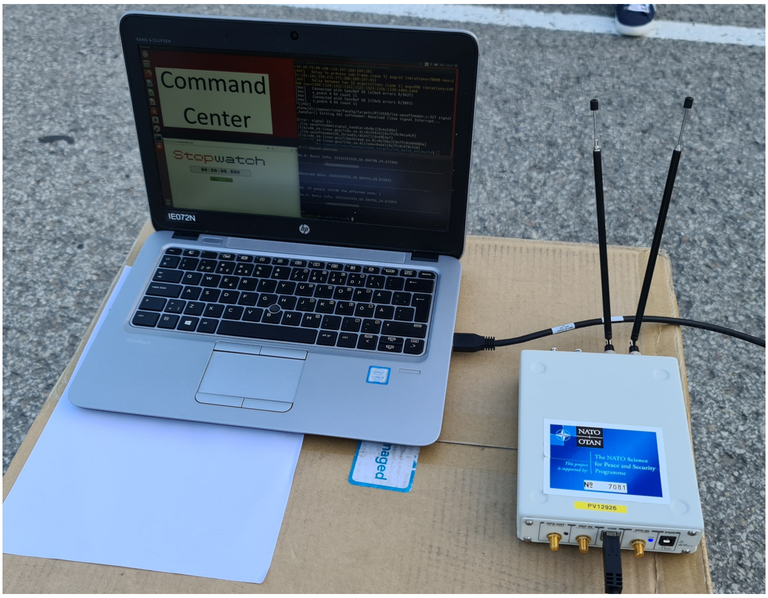
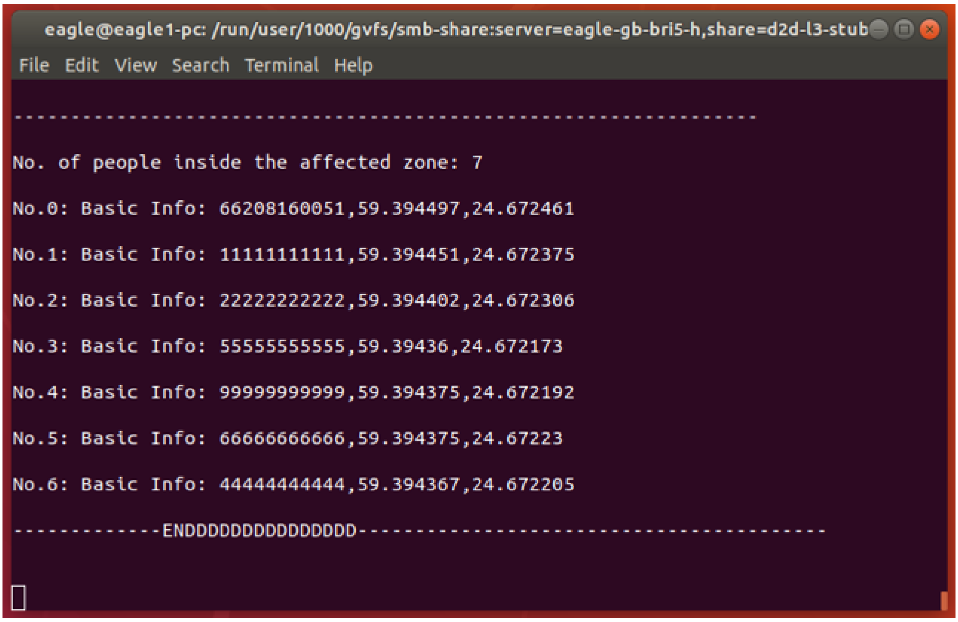


Figure 38: Deployed command centre in outdoor environment.

center, as shown in Fig. 35.

3) External command center: One ProSe-enabled UE has been configured as the external command center and deployed in the outdoor environment, as shown in Fig. 35. The command center receives all the information (such as the number of affected people, their identities and current locations in a disaster zone) and displays it in real-time.



```
------------------------------------------------------------------

No. of people inside the affected zone: 7

No.0: Basic Info: 66208160051,59.394497,24.672461

No.1: Basic Info: 11111111111,59.394451,24.672375

No.2: Basic Info: 22222222222,59.394402,24.672306

No.3: Basic Info: 55555555555,59.39436,24.672173

No.4: Basic Info: 99999999999,59.394375,24.672192

No.5: Basic Info: 66666666666,59.394375,24.67223

No.6: Basic Info: 44444444444,59.394367,24.672205

-------------ENDDDDDDDDDDDDDDD-----------------------------------------
```

Figure 39: Screenshot of some of the information received at the deployed command centre.

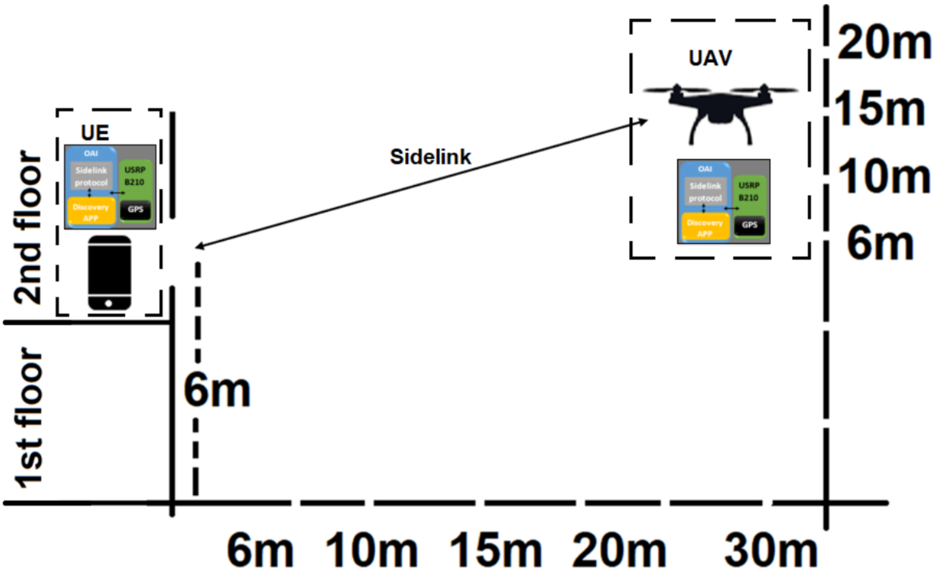


Figure 40: Considered scenario to evaluate the D2D link between UAV and ground UEs.

5.4 Performance evaluation

As previous results [4] show that a reliable direct discovery is a combination of carrier frequency (f), transmitter and receiver amplification gains (G_{Tx}, G_{Rx}), distance between transmitting and receiving devices (D), and different environments. Therefore, it has been made sure to use the best parameters to establish a reliable communication link, i.e., f = 857 MHz, G_{Tx} = 60 dB, G_{Rx} = 60 dB. More details can be found in Chapter 3.

Before deploying the prototype in a real-life scenario, I have investigated it first in a lab environment. A demonstration video[2] illustrates that it took one minute and forty seconds to establish a network and relay data from the affected zone to the command centre. Afterwards, the prototype has been deployed in a real-life outdoor scenario[3], as explained in Sub-section 5.3. The response time is approximately four minutes and thirteen seconds to deploy the UAVs, establish connectivity, and pass information from the affected zone to deployed command centre. Fig. 39 shows the information received at the deployed command centre. It can be seen that the command centre has critical information such as the number of people inside the affected zone, their IDs and current locations. This real-time information can help the first responders to trace the affected UE and speed up the rescue process.

The position of UAV is influential to provide reliable connectivity to ground UEs in such emergency scenarios. Therefore, it is important to evaluate the D2D link between UAV and ground UEs. A UE has been deployed in the indoor environment on the second floor at an altitude of 6m. A UAV has been deployed in the outdoor environment at multiple altitudes to analyze the performance of ProSe direct discovery in terms of reliability and maximum range of discovery, as shown in Fig. 40.

Figure 41 shows the impact on the performance of direct discovery due to the position of the UAV. It can be seen in all considered cases that the average direct discovery

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[2] https://bit.ly/3GDyVMk

[3] https://bit.ly/3A6KDfX

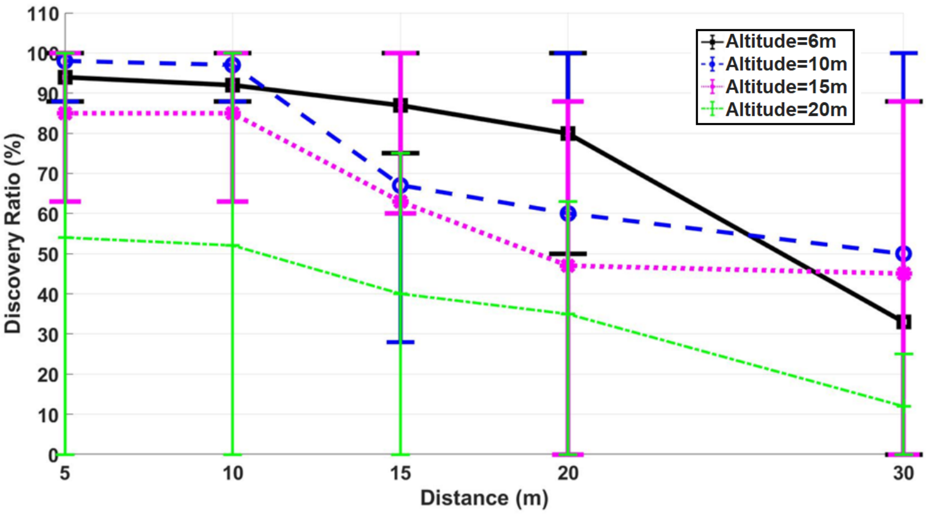

Figure 41: The impact on the performance of direct discovery due to the position of the UAV

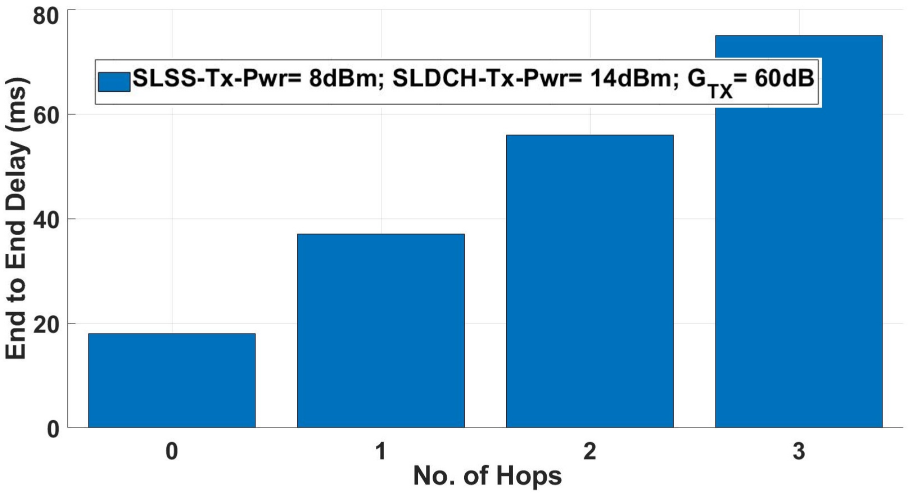

Figure 42: The average time (end-to-end delay) to discover the UE in PS scenarios as a function of number of hops.

decreases gradually by increasing the distance between the UAV and UE in the network. The average discovery ratio is more than 90% when the distance is up to 10 meters between UAV and ground UE, and the altitude of UAV is up to 10 meters. When the distance increases from 10 to 15 meters and the altitude is 10 meters, the discovery ratio decreases abruptly from 97% to 67%, shown as a blue dashed line with circle markers in Fig. 41. After 15 meters, the discovery ratio decreases gradually and reaches 5% at 30 meters.

It can be noticed that as the altitude of the UAV increases, the discovery ratio decreases. The discovery ratio is more than 95% at 5 meters when the altitude of the UAV is up to 10 meters. While the discovery ratio is 55% at 5 meters when the altitude increases to 20 meters. When both the UAV and UE have the same altitude (at 6 meters) that gives the best performance of direct discovery in terms of reliability and maximum range of discovery, shown as a black solid line with square markers in Fig. 41.

The average time to discover the UE (end-to-end delay) is the same in both indoor and outdoor scenarios after establishing a 100% reliable connectivity for direct discovery. Fig. 42 shows that end-to-end delay depends on the no. of hops. When there is no relay node between two UEs, the end-to-end delay is 18 ms. The end-to-end delay increases linearly with the number of hops.

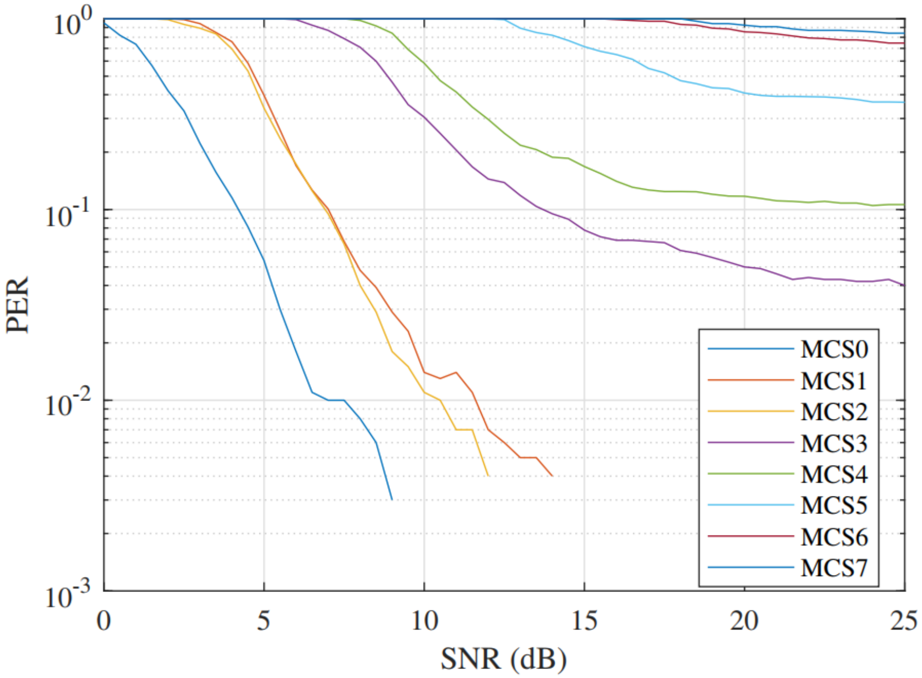

Figure 43: Packet error rate for Air-to-Ground transmission link between the UAV and UE.

The Air-to-Ground (A2G) transmission link between the UAV and UE is very crucial in PS scenarios. The reliability of the A2G transmission link also depends on the signal quality. To evaluate the signal quality of A2G transmission link, simulations have been carried out using MATLAB to measure packet error rate (PER) and throughout with respect to SNR for different MCS indexes. A simple path loss and shadow-fading channel model have been used for simulation purposes, which are generally used to describe the transmission link between the UAV and ground UE [105].

The PER is minimum for lower MCS values and increases for higher values since higher MCS provides more data but also least robust links, so the probability of losing data is higher. Furthermore, as seen from Fig. 43, MCS 0 link provides the lowest PER when the SNR is less than 15 dB. And when the SNR is between 15 dB to 25 dB, MCS 3 link provides the lowest PER.

As seen from Fig. 44, a higher throughput is achieved for higher MCS values for a given range of SNR. For example, MCS 4 and 5 provide higher throughput for SNR above 10 dB. While below 10 dB, MCS 2 achieves better performance, and finally, MCS 0 achieves the best throughput performance for the lowest SNR values. Hence, a higher SNR value shows a stronger signal strength, which provides reliable transmissions and allows higher data rates.

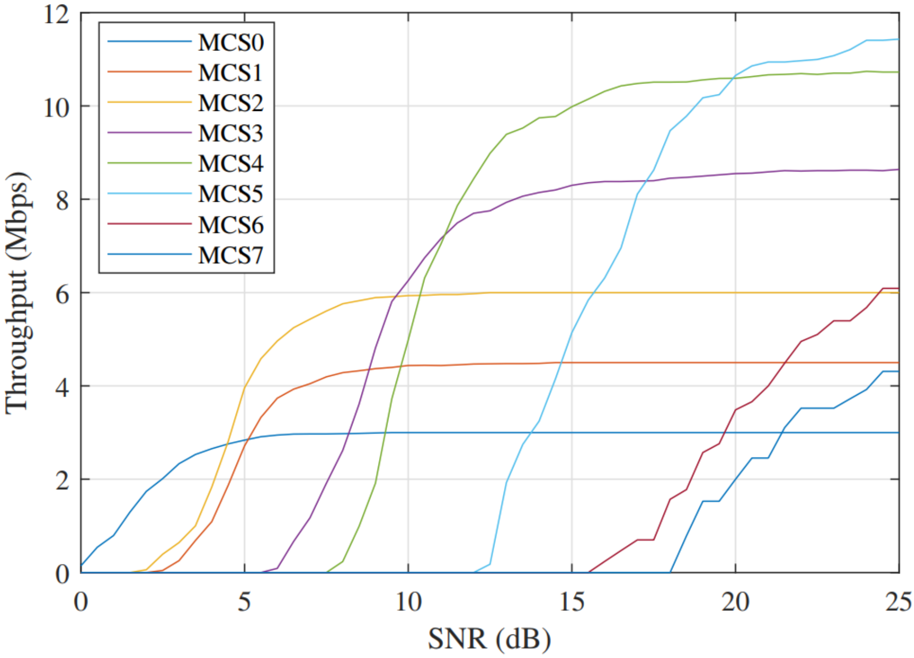

Figure 44: Throughput for Air-to-Ground transmission link between the UAV and UE.

Therefore, some additional experiments have been carried out in a real-time lab environment to further characterize the performance of ProSe direct discovery with respect to SNR. In addition to previous findings, I investigate the impact of the transmission power of SLSS signals (SLSS-Tx-pwr) and PSDCH channel (PSLDCH-Tx-pwr), and G_{Tx} gains on ProSe direct discovery: Here f = 857 MHz and D = 6 m. Fig. 45 shows the effect of the transmission power of SLSS signals and PSDCH channel on the signal-to-noise ratio. It can be observed that SNR values improve by increasing the G_{Tx} gain except if the values of SLSS-Tx-pwr and PSLDCH-Tx-pwr go above 8 dBm and 3 dBm, respectively. The maximum SNR (23 dB) value is obtained when G_{Tx} = 90 dB, SLSS-Tx-pwr = -6 dBm and PSLDCH-Tx-pwr = 3 dBm, shown as a black dashed line with a square marker in Fig. 45. A strong interference can be noticed between SLSS and PSDCH with high values of transmission power and gain. The SNR value improves 0 to 20 dB for G_{Tx} gains ranging from 20 to 60 dB when the value of PSLDCH-Tx-pwr is 14 or more than 14 dBm, shown as magenta lines with asterisk and cross markers. Afterwards, the SNR starts to decrease gradually from 20 dB to 13dB for

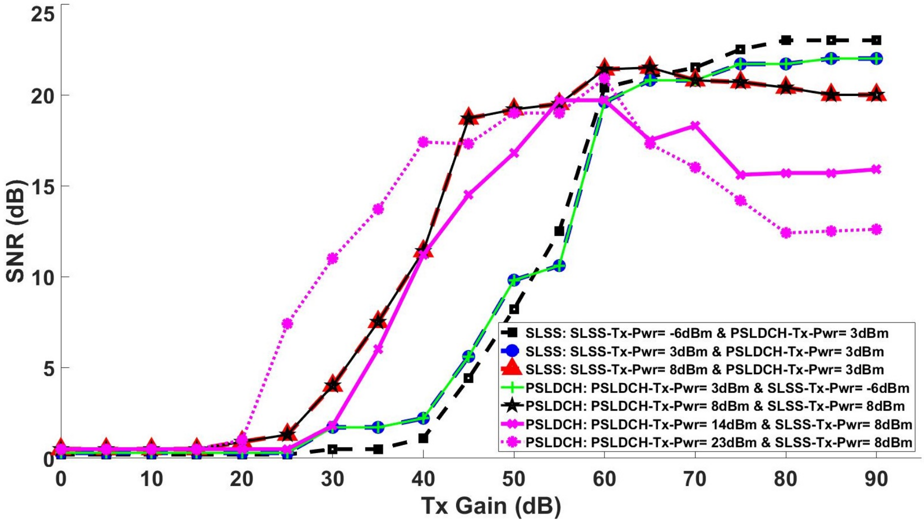

Figure 45: SNR as a function of transmission power (values inset) and transmission gain (X-axis) of SLSS signals and PSDCH channel.

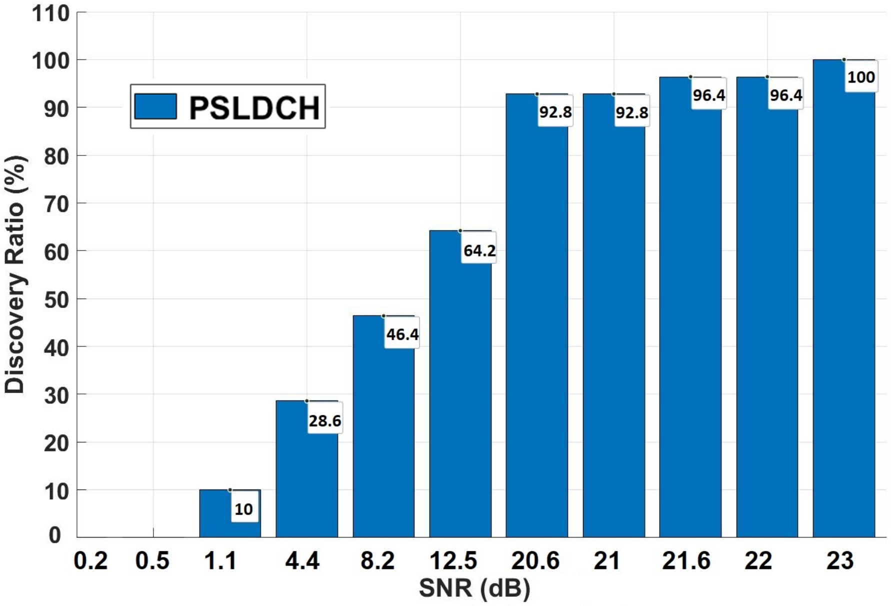

Figure 46: Direct discovery ratio as a function of SNR.

transmission gains ranging from 60 dB to 90 dB, shown as a magenta dotted line with asterisk markers. This shows an interference between SLSS and PSDCH that is not desirable for reliable transmission.

A reliable direct discovery is directly related to SNR. It can be observed from Fig. 46 that as the SNR value increases, the discovery ratio improves as well. The discovery ratio is always more than 90% for SNR values ranging from 20 to 22 dB. When the SNR value is 23 dB, it provides a 100% discovery ratio and the best network connectivity.

Chapter summary

This chapter suggests technologies such as clustering, UAVs, D2Dand relay communication for future PSNs in 5G and beyond, and demonstrates them in real-time scenarios. Such PSN can help the first responders to establish reliable connectivity and get critical information in emergency scenarios. Which can eventually speed up the rescue process and reduce the response time. Furthermore, this chapter provides a description of a developed prototype and analyses the performance of implemented prototype in terms of reliable connectivity and latency. Whereas, next chapter provides the concluding remarks and future research directions.

6 Conclusion

The main goal of my PhD work is to propose an autonomous solution for PSNs to overcome the challenges faced by first responders in PS scenarios, as discussed in Chapter 1, Section 1.2. With regard to this, I addressed the following RQs in this PhD thesis (as stated earlier in Chapter 1, Section 1.5):

1. RQ1: What architecture can provide fundamental information to first responders in emergency scenarios? i.e., what enabling technologies are required to disseminate the critical information from the affected zone to first responders?

2. RQ2: How to create a real-time heterogeneous environment for D2D communication performance analysis when the base stations are not available and what are the suitable parameters to obtain reliable connectivity and maximum range in such a scenario?

3. RQ3: In out-of-coverage scenarios, a D2D-enabled UE transmits the discovery messages with a fixed period. A UE will keep transmitting the messages even if the first responder has already discovered it, or UE does not have any new information to transmit. If a UE transmits redundantly it will consume more energy, and eventually, it will die out swiftly in the network. Hence, how to avoid redundant transmission of information and optimize the communication to improve the lifetime of the network significantly without compromising on the reliable transmission of critical information?

4. RQ4: How to implement autonomous, energy-efficient, context-aware and intelligent PSN to provide up-to-date critical information in a few minutes (as a response time) to first responders in emergency scenarios; and demonstrate it in a real-life scenario?

I selected an applied research method to answer these research questions. To the best of my knowledge, this PhD thesis presents the first experimental study in the open literature with results characterizing ProSe direct discovery in heterogeneous real-time environments. This PhD thesis makes the following contributions:

Contributing towards RQ1, A comprehensive descriptive analysis of PS scenarios, D2D communications, evolution of D2D communications in 3GPP, existing PSNs, recent related funded Projects and the emerging techniques for future PSNs has been presented in [Publication I and Publication II] and discussed in Chapter 2. This analysis helped me in order to understand the challenges faced by first responders in emergency scenarios, as well as, how to develop the future PSN which can cope with first responders during emergency scenarios and speed up the disaster relief.

Then, the OAI open-source software and USRPs hardware platform has been developed to enable the ProSe direct discovery-based D2D communication in the absence of BSs. The developed setup has been used to perform the experimental activity to evaluate the performance of ProSe direct discovery in terms of discovery ratio, reliability, and maximum range of direct discovery in three different scenarios: i) indoor LoS, ii) indoor NLoS, and iii) outdoor LoS [Publication III]. The experimental results highlight that the performance of ProSe direct discovery is a function of carrier frequency, transmission power, transmitter and receiver gains, distance between transmitter and receiver, and number of

UE in the D2D network. The experimental results suggest suitable values for transmission power, gains and frequencies that are required for a reliable D2D network. In addition, the coverage analysis can help the first responders to deploy the UAVs and command center to cover the affected area for reliable communication, and reveal the importance of these factors even at frequencies below 1 GHz. These contributions are in line with RQ2 and discussed in Chapter 3.

Contributing towards RQ3, the proposed approach provides energy-efficient context-aware direct discovery in emergency scenarios that avoids redundant transmissions without compromising the transmission of critical information and improves the UE lifetime significantly (20-52%) in the D2D network compared to the baseline approach [Publication IV]. Moreover, the proposed algorithm (discussed in Chapter 4) provides up-to-date critical information (e.g., number of affected people, their locations and identity) to first responders. Which can help first responders to locate and trace the affected people inside the emergency zone, and speed up the rescues process.

Finally, This PhD thesis suggests technologies such as clustering, UAVs, D2D and relay communication for next-generation PSNs and demonstrates it in a real-life scenario, as discussed in Chapter 5. Such PSN can help the first responders to establish reliable connectivity and get critical information in a few minutes inside the disaster zone. Experiments have been carried out to evaluate the performance of direct discovery in terms of reliable connectivity and latency in real-life scenarios [Publication V]. Experimental results show that the discovery ratio is always higher than 90% for SNR values above 20 dB and reaches 100% for SNR values of 23 dB. The end-to-end delay is as low as 18 ms when there is no relay node between two UEs, and increases linearly with the number of hops. In addition, demonstration videos illustrate that it takes approximately one minute and forty seconds to deploy the equipment, establish network connectivity and relay critical information from the affected zone to deployed command centre in a real-time lab environment, and four minutes and thirteen seconds in a real-life outdoor scenario.

6.1 Future work

To extend the work presented in this thesis, some future directions are discussed as follows:

- Adaptive transmission power: For out-of-coverage scenarios, the UEs use preconfigured values for transmission power. However, it was observed from our experimental results that the transmission power of a UE has an impact on the reliability of D2D network depending on channel conditions and distance between two UEs. It is important for the UE to adapt the transmission power according to channel conditions, which will conserve energy and improve the battery life of a UE [106]; adding such an adaptive mechanism could be included in a next iteration of the presented setup.
- Integration of D2D communication with UAVs: In an affected or remote zone, it is often difficult to establish network connectivity due to lack of infrastructure. However, UAVs can be deployed to provide reliable D2D communications, which makes D2D communication a promising technology for PS scenarios. In a real-life situation, manual flight control of UAVs is not a reliable solution because an affected person can move anywhere and a UAV configured as a SyncRef source has to follow ground UEs to keep the D2D connection alive. Therefore, it is desirable to onboard some

intelligence on the UAVs so that they can change their position autonomously to provide reliable D2D connectivity and discover more ground UEs, as suggested in [107, 108].

- Interference management: Interference is the main reason for performance degradation in D2D networks. Cellular users and D2D users can create Interference. Although various interference aware strategies have been proposed to improve system performance, interference management is still an active research topic [109, 110]. Dynamic algorithms could be implemented in the developed setup as a possible future direction to avoid adjacent channel and inter-channel interference, and intra-cell and inter-cell interference, which could provide better communication links for both cellular and D2D users.

- Compatibility in heterogeneous network: In 5G and beyond, devices can use different protocols (e.g. Wi-Fi, Bluetooth, Sidelink, etc.) to perform D2D communications. Exploiting such diversity remains an open issue to provide fully reliable D2D communication links between devices in a heterogeneous network [111, 112]. Algorithms for automatically and dynamically selecting the most suitable technology and routing paths could be developed as a next step and the presented setup could be extended with such complementary connectivities for improved reliability.

- Indoor positioning: It is envisioned that D2D communications will be highly intelligent and context-aware in 5G and beyond. Location awareness is the most important element of context awareness. GPS provides accurate positioning for outdoor scenarios, but this is not a reliable solution for indoor positioning (our experiments with GPSDO module confirmed that they cannot receive satellite signals properly and have poor signal strength in most indoor scenarios). For accurate indoor positioning in D2D networks, different localization techniques (time of arrival, time difference of arrival, time of flight, etc.) [113] based on e.g. ultra wide band (UWB) technology can be investigated as a future direction.

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Abstract

Implementation and Demonstration of a Device-to-Device Communication System for Emergency and Critical Scenarios

In emergency scenarios (e.g., earthquakes, floods, terrorist attacks) that the availability of the cellular infrastructure, e.g. base station (BS), cannot be guaranteed and is often unavailable due to physical damages. Thus, affected people who are stuck inside a disaster zone cannot communicate with first responders (police, fire department, etc.). The first responders do not obtain the basic but important information such as the number of affected people, their locations and identity, etc. Due to unclear information, the first responders remain unable to take immediate actions and step into the disaster zone to provide relief, even after many hours. Disaster relief can include medical assistance, search and rescues operations, evacuations, etc. The main challenges for the first responders from an ICT point of view in such incidents are to establish reliable connectivity in the absence of cellular infrastructure, disseminate critical information, and locate and trace the affected people inside a disaster zone. However, existing technologies for public safety network (PSN) are not best suited to deal with these challenges and cope with the first responders during disaster situations to speed up the rescue process because a proper communication infrastructure is required for most of the classical PSNs to operate.

Thus, it is highly essential to develop reliable and adaptive PSNs to counter such kind of emergency situations. Device-to-device can play a significant role to design next-generation PSN in beyond 5G (B5G) communication systems. D2D communication allows direct communication between two UEs in proximity regardless of the availability of a cellular BS. Such a technology can support first responders in emergency scenarios to provide important information and speed up the rescue process. It is envisioned that D2D communication in the B5G network will be highly intelligent, markedly context-aware, extremely heterogeneous and exceptionally energy efficient; and support several services in the B5G network such as target monitoring, emergency search and rescue, etc [114, 112, 115].

Aiming at such optimizations, this PhD thesis presents the experimental study on direct discovery-based D2D communication for out-of-coverage public safety (PS) scenarios and the following contributions.

This PhD thesis presents the implementation of a testbed to perform D2D direct discovery in the absence of BSs. Experimental measurements have been carried out in real-time heterogeneous environments to characterize the performance of D2D direct discovery in terms of reliability of successful discovery message reception, and maximum discovery range. The experimental results highlight the impact on the direct discovery due to the carrier frequency, transmission power, transmitter and receiver gains, and the distance between transmitter and receiver in three different scenarios: i) indoor LoS, ii) indoor NLoS, and iii) outdoor (LoS).

Further, this PhD thesis suggests an energy-efficient and context-aware intelligent algorithm for direct discovery based on the current position and battery level of a UE. Which can help first responders to get up-to-date critical information, and locate and trace the affected people in emergency scenarios. The proposed algorithm avoids redundant transmissions without compromising the transmission of critical information, and enhances significantly the lifetime of UEs (20-52%) in the D2D network compared to the baseline approach.

Finally, this PhD thesis demonstrates a cooperative D2D communication system in an emergency scenario to disseminate important information (e.g., the number of people, their IDs and current location) from an affected zone to the external command centre

deployed by first responders in the absence of a BS. This research work suggests context-aware proximity services-based direct discovery along with UAVs as a possible solution to implement the next generation PSN in B5G networks. Furthermore, this PhD thesis evaluates the performance of direct discovery in terms of connectivity reliability and latency in emergency scenarios. Under specific emergency scenarios, it is possible to deploy the equipment, establish connectivity, and pass information from the affected zone to deployed command center in approximately one minute and forty seconds in a real-time lab environment, and four minutes and thirteen seconds in a real-life outdoor scenario.

Kokkuvõte

Seadmetevahelise sidesüsteemi rakendamine ja demonstreerimine hädaolukorra ja kriitiliste juhtumite jaoks

Hädaolukorra juhtudel (nt maavärinad, üleujutused, terrorirünnakud), mobiilside taristu (nt tugijaamad (BS)) kättesaadavus ei ole garanteeritud ja sageli pole saadaval füüsiliste kahjustuste tõttu. Seega ei saa katastroofipiirkonda jäänud inimesed suhelda eesliini töötajatega (politseinikud, tuletõrjujad, jne). Eesliini töötajad ei saa olulist põhiinformatsiooni, näiteks mõjutatud inimeste arv, nende asukoht ja isik jne. Ebaselge informatsiooni tõttu ei saa eesliini töötajad koheselt tegutseda ja katastroofipiirkonda abi osutada isegi mitme tunni pärast. Katastroofiabi võib hõlmata meditsiinilist abi, otsingu- ja päästeoperatsioone, evakueerimist jne. Peamised väljakutsed eesliini töötajatel IKT vaatenurgast selliste vahejuhtumite puhul on usaldusväärse ühenduvuse loomine mobiilside taristu puudumisel, kriitilise informatsiooni levitamine ning mõjutatud inimeste leidmine ja jälgimine katastroofipiirkonnas. Olemasolevad avalike teenuste võrgustiku (PSN) tehnoloogiad ei sobi aga kõige paremini nende väljakutsetega toimetulemiseks ja katastroofiolukordades eesliini töötajatele päästeprotsessi kiirendamiseks, kuna enamiku klassikaliste PSN-ide toimimiseks on vaja korralikku side taristut.

Seega on selliste hädaolukordade lahendamiseks väga oluline välja töötada usaldusväärsed ja kohanduvad PSN-id. Seadmetevaheline side (D2D) võib mängida olulist rolli järgmise põlvkonna PSN-i kujundamisel 5G (B5G) sidesüsteemides. D2D-side võimaldab otsesuhtlust kahe läheduses asuva kasutajaseadme (UE) vahel sõltumata mobiilsidevõrgu tugijaama saadavusest. Selline tehnoloogia võib toetada eesliini töötajaid hädaolukorra juhtudel, et anda olulist informatsiooni ja kiirendada päästeprotsessi. Eeldatakse, et D2D-side B5G võrgus on väga intelligentne, selgelt kontekstiteadlik, äärmiselt heterogeenne ja erakordselt energiasäästlik ning toetab mitmeid B5G võrgu teenuseid nagu objekti jälgimine, hädaabiotsing ja -pääste, jne. Käesolev doktoritöö tutvustab eksperimentaalset uuringut otsese avastuspõhise D2D-side kohta levita avaliku turvalisuse (PS) stsenaariumide ja järgnevate kaastööde jaoks.

See doktoritöö tutvustab testplatvormi rakendamist D2D otsetuvastamise teostamiseks tugijaama (BS) puudumisel. Eksperimentaalsed mõõtmised on läbi viidud reaalajas heterogeensetes keskkondades, et iseloomustada D2D otseavastamise toimivust eduka avastussõnumi vastuvõtmise usaldusväärsuse ja maksimaalse avastusulatuse osas. Katsetulemused toovad esile mõju otsetuvastuse sõltuvust kandesagedusest, ülekandevõimsusest, saatja ja vastuvõtja võimendusest, ning saatja ja vastuvõtja vahelisest kaugusest kolme erineva stsenaariumi korral: i) siseruumides (otsenähtavus), ii) siseruumides (mitte otsenähtavus) ja iii) väljas (otsenähtavus).

Lisaks soovitab käesolev doktoritöö energiatõhusat ja kontekstiteadlikku intelligentset algoritmi otsetuvastamiseks, mis põhineb kasutajaseadme (UE) praegusel asukohal ja aku tasemel, mis võib aidata eesliini töötajatel saada ajakohast kriitilist informatsiooni ning tuvastada ja jälgida mõjutatud inimesi hädaolukorra juhtudel. Pakutud algoritm väldib üleliigseid edastusi säilitades sealjuures kriitilise teabe ja pikendab oluliselt kasutajaseadmete (UE) eluiga (20-52%) D2D-võrgus võrreldes algse lähenemisviisiga.

Lõpetuseks demonstreerib käesolev doktoritöö ühist D2D-sidesüsteemi hädaolukorra juhtumi korral, et levitada olulist informatsiooni (nt. inimeste arv, nende ID-d, praegune asukoht) mõjutatud tsoonist välisele juhtimiskeskusele, mis on loodud eesliini töötajatele tugijaama (BS) puudumise korral. Võimaliku lahendusena järgmise põlvkonna PSN-i rakendamiseks B5G-võrkudes pakub see uurimistöö välja kontekstiteadliku lähedusteenust koos UAV-de kasutamisega. Lisaks hinnatakse käesolevas doktoritöös otsetuvastamise toi-

mivust ühenduvuse usaldusväärsust ja latentsust hädaolukorra juhtudel. Spetsiifiliste hädaolukorra juhtudel on võimalik reaalajas laborikeskkonnas seadmed kasutusele võtta, ühenduvus luua ja edastada informatsiooni mõjutatud tsoonist kasutusele võetud juhtimiskeskusesse ligikaudu ühe minuti ja neljakümne sekundiga ning nelja minuti ja kolmeteistkümne sekundiga välitingimustes reaalses olukorras.

Appendix 1

I

Ali Masood, Navuday Sharma, M Mahtab Alam, Yannick Le Moullec, Davide Scazzoli, Luca Reggiani, Maurizio Magarini, and Rizwan Ahmad. Device-to-device discovery and localization assisted by UAVs in pervasive public safety networks. In *Proceedings of the ACM MobiHoc workshop on innovative aerial communication solutions for FIrst REsponders network in emergency scenarios*, pages 6–11, 2019

Device-to-Device Discovery and Localization Assisted by UAVs in Pervasive Public Safety Networks

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ABSTRACT

Device-to-device (D2D) can be a key paradigm to design Pervasive Public safety Networks (PPNs) which could allow the User Equipment (UEs) to communicate directly in disaster scenarios. Recently, the use of Unmanned Aerial Vehicles (UAVs) has been suggested in PSNs to enhance situational awareness and disseminate critical information to the deployed Base Station (BS) by providing reliable connectivity. In this paper, we are interested in direct discovery, one of the functions provided by Proximity Services (ProSe). We consider a disaster situation when no core network is available and transmit the discovery message over an UAV-to-UE link. Simulation results are presented and discussed based on the root-MUSIC algorithm to locate the affected UE assisted by UAV, achieving a ca. one meter accuracy at over 200 m. Furthermore, we analyse the performance of the link by calculating Packet Error Ratio (PER) and throughput, achieving up to 11 Mbps.

KEYWORDS

Device-to-device communication, UAV, Pervasive public safety network, Proximity Services, Direct Discovery, Packet Error Ratio.

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1 INTRODUCTION

Pervasive Public Safety Network (PPSN) can play a significant role to save lives and infrastructure in emergency scenarios such as natural disasters, terrorist attacks, fires, etc. The latest services provided by the 3rd Generation Partnership Project (3GPP) standardization can be a vital paradigm to design next generation PPSNs such as proximity services (ProSe) in the long-term evolution (LTE) standard. ProSe, also referred to as device-to-device (D2D) communication, allows direct communication between user equipment (UEs) that are in close proximity [2].

D2D communication can be operated in three scenarios depending on the network condition of the UEs: in-coverage, out-of-coverage, and partial coverage. In in-coverage, UEs are assisted by the base station (BS). When UEs are out-of-coverage, they use preconfigured parameters. In partial coverage, out-of-coverage UEs are assisted by UEs within the coverage area to connect with the BS [17]. D2D communication enables reducing the network burden of the cellular network, and improves the energy efficiency, spectrum efficiency [9], and (as of particular interest in this paper) cellular coverage in disaster scenarios through multi-hop based D2D communication [6].

Direct Discovery, one of the key features of ProSe, detects and identifies other ProSe-enabled UEs in proximity using direct radio signals. For public safety (PS) use, two models are defined for Direct Discovery: modal A ("I am here") and model B ("who is there?") [2]. In PS direct discovery with model A, the announcing UE transmits the announcement message, while the other UEs just monitor. On the other hand, Model B is two way process. In the first step, the discoverer UE will ask from other UEs what they have to share by sending solicitation discovery messages. In the second step, the discoveree UE transmits the response discovery message.

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Projects	Year	Funding Organization	Architecture	Standards	D2D Communications	Protocols Stack	Target Applications
BSA-D2D [1]	2011-2012	FP7 Ref. Nr: 274523	LTE	In-coverage	Improve network capacity	PHY layer	Cellular communication
PSS [15]	2016-2019	NSF, USA Ref. Nr: NSF EARS-2014-1443946	LTE	In-coverage mode, WiFi spectrum sharing	Spectrum efficiency	PHY layer	General purpose public safety
UAV4PSC [14]	2015-2020	NSF, USA Ref. Nr: CNS-1453678	5G	WiFi, LTE-A, LTE-U	UAVs to ensure connectivity	PHY and MAC layer	Public Safety Communication
COUNTER-TERROR [20]	2018-2021	NATO-SPS	LTE-Release 14 (ProSe design and evaluation)	Out-of-coverage mode: Direct, relay and multihop	Dynamic heterogeneous resource management, reliable and robust connectivity	PHY, MAC, and Network layers	Public safety in terrorist attack

Table 1: Summary of the up-to-date related funded Projects.

The size of the discovery message for Group Member Discovery Announcement is 29 bytes with Model A, including information about the announcing UE, as used for our simulations presented later in the paper. The other parameters included in this message and detailed information about the discovery messages can be found in [3].

Recently, the use of unmanned aerial vehicles (UAVs) has been proposed in PSNs [14, 20] to have detailed situational awareness. UAVs could reduce the response time for rescue teams to take certain actions by providing the accurate location [12] of the affected persons in a disaster situation and save many lives. UAVs could connect the emergency zone with the BS, and provide reliable relay communication [19, 21] in the case of network failure or even when the signal power is too weak to propagate.

Existing communication systems like M-Urgency, SafeCity [11], and social media websites like Facebook and Twitter allow live streaming in natural disaster scenarios but need a core network. Hence, UAVs along with LTE D2D communication with novel architecture, as described in Section 3, can not only disseminate updated critical information to the deployed BS, but also reduce the response time and provide robust and reliable connectivity.

For this paper, we consider an emergency situation where an UE creates a direct transmission channel with an UAV by sending direct discovery message having identifying information. We analyse the Packet Error Rate (PER) and throughput against the direct transmission link. Additionally, we locate the discovered UE in an affected area with UAV using localization technique based on the root-MUSIC algorithm.

2 RELATED WORK

Over the last decade, work related to disaster communication management has attracted increased attention. The latest 3GPP standardization of services, i.e., mission critical push to talk (MC-PTT) [7], and ProSe [2] features enabling D2D communication (such as ProSe discovery and ProSe direct communication) will help to design more robust and heterogeneous PSNs. D2D allows the devices to communicate directly over in-band and out-band modes. In-band D2D shares the cellular spectrum with D2D users to improve the spectrum efficiency and enhance the throughput [22], whereas unlicensed bands are used for out-band D2D communication. The main issue of out-band D2D is the coordination of communication between two different bands because D2D communication happens on a second radio interface such as Bluetooth or WiFi Direct [5], [8].

Some ongoing and completed research projects are discussed below and summarized in Table 1. BS aided D2D communication (BSA-D2D) in cellular networks has received funding from the research Framework Program 7 (FP7) [1]. The focus was to improve the system capacity in a dense urban scenario by exploring interference alignment, network coding, multiple description source coding, regenerative storage codes, and joint source-channel coding.

Pervasive Spectrum Sharing (PSS) for public safety communications is a project funded by National Science Foundation (NSF) [15]. The key idea of the project is to improve spectral efficiency in emergency scenarios by exploring game theory, networking and wireless communications, public safety administration, and mathematics.

UAV-assisted heterogeneous networks For Public Safety Communications (UAV4PSC) is a project funded by NSF [14]. This project proposes video streaming during disaster situations using UAVs along with cellular technologies to seamless connectivity by reducing interference between UEs, UAVs and BS. Networked Infrastructureless Cooperation for Emergency Response (NICER) has received funding from LOEWE [10]. This project explores how to enable cooperative communication where communication infrastructure is not available. Thus people in affected area can cooperate together to handle the situation.

Device-to-Device System (DDPS) for Public safety is a project funded by National Institute of Standards and Technology (NIST) [13]. Key services of this project are to provide mission critical voice, and 3GPP ProSe. The main goal of this project is to provide essential technologies for PSNs, and to design, implement and test the vital DDPS components, and prototyping using OpenAirInterface (OAI) platform.

COmmUNication in conTExt Related to Terror Attacks (COUNTER-TERROR) has received funding from the NATO Science for Peace and Security (SPS) Programme [20]. The main goal and novelty of our project is to reduce time response by providing critical information to law enforcement agencies such as the number of trapped people inside the terror zone, their identity and location, the number of terrorists, etc. To achieve our goal, we are exploring LTE-Sidelink, beamforming and localization for UAVs, and multihop D2D routing for PSN in the context of terrorist attacks.

3 SYSTEM OVERVIEW

COUNTER-TERROR strives to provide all core features in emergency and terrorist attack scenarios where communication infrastructure is either only partially available or completely damaged. The project proposes a novel system architecture where ProSe-enabled Public Safety UEs inside the terror zone coordinates with each other using D2D communication. Moreover, UAVs and an external command centre are deployed near the affected area to send critical information to the deployed BS to reduce time response, and also to provide robust and reliable connectivity. The suggested architecture for this project is categorized into the following three parts:

(1) **Mobile BS Architecture:** The central processing unit of the mobile BS has the main control of the operations. A software defined radio (SDR) based connection emulates the BS connectivity services for scenarios where cellular connectivity is totally unavailable. A local database stores the information coming from the UAVs such as UEs localization data, critical information from victims, etc. A fleet management system provides support to deploy the UAV fleet according to the required situation during the operation.
(2) **UAV Unit Architecture:** The UAV architecture has many components to achieve device discovery, localization, and beamforming. The processing unit is responsible for the main operations. The developed algorithms take the inputs of the Multiple-Input-Multiple-Output (MIMO) system and perform beamforming, localization, and D2D communication. The priorities of flight control change during the operation, i.e., at the beginning device discovery and localization have high priority, and then later priority is given to D2D communication and backhaul connectivity. The SDR component controls the phase rotation of each antenna. The power supply affects the performance of each UAV according to its charge level.
(3) **UE Architecture:** The UE contains WiFi and/or LTE modules to provide D2D connectivity. The D2D link can be established with UEs and the UAVs in the affected area.

4 PRELIMINARY RESULTS

4.1 Signal scanning and localization

The operations considered in the COUNTER-TERROR project within the physical layer are designed in order to make possible the discovery, detection, and localization of the devices on the ground that are involved in a disaster situation, such as a terrorist attack, by means of the use of UAV units, possibly equipped with multiple antennas, capable of performing beamforming techniques.

In fact, prior to direct D2D communications, in our scenarios the user devices on the ground need to discover the presence of UAVs, which then forward the signals and some parameters associated to the signals reception. The discovery occurs relying on the transmission from the UAV of some reference signals, e.g. the Primary Sidelink Synchronization Signal (PSSS) and the Secondary Sidelink Synchronization Signal (SSSS) in the D2D LTE based solutions. The correct detection of these signals from the devices on the ground opens a D2D procedure between the devices and the UAV(s), composed by the exchange of messages for service discovery with the basic information necessary for evaluating the number of active devices on the ground and their identity.

This overall process is combined with the beamforming capability installed on the UAV in order to acquire more efficiently the following objectives:

- The increase of the Signal-to-Noise-Ratio (SNR) at the receivers, either the same UAV or the devices on the ground;
- The estimation of the Directions of Arrival (DoAs) of the signals, at the UAV, in order to make possible

the application of some localization algorithm to the devices in the area interested by the attack.

Therefore, the two preliminary, fundamental phases are the signal (i) scanning and (ii) localization. The signal scanning is divided into two phases, a coarse scanning for a preliminary identification of the sub-areas interested by the presence of devices and a fine scanning, possibly integrated by the localization process, operated on the responses sent by the devices and received at the UAV side, as sketched in Fig. 1. The coarse and fine scanning are determined by the area to be covered, by the UAV altitude and by the antenna array size and they are obtained by exploiting the serial activation of different beamforming weights patterns in the on-board array for transmitting and receiving the signals.

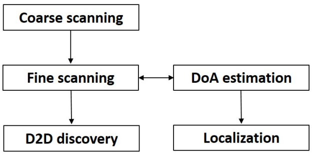


Figure 1: Scanning and localization process between UAV(s) and devices on the ground.

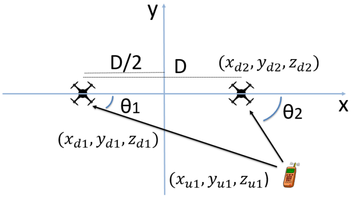
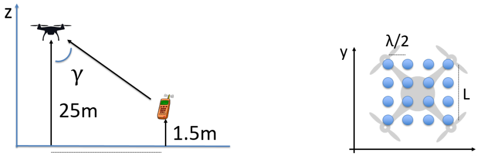


Figure 2: Localization scenario for obtaining test results. The drone takes two measures at $[-D/2, 0, 25]$ and $[+D/2, 0, 25]$. θ represents the Angle of Arrival.



[] []

Figure 3: Localization scenario (a) for UAV and UE heights. UAV planar array configuration (b), for $f = 1.8GHz$ we have $\lambda/2 = 8.3cm$ and $L = 25cm$.

In the localization phase, for the estimation of the DoAs, we implemented an estimator based on the root-MUSIC algorithm[16]; the objective is to extract DoA information from the signal captured by a 4×4 antenna array in a 3D scenario as shown in Fig. 2 and 3. We simulated a scenario where the drone is flying at 25 m, and the UE is located at 1.5 m height and at certain fixed positions in the x, y plane. We generate a reference LTE waveform using the lteRMCULTool; for our simulations we used reference waveform A3-1 as it consists of a signal spanning only one resource block thus simplifying calculations. These particular heights were chosen in order to implement the 3GPP channel specified in [4]. Given the measures of the angle and zenith of arrival, θ_i and γ_i, we can express the direction in 3D space using Eq.1.

$$\begin{array}{rcl} u_{ix} & = & cos(\theta_i)sin(\gamma_i) \\ u_{iy} & = & sin(\theta_i)sin(\gamma_i) \\ u_{iz} & = & cos(\gamma_i) \end{array} \tag{1}$$

If we have at least two measures of the angle of arrival (AOA) from two different points in space, we can estimate the position of the UE that is transmitting. One way to do so is finding the point of closest approach for the straight lines passing by the points where the measures were taken (x_i, y_i, z_i) that have direction $\overline{u_i}$. For example, using only two measures we can calculate the position by imposing $\overline{PQ} \cdot \overline{u_i} = 0$ where the points P and Q are given by Eq.2. By solving Eq.2 for the parameters S_1 and S_2 we can find P and Q and estimate the user position as the middle point between them.

$$\begin{cases} P = (x_1, y_1, z_1) + S_1 \cdot \overline{u_1} \\ Q = (x_2, y_2, z_2) + S_2 \cdot \overline{u_2} \end{cases} \tag{2}$$

We have performed two simulations where the results are an average of ten independent trials; the results are shown in Fig.4 and Fig. 5. The two points where we measure DoA are indicated in the figures by small circles. These results show the scenario where the UE transmits with an SNR with respect to the noise floor of 20 dB and 30 dB. In the first case we have a localization with approximately one meter accuracy only within a range of 100 to 150 m, while in the second case we can achieve this accuracy at over 200 m of distance. From the figures we can see a higher precision over the y axis, as should be expected since the UAV moves over the x axis thus giving the largest angular differences when the UE is located on the $x = 0$ axis. A particular result is the blind spot when the UE is at an angle of +/-180°with respect to the drone, as the root-MUSIC estimator we implemented has a blind spot at that exact angle.

4.2 Transmission over PC5 interface for D2D discovery in UAV-UE scenario

Three transmission links have been considered in the multihop scenario, *i.e*, UE-to-UE, UAV-to-UAV and UAV-to-UE.

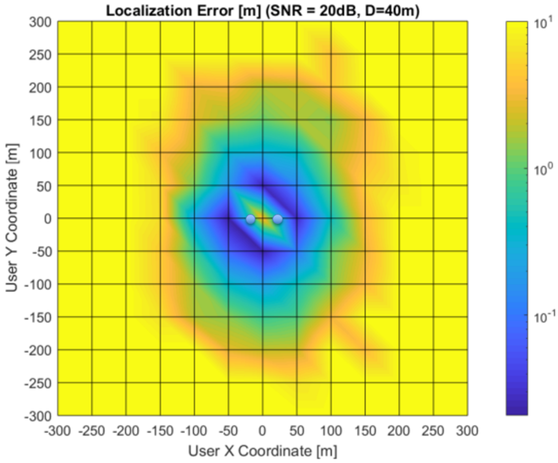


Figure 4: Absolute localization error in meters for SNR of 20 dB. The two circles on the graph represent the two different locations where the measures are taken.

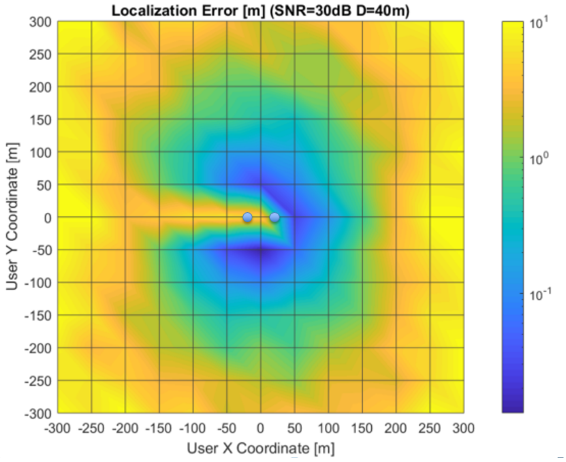


Figure 5: Absolute localization error in meters for SNR of 30 dB. The two circles on the graph represent the two different locations where the measures are taken. A blind spot can be seen from the results when DoA is close to +/- 180°.

Here, we present the baseband simulation results for UAV-UE links for direct discovery. The Air-to-Ground (A2G) channel model and its parameters have been implemented from [18] for a low altitude. In Fig. 6 and 7, Packet Error Rate and Throughput results are shown, respectively. The simulations have been carried out for A2G transmission with UAV transmission power of 18 dBm for different modulation and coding scheme (MCS) indexes when 29 bytes of information is transmitted, as per Model A of D2D discovery.

The PER is minimum for lower MCS values and increases for higher values since higher MCS provides more data but also least robust links, so the probability of loosing data is higher. Furthermore, as seen from Fig. 6, MCS 0 link provides the lowest PER for SNR lower than 15 dB and MCS 3 for larger SNR values. As seen from Fig. 7, a higher throughput is achieved for higher MCS values due to more data transmission for a given range of SNR. For example, MCS 4 and 5 provide higher throughput for SNR above 10 dB while below 10 dB, MCS 2 achieves a better performance, and finally MCS 0 achieves the best throughput performance for the lowest SNR values. An adaptation mechanism could be deployed to achieve the best throughput by adaptively selecting the MCS value as a function of the SNR.

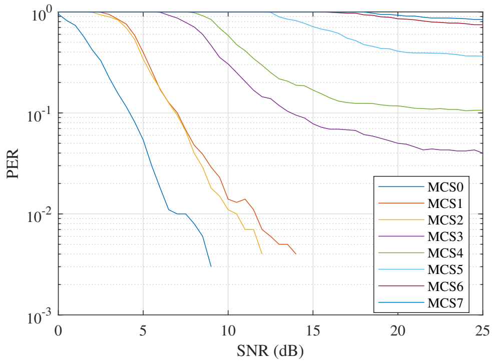


Figure 6: Packet Error Rate for UAV-UE link.

5 CONCLUSION AND FUTURE WORK

In this paper we have proposed using D2D communication and ProSe services in disaster scenarios so that UEs can communicate directly is a multihop fashion. In addition, we have proposed using UAVs to improve situational awareness and help disseminating critical information to the deployed BS. Our preliminary results indicate the effectiveness of the proposed scanning method to discover, detect, and locate affected UEs on the ground in a disaster situation. The preliminary results also indicate that suitable PER and throughput values can be achieved for direct discovery in the UAV-UE scenario. In the next steps, we will evaluate the performance

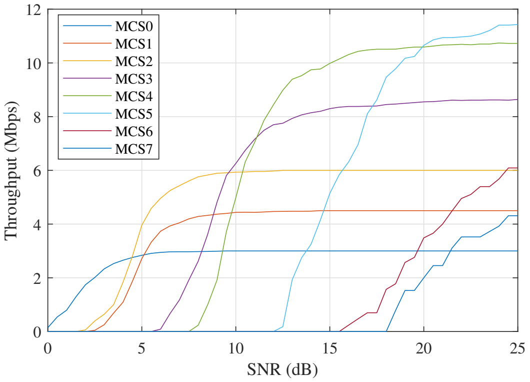


Figure 7: Throughput for UAV-UE link.

of UE-UE and UAV-UAV communications; we will also develop a HW/SW prototype to validate the proposed approach in real-life.

ACKNOWLEDGMENT

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Appendix 2

II

Ali Masood, Davide Scazzoli, Navuday Sharma, Yannick Le Moullec, Rizwan Ahmad, Luca Reggiani, Maurizio Magarini, and Muhammad Mahtab Alam. Surveying pervasive public safety communication technologies in the context of terrorist attacks. *Physical Communication*, 41:101109, 2020

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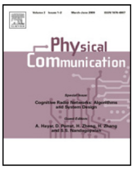

Full length article

Surveying pervasive public safety communication technologies in the context of terrorist attacks

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Localization
Beamforming
Software-defined networking
Routing protocols

ABSTRACT

Existing public safety networks (PSNs) are not designed to cope with disasters such as terrorist attacks, consequently leading to long delays and intolerable response times. First responders' life threats when accessing the attacked zone are more severe in comparison to other disasters and the accuracy of basic information such as the number of terrorists, the number of trapped people, their locations and identity, etc., is vital to the reduction of the response time. Recent technologies for PSNs are designed to manage natural disaster scenarios; these are not best suited for situations like terrorist attacks because a proper communication infrastructure is required for operating most of the classical PSNs. This serious concern makes it highly desirable to develop reliable and adaptive pervasive public safety communication technologies to counter such a kind of emergency situation. Device-to-device (D2D) communication can be a vital paradigm to design PSNs that are fit for dealing with terrorist attacks thanks to long-term evolution (LTE)-sidelink, which could allow the devices that people carry with themselves in the attacked zone to communicate directly. To our best knowledge, this is the first survey paper on public safety communication in the context of terrorist attacks. We discuss PSN scenarios, architectures, 3rd generation partnership project (3GPP) standards, and recent or ongoing related projects. We briefly describe a system architecture for disseminating the critical information, and we provide an extensive literature review of the technologies that could have a significant impact in public safety scenarios especially in terrorist attacks, such as beamforming and localization for unmanned aerial vehicles (UAVs), LTE sidelink for both centralized (base-station assisted) and decentralized (without base-station) architectures, multi-hop D2D routing for PSN, and jamming and anti-jamming in mobile networks. Furthermore, we also cover the channel models available in the literature to evaluate the performance of D2D communication in different contexts. Finally, we discuss the open challenges when applying these technologies for PSN.

1. Introduction

Pervasive public safety communication (PPSC) is critical in disaster scenarios such as terrorist attacks. Terrorism is an ominous threat worldwide. Terrorist attacks have not only damaged infrastructures and taken many innocent lives but also created long-term social and psychological repercussions on people. The number of attacks has raised significantly worldwide, especially after 2001 [1]. Recently, in Western Europe only, a record number of attacks (*i.e.*, 211) was reported in 2015 [2]. In 2016, 151 deaths and 548 injuries happened due to terror attacks in Belgium, France, Turkey, and Germany alone [3]. During 2003–2017, over 750 civilians have died because of terrorism in Europe [4]. The economic losses are huge; Belgium suffered losses up to 1 billion USD in 2016 [5]; in the same year the estimated loss in Paris region was of 858 million USD [6]. In particular, the tourism industry, which amounts to 10% of the European Union (EU) gross domestic product (GDP) [7], is suffering significantly. Similarly, in Asia and Africa, many lives were lost and significantly negative financial impacts are reported especially in Afghanistan, Iraq, Pakistan, Syria, and Nigeria [8,9].

Terrorist attacks are more critical than predictable emergency scenarios (e.g. floods, hurricanes). In predictable disasters, first responders have a reasonable time to prepare for expected incidents and can access the affected area during the emergency

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Table 1
Comparison with existing surveys on emergency PSNs.

Ref.	PSN architecture		*3GPP standards*	*On going projects*	D2D communication		*Beamforming/ Localization*	*Multi-Hop Routing*	*Jamming*
	Natural disaster	*Terrorist attacks*			*Centralized*	*Decentralized*			
[10] 2013	[c]								
[11] 2014	[c]	[a]		[a]	[a]				
[12] 2017	[c]				[b]		[a]		
[13] 2018	[c]	[a]	[b]		[c]	[a]	[a]		
[14] 2019	[c]				[a]				
[15] 2019	[c]				[c]			[a]	
Our Survey	[c]	[c]	[c]	[c]	[c]	[c]	[c]	[c]	[c]

[a] Narrowly addressed.
[b] Partially addressed.
[c] Extensively addressed.

situation with some calculated life threats and take quick actions to rescue affected people. In contrast, one of the fundamental issues in most of the unpredictable emergency scenarios, especially in terrorist attacks, is the slow response time, as it is observed that, even after many hours, police and law enforcement agencies often remain unable to take immediate actions against terrorists due to serious life threats, unclear information, and situational facts such as the number of people trapped inside the affected zone, the number of terrorists, their location, the type of weapons, etc. [16,17].

From an information and communication technologies (ICT) point of view, which is the main focus of this paper, existing land mobile radio systems (LMRS) and LTE-based public safety networks (PSNs) are not designed and are not able to deal with the challenges of unpredictable emergency scenarios like terrorist attacks. Communication technologies like mission-critical push-to-talk (MC-PTT) [18], M-Urgency and Safe-City [19,20] are facilitating victims to share mobile data and live video streaming during disaster situations but require the proper network infrastructure. WiFi-Direct is an established technology that brings a solution to overcome such challenges by creating ad-hoc communication. However, WiFi-Direct faces connectivity problems when communicating with more than two devices [21]. During emergency scenarios, common social media websites like Facebook and Twitter become flooded with messages for help requests [22]. Such massive numbers of requests degrade the quality of service (QoS) of the existing network. Many researchers have proposed extended coverage approaches [23–25] to connect the out-of-coverage user equipment (UE) with the nearest base stations using relay communication for the public safety application. However, this is not useful in such disaster situations because the response time would be increased and rescue teams would not be able to take proper actions due to scattered information.

The main challenges in unpredictable emergency scenarios, such as terrorist attacks and earthquakes, are to establish connectivity when the base station is not available and send important information from an affected area to public safety services [16,17]. To establish and maintain connectivity in such non-trivial situations, long-term evolution (LTE) sidelink allows two devices to communicate directly with each other regardless of the base station [26,27]. To send important information to public safety services, it is important to disseminate basic information over the multi-hop device-to-device (D2D) network [23,25], connecting with unmanned aerial vehicles (UAVs) and, finally, reaching the deployed command center [28,29]. Once the fundamental information about the on-scene available (OS-A) devices is gathered, devices should conserve their energy to remain available for a long period of time. Such dynamic adaptation and intelligence at the device level are important in order to reduce the dissemination of redundant information. These challenges must be dealt with efficient routing, accurate positioning and, at the same time, a reliable communication network.

To cover the above-mentioned challenges in the given terror context, a comprehensive survey is provided with the following key contributions:

- A comprehensive description of scenarios, architectures, contributions from standards, as well as up-to-date list of funded projects.
- A survey of the technologies necessary for the given context including the point of view of direct communication between (i) on-ground devices, (ii) on-ground devices and UAVs, and (iii) UAVs. Important aspects such as localization, beamforming, suitable channel models, jamming and routing approaches are described in detail.
- Open challenges, which highlight the limitations and way-forward in terms of execution of the application scenario, architectures, and technologies.

There is a relatively limited number of surveys on emergency PSNs in the literature. In [10], the authors discussed future PSNs to provide voice communications to first responders. In generic terms, voice communications over LTE standard, known as VoLTE, can be implemented using four different methods: (i) circuit switched fallback (CSFB), (ii) One Voice/VoLTE, (iii) simultaneous voice LTE (SV-LTE), and (iv) voice over LTE via generic access network (VoLGA). The authors provided a detailed history of LMRS and a discussion on VoLTE as a vital feature of PSNs. Recommendations for implementing and testing the PSN according to the FirstNet architectures are given. The survey in [14] provides a basic overview of LMRS, LTE, and the 700 MHz radio spectrum for public safety. The existing non-mission-critical and mission-critical public safety services over LTE are briefly discussed. Advanced enabling technologies for PSNs, such as software-defined radio (SDR) access network and radio access network slicing, are presented. A comparative survey is presented in [12] with numerical simulation analysis of LMRS and LTE using the network simulator-3 (NS-3) simulator. In addition, the challenges involved with existing PSNs and the benefits of LTE based PSNs over LMRS are discussed. The development of PSN is presented along with the spectrum allocation for PSNs across all the frequency bands in the United States. In [11], the authors surveyed the status of many wireless technologies, e.g. TETRA, APCO 25, TETRAPOL, satellite networks, digital mobile radio, etc. for PSNs. The current regulatory, standardization and research activities are discussed to identify the recent challenges faced by PSNs in Europe and United States. A high-level overview of future wireless communication technologies, e.g. SDRs, cognitive radio and LTE, is provided. The authors of [13] present an overview of the existing literature on D2D communication and dynamic wireless networks (DWN) to support public safety communication. Open challenges and possible

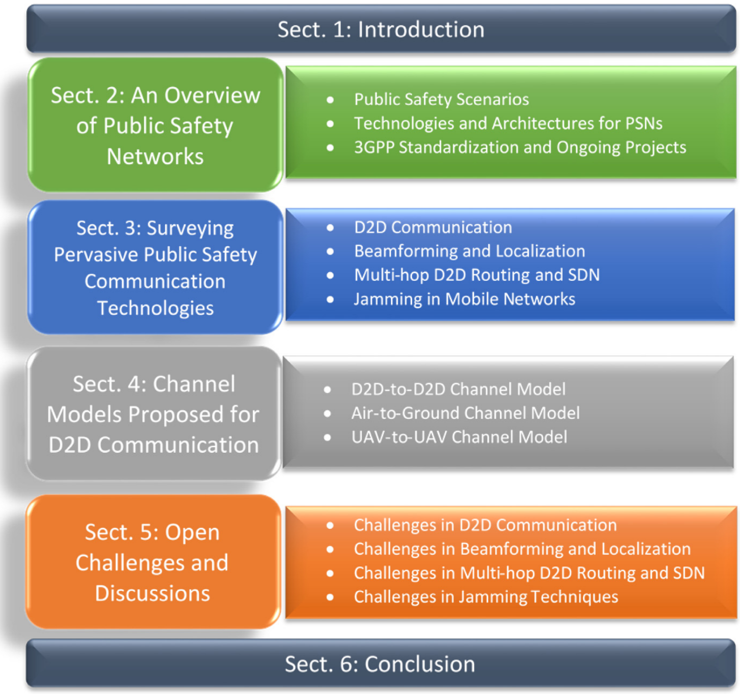

Fig. 1. An outline of this paper.

solutions for D2D communication, DWN deployment, modeling, security and resilience, modeling, performance evaluation, and emerging techniques for PSNs, e.g. IoT and cloud/edge computing, are discussed. Another survey in [15] provides the history of LMRS and LTE based PSNs, rapid emergency deployment, spectrum allocation and management requirements for public safety, architecture of LTE-based PSNs, and radio resource management schemes in PSNs.

We summarize and compare the contributions of different survey papers on PSNs in Table 1 to position the present paper. It can be seen from the table that all the existing papers focus on emerging technologies for predictable safety events (e.g. large-scale gatherings, and concerts); only two papers [11,13] barely discussed the architectures and technologies for unpredictable safety events such as terrorist attacks; more details about different emergency scenarios will be provided in Section 2.1. On the other hand, this survey provides a detailed description of the architecture and the possible technologies for predictable as well as for unpredictable dangerous events as, for example, in the case of terrorist attacks.

Moreover, the existing studies [11,13–15] cover many details about D2D communication in the in-coverage scenarios when the base station works properly. In comparison, to the best of our knowledge, this is the first survey paper presenting a detailed review of D2D communication for both in-coverage and out-coverage scenarios, along with up-to-date standards and projects. Additionally, we provide an extensive literature review of the technologies that could have a significant impact in advance PSNs, such as beamforming and localization for UAVs, multi-hop D2D routing, and jamming and anti-jamming in mobile networks.

The remainder of this paper is organized as follows. In Section 2, we discuss PSN scenarios, architectures, 3GPP standards and recent, or ongoing, related projects. Section 3 is devoted to the technologies with a potential impact in this scenario and it is divided into the Physical, MAC and Network layer subsections. In Section 3.1 – the physical layer – device discovery, beamforming for UAVs and localization are discussed as the technologies with the greatest expectations and challenges to the specific terrorist scenario. In Section 3.2 – the MAC layer – D2D communication in centralized and decentralized modes, resource, and power allocation approaches are considered as playing a crucial role in the achievement of an efficient communication. In Section 3.4 - the network layer - multi-hop D2D routing for PSN is carefully discussed as a key enabling technology for the system. In Section 3.5, the main characteristics of jamming are discussed together with a survey of the recent literature. Then Section 4 is dedicated to the channel models proposed for D2D communication in the literature. Finally, in Section 5, we discuss the open challenges in the context of these technologies applied to PSN in the case of terrorist attacks. Concluding remarks are given in Section 6. Fig. 1 shows an outline of the paper.

2. Public safety scenarios, architecture, standards, projects

2.1. Public safety scenarios

Each year, thousands of people suffer because of disasters and this situation worsens if public safety services are not able to take proper actions on time. Any emergency situation can be referred to as a disaster that can affect the routine procedures causing deaths, illness, injuries and property damage [30,31]. For classification purposes, disasters are categorized into two main groups: natural and man-made disasters. Both of them can be further divided into different subgroups [32–34]. as shown in Fig. 2.

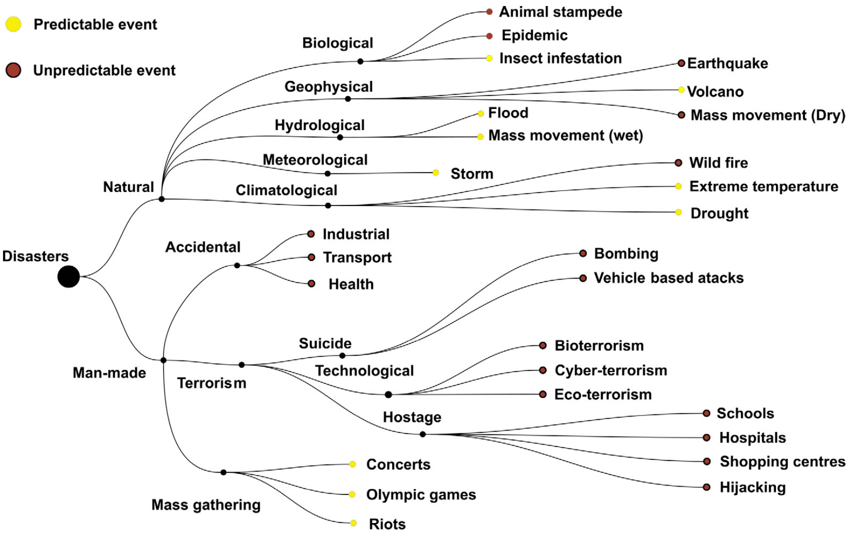

Fig. 2. A taxonomy of disaster types.

2.1.1. *Natural disasters*

People depend on key facilities for ensuring viable and safe societies; such facilities include e.g. transportation systems, energy and fuel subsistence systems, information and communications infrastructure, schools, hospitals, emergency rescue services, etc. [35–37]. It is observed that natural disasters can disable some of the key infrastructure facilities in affected areas up to 72 h or even longer, which not only threatens the lives of people but can also isolate such areas from the outside world [38]. Risk management techniques help to manage natural disasters, estimating which areas will become isolated or not. Studies assess the conditions of key facilities before, during, and after disasters, which can help to manage and reduce their consequences [39–42]. It is worth observing that people often use social media platforms to request aid during natural emergencies [43–45]. Information shared on social media is very ambiguous while rescue services using machine learning methods can differentiate between spam and clear signal, thus allowing to identify who actually needs aid [46–49].

- **Geophysical:** Disasters originating from solid earth are referred to as geophysical or geological disasters (e.g., ground movement, tsunami, landslide, lava flow, etc.). Such disasters cause deaths, injuries and infrastructure breakdown. It is observed in several disasters that damaged roads, bridges, and communication infrastructure are the main obstacles to providing emergency support and aid [50,51].
- **Hydrological:** Sudden distribution or movement of water (e.g., flood, debris flow, avalanche, etc.), possibly on dry land, causes hydrological disasters. Such disasters partially or fully disconnect the ground connection of affected areas, which is one of the main challenges faced by rescue teams [38,52].
- **Meteorological:** Short-lived disasters caused by intermediate atmospheric conditions (e.g., tornado, thunderstorm, dust storm, excessive rainfall, blizzard, etc.) are called meteorological disasters. Extreme weather conditions affect the rescue process causing long delays [53].
- **Climatological:** Long-lived disasters caused by extreme atmospheric conditions (e.g., frost, snow pressure, icing, etc.) are called climatological disasters. Such disasters cause economic loss, property damage, communications failures, and extreme burden on public safety services such as hospitals, fire, police, etc. [54].
- **Biological:** Biological disasters caused by the exposure of living organisms to germs and toxic substances such as viral diseases, bacterial diseases, fungal diseases, etc. A significant number of cases appear in a virus-free region, spread from affected areas. The challenge for public safety services in such cases is to provide antibiotics and vaccines for infection prevention and control [55]. It is also observed during the epidemic situation that public safety services use drones to monitor the movement of people to contain the virus outbreak [56].

2.1.2. *Man-made disasters*

Man-made disasters are the consequence of different human actions and can be categorized into two main subgroups: accidental, civil disobedience and terrorism.

Accidental disasters

Accidental disasters are caused by human error, negligence, and technological failure, for instance, fires, industrial and transport accidents, structural failures and collapses, and nuclear explosions or radiation. Many studies on risk assessment propose quantitative, qualitative, and hybrid techniques to examine and assess risk solutions to avoid such events [57–59].

Mass gathering

A mass gathering is an event for a common purpose when a large number of persons come close together at one place; it can take place indoor or outdoor. The gathering could be organized for a defined period, be instantaneously motivated by participants or organizers, or due to an emergency situation.

Terrorism

Terrorism is the deliberate use of violence for creating fear in order to achieve political and social objectives. Terrorist activities are diversified, having a large range of targets, including citizens, government officials, law enforcement officers, public building, or government buildings [60].

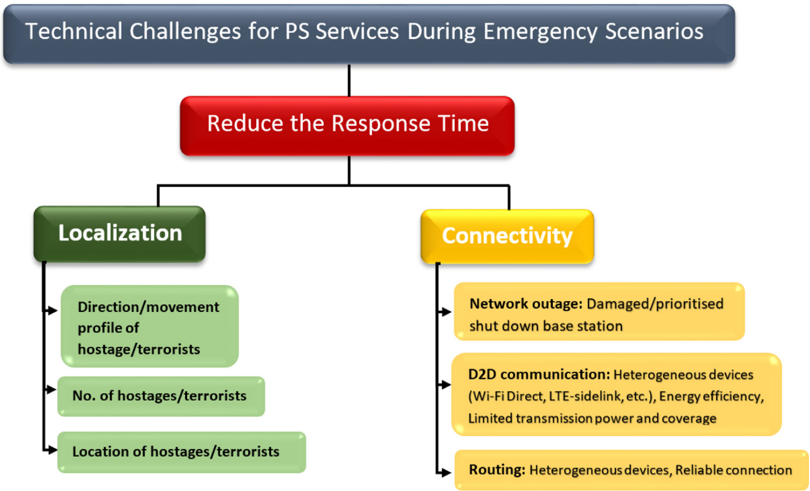

Fig. 3. Technical challenges for PS services during emergency scenarios.

- **Suicide Attacks:** in a suicide attack, a terrorist deliberately takes his own life to damage, harm, or destroy the target. Two counter tactics are used to fight against suicide terrorism: nonlethal preventive measures and lethal offensive measures. In nonlethal measures, law enforcement agencies arrest the terrorists and leaders, and drive information from them. In lethal offensive measures, agencies target the terrorist leaders or operators and kill them. Target killings appear to further increase the number of suicide attacks, while preemptive arrests seem to reduce such attacks [61,62].
- **Technological Attacks:** such attacks attempt to expose, steal, alter, destroy, or gain unauthorized assets or access. Risk assessment strategies propose to prevent such activities, while it is challenging for law enforcement agencies to identify the criminals and their network [63–65].
- **Hostage Situation:**
  Hostage situation is considered as one of the most significant and newsworthy scenarios, which affects and challenges the actions of the authorities [16,66,67]. There are two main scenarios: (i) where hostages are captured by the terrorist or (ii) where hostages are hiding in the area controlled by the terrorists. Law enforcement agencies cannot take a proper action during hostage situations because they do not have critical information such as the number of terrorists, the number of trapped people, their identity and locations, etc. [16,17].

We further categorize the emergency scenarios, i.e. man-made and natural disasters, into two types of events: predictable and unpredictable. In predictable emergency scenarios, public safety services (rescue, fire, police, etc.) can foresee and have a reasonable time to prepare for expected incidents. Generally, public safety services put high efforts into disaster prevention in order to reduce the response time, thus, they will not have to put significant efforts into the disaster management and relief phase. For instance, in a predictable man-made disaster that could take place during e.g. a mass gathering, police departments arrange additional police force to provide security, implement safety arrangements for the crowd and ensure avoiding any undesired incident. Fire and rescue teams are also fully prepared to meet any incident. In a predictable natural disaster, for example floods, rescue teams evacuate the possible affected area for prevention, whereas during or after the emergency incident, damaged infrastructures are the major cause of the formation of isolated areas and a factor that slows down the rescue process. The emergency rescue teams gain access to the disaster site using e.g. rescue boats and helicopters with a slight (if not without) direct life threat and provide disaster relief immediately.

On the other hand, in unpredictable emergency scenarios, public safety services may not get enough time for disaster prevention due to the abruptness of the incident. Thus, a great amount of effort will have to be put into the disaster management and relief phase to reduce the response time. Typically, wildfires and earthquakes are considered as unpredictable natural disasters. Human failures and terrorist attacks are common examples of unpredictable man-made disasters. For instance, in the case of terrorist attacks, rescue and law enforcement teams remain unable to immediately step-in because of serious life threats, unclear information and situational facts (i.e., number of terrorists, their positions, the number and type of weapons used and severe consequences, etc.) Thus, the response time for disaster relief becomes very long.

Nowadays, concerns are raising for the design of highly reliable and adaptive PSNs. From an ICT point of view, the classical PSNs are not designed to cope with public safety services during emergency scenarios (e.g., floods, earthquakes, riots, terrorist attacks). The main challenge for public safety services is to reduce the response time in such cases, as illustrated in Fig. 3. We are discussing a system architecture in Section 2.2 for disseminating the up-to-date information and reduce the response time, exploring the technologies that could have a significant impact in such scenarios, such as beamforming and localization from UAVs, LTE sidelink for both centralized (base-station assisted) and decentralized (without base-station) architectures, and multi-hop D2D routing for reliable PSN.

2.2. Technologies and architecture for PSNs

Technologies for PSNs

When BSs are switched off or non-functional, mobile users are not able to communicate with first responders. A feasible solution to overcome this problem is to relay the signals via other devices that act as a link between users and operational BSs using D2D

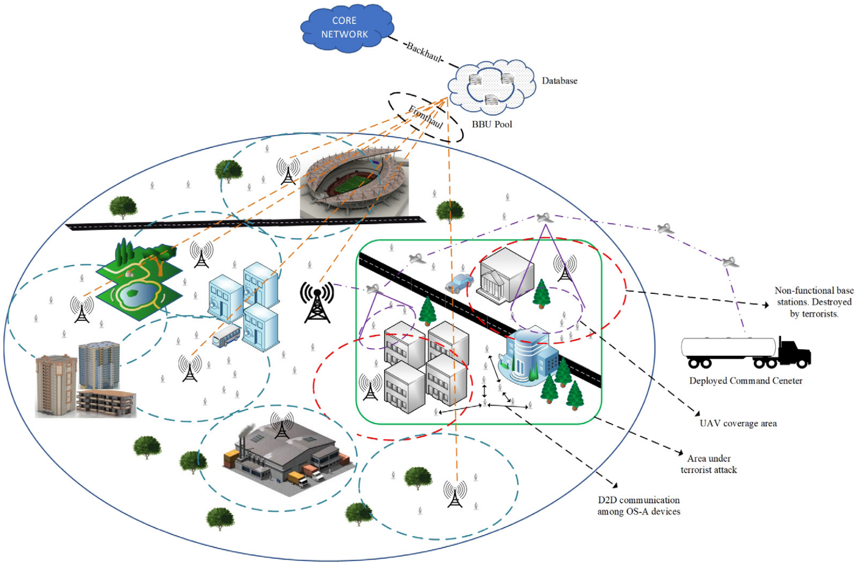

Fig. 4. Architecture for public safety scenarios.

communication. In particular, the UEs that are not in the coverage area of the BS can use the mobile devices that are in the coverage area as relays, thus accomplishing a multi-hop connection with the cellular network [68]. Under exceptional circumstances, these D2D links, standardized in the 3GPP Release 13, play an important role in filling coverage holes and providing seamless coverage. Due to the division of the transmission range into two or more hops using D2D relays, the reduction in power consumption of mobile devices becomes one of the major benefits of such relayed communication. Further, with low link distance between the D2D devices, the battery life of the devices is prolonged, which is highly beneficial especially in critical conditions.

Reference [69] proposes a relay selection scheme for D2D enabled relay communication, as a measure to fill coverage holes in public safety LTE (PS-LTE). The scheme is based on selecting an optimal relay terminal through an effective path throughput from an out-of-coverage terminal to a BS via in-coverage relay terminal. From the simulation results in [69], the proposed scheme is able to satisfy the throughput requirement for video transmission in case of a large number of users.

It is worth observing that relaying of signals can also be done through moving relays e.g. devices that are installed on moving vehicles such as UAVs or trucks. In [28], a cost-effective network architecture is proposed where a smart UAV enabled with D2D communication is deployed to carry a relay that provides the connection. The use of drones is more feasible when the risk factor is high. This allows public safety agents to deploy relays in some area, which is the case considered here of a terrorist attack.

A drone, or swarm of drones, is directed towards a certain location to connect the desired mobile devices that need coverage with a distant active BS, thus acting as a relay to bypass failed BSs. The drones are installed on-board the transceivers to transfer the signals from the mobile devices to the distant BSs, and vice-versa, thus realizing a multi-hop link. However, the number of drones that is required to cover the affected area depends on the cell coverage provided by each drone, which is lower as compared to terrestrial microcell BSs and further depends on its transmission power, drone altitude, interference effects, etc., as addressed in [70]. The problem of searching for the optimal UAV position to increase the end-to-end throughput performance is addressed in [29]. In contrast to methods that rely on propagation distance minimization and statistical models for the presence or absence of a line-of-sight (LoS) component, the proposed approach is capable of leveraging local topological information to guarantee better performance. The position of drones is set by utilizing GPS and location detection services in LTE.

Architecture for public safety scenarios

It is envisioned that smartphones, and/or OS-A devices, which have enabled direct communication features in the emergency scenarios (such as earthquakes, fire, terrorist attacks), can be exploited to get the fundamental and critical information to reduce the response time [26,27]. Inside the affected area, enabled OS-A devices with D2D functionality could cooperate with each other in a multi-hop communication fashion to improve the communication reliability in case of harsh propagation conditions and to ensure end-to-end network connectivity [23,25]. An external deployed command center and aerial platforms (APs), or UAVs, will be deployed near the attacked zone. Multiple APs/UAVs can provide reliable network connectivity, increased positioning accuracy in the OS-A devices, and relay communication to external deployed command center when the BS is not available, especially when the signal power is too weak to propagate [28,29]. Hence, this network architecture can disseminate up-to-date critical information to the deployed command center, thus allowing for a reduction of response time and the provisioning of a robust and reliable connectivity [71,72], as shown in Fig. 4.

The considered architecture is feasible for public safety scenarios, like fire, earthquake, terrorist attacks, etc., and can be divided into the following three parts:

1. **Mobile BS Architecture:** The central unit of command will have a system capable of enabling emergency responder personnel for obtaining a deep control of the operations; its architecture is shown in Fig. 5. An SDR based connection will emulate the BS connectivity services for scenarios where cellular connectivity is totally unavailable. Information coming from the drone fleet will be collected in a local

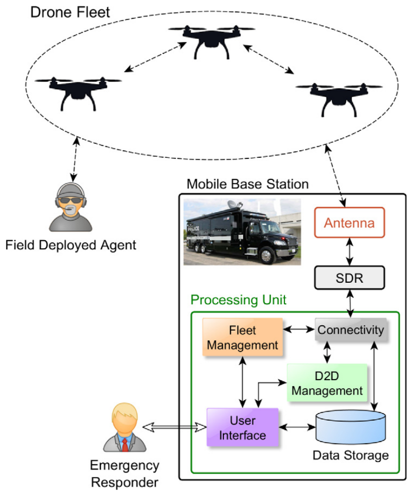

Fig. 5. Mobile BS main components and architecture.

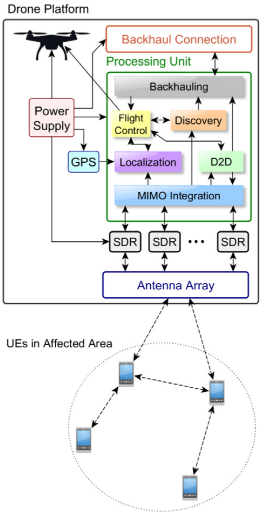

Fig. 6. UAV Remote Radio Head main components and architecture. Within the multiple-input-multiple-output (MIMO) integration block other sub-algorithms such as beamforming and weak signal detection will be included.

database. This information will include UE localization data as well as data coming from victims and field-deployed agents. A fleet management protocol will enable the emergency responders to deploy the UAV fleet where it is most needed during operations.

2. **UAV Unit Architecture:**
The system to be deployed on the UAV is shown in Fig. 6. It includes various components for achieving device discovery, beamforming, and localization. The system is divided into:
   - an antenna array;
   - an SDR component, responsible for the phase rotation to be applied on each antenna;

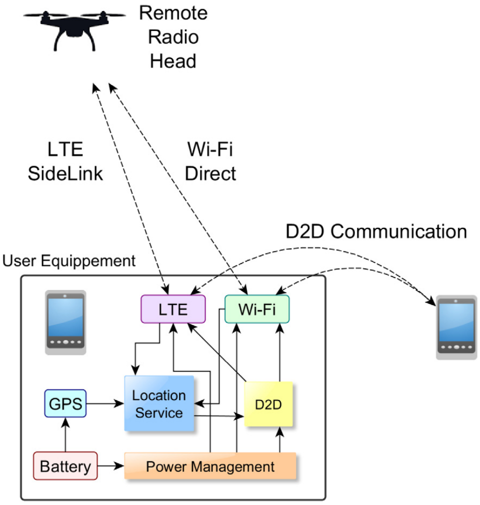

Fig. 7. Expected architecture and components for typical UEs.

   - the main processing unit on which the algorithms developed in the project will be deployed and interact with drone flight controls. These algorithms will take the inputs of the MIMO antenna system and perform UE localization, beamforming, and D2D communication.

   The priorities of the individual algorithms w.r.t. access to the flight controls will vary during the mission, with the initial phases prioritizing device discovery and localization and, later, the D2D and backhaul connectivity. The power supply will change the behavior of the UAV according to its charge levels. A separate connection from the main antenna array will be used to provide backhaul connectivity to the ground stations.
3. **UE Architecture:** The UE contains WiFi and/or LTE modules, able to provide D2D connectivity (Fig. 7). The D2D link can be established with the UAV or to other UEs in the area. User location services such as GPS can be used to aid in connectivity and localization if present and active.

2.3. 3GPP standardization and ongoing projects

In Release 12, the 3GPP recognized D2D communication as a potential contender to manage the network capacity/coverage problem, through ProSe [73,74]. Further enhancements in ProSe with integration to internet-of-things (IoT) and vehicle-to-everything (V2X) communications became a part of future releases as depicted in Fig. 8. D2D services can be exploited by introducing new features and functionalities in the current cellular architecture, which are addressed in this section. D2D is expected to be integrated into existing LTE-A cellular networks as presented in [75]. Further, the requirements of the features that would support such integration are addressed in [76] such as enhancement of the evolved packet core (EPC) with the addition of new interfaces and entities to support D2D services. Later, the results from [76] formed the foundation for the specification of 3GPP Release 12 [77]. With this release three main entities were introduced in the network: ProSe function, ProSe Application Server, and ProSe application at the UE.

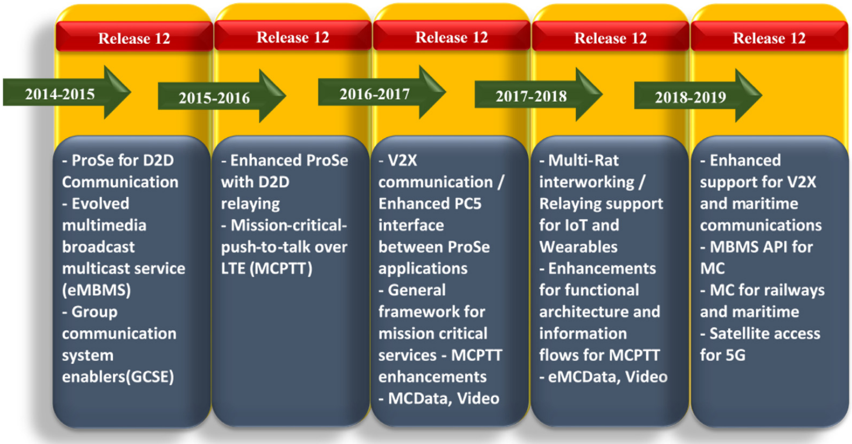

Fig. 8. Mission Critical and D2D service Enhancements with 3GPP releases.

The ProSe function is executed as a logical function, which further provides three sub-functions: Direct Provisioning, Direct Discovery Name Management, and EPC-level discovery ProSe function. Direct Provisioning function caters to D2D discovery and D2D communication. Such criteria, which are related to the authorization policy and radio parameter configuration of UE to perform D2D discovery and communication, are listed in [77]. The Direct Discovery Name Management Function supports the network operator for D2D discovery and application while the EPC-level Discovery ProSe Function provides some network functionalities such as subscriber information management and authorization etc. In 3GPP Release 12, only the ProSe function is considered. Therefore, management and cooperation among multiple ProSe functions are left as an open challenge.

Further, the ProSe application server [78] distributes services to different ProSe applications and maps the UEs to individual functions. The ProSe application server is connected to the ProSe function via a PC2 interface, which is responsible for enabling interaction between the two entities, as given in [78]. Also, UEs must be reconfigured to support D2D communication and relay functionality with extensions required to support D2D discovery and communication by the ProSe application. Such an authorization policy is managed over a PC3 interface as described in [79].

The basic architecture of 3GPP ProSe is shown in Fig. 9. Besides new entities, home subscriber server (HSS) and mobility management entity (MME) should also be enhanced in order to authorize user information regarding ProSe services [77]. To accomplish this, a new interface, PC4, has been introduced in [80] and is shown in Fig. 9. Also, the upgrade of the S6a interface is needed to enable information exchange related to ProSe subscription [77]. Such enhancements in interfaces and introduction of new entities lead to security threats and risks related to D2D communication; therefore, [81] proposes a key management system among common LTE-A and newly introduced entities.

Further, the 3GPP meeting for the integration of D2D services into IoT was discussed in [82], which would meet the requirements of longer battery life and better connectivity of IoT devices in close proximity by forming D2D connections.

Also, wearable devices for medical care systems for patient monitoring in hospitals and remote monitoring from homes and offices gained a lot of improvements from D2D communication. A review of multiple standards and technologies for D2D enabled wearable cognitive wireless systems is given in [83]. Enhancements have been also introduced to enable QoS, end-to-end security, and efficient path switching between LTE and D2D interfaces [84]. In Release 14, V2X was included for the first time in D2D communications with improvements done for safety-related scenarios and extended sensors local communication [85]. In addition to the above mentioned standardization activities, many completed or active research projects are summarized in Table 2.

- **BSA-D2D:** Base Station Aided D2D communication is an initiative of the European Commission (EC) [86]. The main aim of this project was to increase the system capacity by exploring network coding, interference alignment, regenerative storage codes, multiple description source coding and joint source-channel coding.
- **MCN:** Multilayered Communication Network is an initiative of the Japanese government for research in disaster Management [87]. The objective of this project was to establish an alternative communication route and technologies when the 3G network is not available.
- **ABSOLUTE:** Aerial BSs with Opportunistic Links For Unexpected and Temporary Events (ABSOLUTE) project is a Framework Programme 7 (FP7) initiative that aims to design and validate innovative rapidly deployable networks [88].
- **CODEC:** The Cellular Network based D2D Wireless Communication (CODEC) project is funded under FP7 framework [89]. It focuses on achieving QoS, energy and spectral efficiency through efficient resource management in D2D Cellular communications.
- **D2D-LTE:** Device-to-Device Communication: Fundamentals with Applications to LTE (D2D-LTE) is a project funded by the National Science Foundation (NSF), USA [90]. The key idea is to exploit direct communication between nearby devices to achieve throughout, improved spectrum utilization and energy efficiency. In addition, this project explores new peer-to-peer and location-based applications and services.
- **PSS:** Pervasive Spectrum Sharing (PSS) for public safety communications is an NSF funded project [91]. The main aim of the project is to improve spectral efficiency. The main idea is to provide incentives to users that opportunistically share their spectrum as substrates (*e.g.*, 3G data and WiFi connectivity), and open D2D protocols.

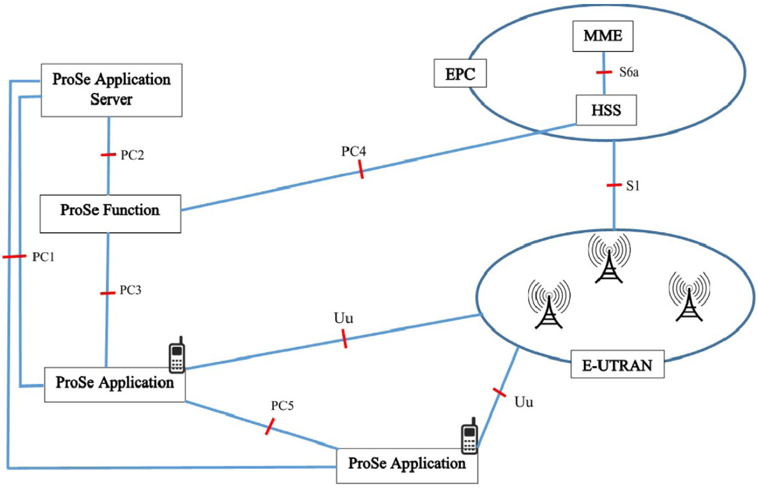

Fig. 9. D2D communication architecture with enhancements from LTE-A.

- **COHERENT:** The coordinated control and spectrum management for 5G heterogeneous radio access networks (COHERENT) framework aims at improving the existing control solutions for inter-network coordination [92]. The project is funded by Horizon 2020 (H2020) programme. It devises theories and methods to abstract network states and behaviors.
- **METIS:** Mobile and wireless communications Enablers for Twenty-twenty Information Society (METIS) is a research project funded by FP7 [93]. The objective of the project is to design a system concept that delivers the necessary scalability, efficiency, and versatility for a 5G wireless communications system. Direct D2D communication is one potential technology and is used to improve coverage in terms of availability, reliability and cost efficiency.
- **UAV4PSC:** CAREER: Towards Broadband and UAV-Assisted Heterogeneous Networks for Public Safety Communications (UAV4PSC) is an NSF funded project [71]. The main idea of this project is to use UAVs along with cellular technologies to ensure connectivity with potentially damaged network infrastructures, dynamically manage interference between UAV, BS, UE, and allow smooth handovers.
- **NICER:** Networked Infrastructure-less Cooperation for Emergency Response (NICER) is a LOEWE funded project [94]. It explores how infrastructure-less information and communications technology that can establish links between people in the event of a crisis, thus enabling them to work together to overcome the crisis.
- **BROADMAP:** BROADMAP is another H2020 funded project [95]. The project aims to develop next generation broadband inter-operable radio communication systems for public safety and security in the EU. BROADWAY [98] is a new project working on carrying forward BROADMAP initiatives.
- **LCMSSER:** Location-based Control and Management System for Safety and Emergency Rescuing Services using LTE D2D (LCMSSER) is a British Council funded project through its Newton Fund initiative [96]. The aim of the project is to support mobile users through the location-based system that provides emergency services in the event of disasters.
- **DDPS:** The DDPS project aims at providing mission-critical voice, 3GPP ProSe, one to one and one to many group communication as key services [97]. The project is funded by the National Institute of Standards and Technology (NIST) and the main partners are US Army Vencore Laboratory and Eurecom. The project involves building a complete ProSe stack for mission-critical voice based on 3GPP standard and open source OpenAirInterface (OAI) and demonstrate in a hardware test-bed.
- **COUNTER-TERROR:** COmmUNication in conTExt Related to Terror Attacks (COUNTER-TERROR) is a new project that has been recently funded by the North Atlantic Treaty Organization (NATO) within the science for peace and security (SPS) programme [72]. The project aims to establish and maintain connectivity in the case of terrorist attacks, which cause partial or total network failure, exploiting multi-hope D2D communication, beamforming and localization, and jamming and anti-jamming techniques for reliable PSN.

3. Surveying pervasive public safety communication technologies

3.1. Physical layer

The main physical layer technologies that make possible a decentralized communication and related services in an area that is concerned with a terrorist attack are:

- *Discovery* of the devices for establishing D2D communications, in particular with the support of aerial relaying stations. In fact, before setting up a direct D2D communications, user devices need to discover the presence of nearby devices, or UAVs, and identify whether the D2D pairs need to communicate with each other. This process, called device discovery or peer discovery, is particularly challenging when the infrastructure is not available.
- *Beamforming*, for enhancing signal quality in any context of the operations, from discovery and detection of the weak signals in the area of localization and communications. In particular, in the scenario considered here, the papers of interest are dedicated to the application of beamforming to UAVs that are deployed in the emergency area.
- *Localization* of the devices, useful for providing additional information about the positions of the persons involved in the attack.

The next subsections are devoted to the survey of the main recent papers in the above-mentioned areas.

Table 2
Summary of the up-to-date related funded Projects.

Projects	Year	Funding organization	Architecture	Standards	D2D communications	Protocols stack	Target applications
BSA-D2D [86]	2011–2012	FP7 Ref. Nr:274523	LTE	In-coverage	Improve network capacity	PHY layer	Cellular communication
MCN [87]	2011–2012	Japanese Government	WiFi Adhoc	Zigbee, Bluetooth, WiFi, LTE-A, WiGig	Delivery delay	Network Layer	Disaster management
ABSOLUTE [88]	2012–2015	FP7 Ref. Nr. ICT 318632	LTE-A	In-coverage mode: Direct and relay	Aerial BS to device	PHY layer	General purpose public safety
CODEC [89]	2014–2016	FP7 Ref. Nr: 630058	LTE- Release 12	LTE-A, TETRA	Spectrum efficiency	PHY layer	Cellular communication
D2D-LTE [90]	2014–2016	NSF, USA Ref. Nr: CIF 1016649	LTE Release 12. ProSe design	In-coverage mode: Offloading, relay and direct	Spectrum, resource optimization	PHY layer	General purpose public safety
PSS [91]	2016–2019	NSF, USA Ref. Nr: NSF EARS2014–1443946	LTE	In-coverage mode, WiFi spectrum sharing	Spectrum efficiency	PHY layer	General purpose public safety
METIS-II [93]	2015–2017	H2020 Ref. Nr. 671680	5G	5G Hetnet	Spectrum, resource allocation	PHY layer	General purpose public safety
UAV4PSC [71]	2015–2020	NSF, USA Ref. Nr:CNS-1453678	5G	In-coverage mode:Offloading, relay and direct	UAVs to ensure connectivity	PHY and MAC layer	General purpose public safety
NICER [94]	2015-On going	LOEWE	5G	WiFi, LTE-A, LTE-U	Relays for out of coverage users	Network layer and security	Emergency response for disaster, terrorism and violence
BROADMAP [95]	2016–2017	H2020 Ref. Nr. 700380	Interoperable, broadband (LTE)	Multiple standards	Interoperability of devices	Interoperability of different networks	Public safety in disasters
LCMSSER [96]	2016–2018	Newton Fund British Council	LTE	LTE	Relays for out of coverage users	PHY layer	Public safety in disasters
DDPS [97]	2017–2019	NIST	LTE-Release 14	On-network, Off-network, and Partial-on-network	Discovery, synchronization,	PHY, MAC, and Network layers	Public safety in disasters
COUNTER-TERROR [72]	2018–2021	NATO-SPS	LTE-Release 14 (ProSe design and evaluation)	Out-of-coverage mode:Direct, relay and multihop	Dynamic heterogeneous resource management, reliable and robust connectivity	PHY, MAC, and Network layers	Public safety in terrorist attack

3.1.1. *Device discovery*

In a disaster scenario, one of the main problems is the discovery and selection of the devices with the best signal-to-interference-and-noise ratio (SINR) and the implementation of algorithms that are able to guarantee a sufficient QoS.

According to 3GPP, "direct discovery" expresses the capability of communicating only among the UEs.

In general, devices that are announcing their presence to the neighbors broadcast discovery messages at pre-defined intervals, while devices that are monitoring these messages scan the pre-defined frequencies of broadcast [77]. The presence or absence of network coverage changes the D2D discovery mechanisms: in a network-controlled scenario, D2D depends on the core network. Therefore, the network can use specific control signals for the discovery process, coordinating time and frequency of the process without collisions. This approach obviously provides several advantages in all the steps of the D2D connection, from the synchronization to the communication setup [99].

In the out-of-coverage scenario, the discovery is made by the devices themselves through known synchronization or reference signal sequences. These specific packets, also known as beacons, advertise the presence of the device, which makes peer discovery possible independently from the BSs; this is a natural solution for PSNs [100].

The out-of-coverage D2D discovery process is characterized by the following features:

- direct discovery instead of discovery supported by the network;
- the possibility of leveraging discovery by underlaying coexisting technologies such as WiFi or Bluetooth;
- being, in general, an asynchronous process.

At the same time, the peculiarities and the main issues of the discovery process in PSNs are:

- typically to be tested in the worst-case scenario, *i.e.* out-of-coverage or decentralized;
- device discovery without network assistance is usually time and energy-consuming;
- the quality of the discovery process is determined by (i) high power efficiency, (ii) discovery range, (iii) spectral efficiency or low use of spectral resources, and (iv) rapidity.

In the literature, there are many studies focused on performance and energy efficiency for out-of-coverage conditions in D2D networks. In the past, several solutions have focused mainly on the optimization of the probing interval, *i.e.* with mechanisms for optimizing the duty cycle between sleeping and waking up phases. Other studies are specifically focused on wireless technologies such as WiFi and Bluetooth, which appear of interest for the possibility of using these underlying technologies as leverage for D2D discovery also in emergency scenarios.

General Discovery Approaches: In [101], an approach is proposed for adaptive wake-up schedule based on power-law distributed contacts; the key point of the proposed solution is that the nodes stay asleep when a contact is unlikely to happen and wake up only when the possibility of a successful contact is sufficiently high, guaranteeing a reduction of energy consumption in opportunistic networks (up to 30% w.r.t. other wake-up techniques).

Discovery for WiFi, Bluetooth: An overview and an experimental evaluation of WiFi Direct is provided in [102]. In [103], an energy efficient device discovery protocol is based on the underlying wireless technology Bluetooth. The protocol adapts the duration and interval of Bluetooth inquiry in dynamic environments, by using history information on discovered peers. The performance has been validated by an experimental prototype. In [104], the WiFi Neighbor Awareness Networking technology, standardized by the WiFi Alliance, is presented and evaluated using packet level simulations; this technology allows devices to continuously discover surrounding services and devices operating in a background energy-efficient way. In [105], the Bluetooth low energy (BLE) discovery mechanism is modeled and evaluated using intensive simulations and characterized through its discovery probability, latency, and energy consumption as a function of the parameter settings.

Discovery Approaches with UAVs: In [106], a scenario in which UAVs enhance public safety services is studied; the proposed ComProSe system is an innovative ProSe-enhanced multimedia communication framework, which makes use of UAVs as relays and provides direct discovery and QoS-aware communications between public safety UEs from different organizations. The paper presents interesting real-life tests concerning the cooperation between UAVs and public safety users.

3.1.2. Beamforming solutions for UAVs

An array of antennas, composed by linear, rectangular or circular series of simple antennas or elements, is used for controlling the array directivity function by adjusting the phases between different antennas. When the phases of signals coming or transmitted by the different elements are adjusted such that they combine coherently on a given direction in the space, the array forms the corresponding beam, directed with the maximum gain. The array and the beamforming are called adaptive when the phases (possibly also the gains) at the different elements are changed dynamically as a response to some feedback from the system, based on the maximization of the signal strength, SINR or the corresponding minimization of the interference. As an example, in the context of PSN and emergency scenarios, the adaptive array mounted on the relaying station, *e.g.* the UAV, should enhance the signals coming from some directions for discovery, communication or localization purposes, rejecting at the same time interference or other signals from other positions in the emergency area; this type of mechanism could maximize the output SINR.

Here we report the main recent works that have considered the application of beamforming to UAVs. Most of the papers are concerned with strategies for optimizing communications with devices on the ground. More recently, research has focused on channel impairments related to UAV mobility and energy efficiency aspects.

In [107], a UAV platform exploits beamforming for mitigating the mutual interference among mobile single-antenna devices on the ground and achieving spatial division multiple access. The work also addresses the control of the UAV using a Kalman filter for tracking the positions of the devices on the ground; according to the predicted positions, the system adjusts UAV's heading in order to optimize a bound on the achievable communication rate between the ground and the UAV. In [108], the UAV is used as a relay between single-antenna devices on the ground and a BS; in this context, the design of beamforming (BF) and UAV path for optimizing the signal-to-noise ratio (SNR) of the dual-hop relay link is presented. Numerical simulations show: (i) that the proposed method approaches the optimal flying path and outage performance; (ii) the impact of the number of antennas at the BS and of the UAV heading angle on system performance. In [109], UAVs are just considered as solutions for providing temporary wireless connectivity after disasters compromising communication infrastructures. Also, the optimal placement of UAVs making use of multi-antenna arrays is studied according to the principle of SNR maximization at ground nodes. The scenario considers the communication between two UAVs and two single users, in order to achieve maximum angular separation and maximum SINR. In [110], the UAV support to cellular networks is extended to mm-waves. Here, the beamforming phase selection is based on beamforming codebooks with a hierarchical structure, in order to enable fast training, tracking and reduce the challenging aspects related to the high frequencies. Among the interesting results of the paper, we can mention: (i) the study on the Doppler effect resulting from UAV movements, which could be potentially catastrophic especially for the high gain directions; (ii) the spatial-division multiple access potential at these frequencies; (iii) the proposition of an adaptive UAV cruising algorithms for contrasting signal blockage; and (iv) the study of the relationship between UAV positioning and user discovery with antenna arrays. In [111], a measurement study has been proposed for characterizing the air-to-ground channel at several frequencies, from 900 MHz and 1800 MHz to 5 GHz. Also, drone-based beamforming systems are investigated in terms of (i) channel reciprocity, (ii) feedback overhead, and (iii) update rate for channel estimation. Over the different bands, it is found that the optimal channel update rate is similar and the phase error depends on mobility, differently from the amplitude one. In [112], the coverage of a UAV-based BS has been optimized under the constraint of the transmitting power; the optimization problem is formulated w.r.t. the UAV altitude and beam angle, providing an interesting tool for relating the array weights patterns to the altitude for the coverage optimization with limited power consumption. Finally, in [113], an adaptive beamforming technique is exploited in a drone surveillance system; the weights adaptive algorithm is conceived for being robust to interference motion and array steering mismatch problems. Numerical results are used to validate the SINR performance improvement.

Table 3
Qualitative classification of localization technologies and approaches.

Method	Accuracy	Energy consumption	Localization method	Literature representation
RSSI	Low	Low	Trilateration	High
ToA/TDoA	High	High	Trilateration	Low
AOA	Low	High	Triangulatoin	Medium
Fingerprinting	High	Medium	Radio map	Low

3.1.3. *Localization strategies*

This section is devoted to the survey of novel localization solutions for PSN that exploit or may exploit UAVs. Localization is mainly based on measures that can be derived from the signal received by other devices or fixed reference points (usually denoted anchors or beacons), as the received signal strength indicator (RSS or RSSI), time of arrival (ToA), time difference of arrival (TDoA), and angle of arrival (AoA). The vast majority of practical techniques rely on RSSI or hybrid RSS/AoA techniques [114–118] and the reason is mostly due to constraints on hardware weight, which translates to constraints on precision for TDoA and ToA techniques. The most apparent contrast for traditional UE localization when UAVs are involved in their ability to move and quickly cover large distances. This ability allows the development of algorithms that define a flight plan for the drone to achieve the highest localization accuracy [114–116,118]. The main qualities of the most prominent localization strategies as well as their applicability are summarized in Table 3. Localization systems and their applications are becoming increasingly popular also in the context of 5G. With the 5G and the distribution of massive MIMO antennas, new localization schemes, based on the additional contribution of the AoA, are acquiring more interest than in the past [119]. In a terrorist attack scenario, in which UAVs have to cooperate for recovering the positions of the devices on the ground, a hybrid approach making use of all the available information and measures is surely one of the most reasonable approaches. In the sequel, the review of the state of the art follows a classification based on the type of measures used for the localization process.

UAV Based Localization Through RSSI: In [114], the authors present an AoA localization, based on RSSI measures, that is designed to be used on drones. The main strength of the work is the usage of Moxon antennas, cheaper and lighter than other commercial antennas. Their experimental solution is deployed on an SDR component installed on the RTL2832U chipset. The AoA is estimated through RSS measures from a front and a back antenna. Multiple measures are taken and a belief based algorithm refines the position based on current and past measures. A similar approach was used in [115] where multiple antennas are mounted on a drone and the user's bearing, with respect to the drone, is estimated by a weighted RSS algorithm. Yet another approach based on RSS is shown in [116], where the authors show an approach based on a single omni-directional antenna and RSS measures affected by stochastic channel fading and measurement noise. This work offers the joint evaluation of two localization algorithms, extended Kalman filter and recursive Bayesian estimator, alongside two-path planning algorithms, steepest gradient descent, and bio-inspired heuristic planning. One of the challenges of estimating the distance based on RSS measures is that transmitter power needs to be known in order to derive distance from RSS measures, because of this many works assume transmitter power known or constant. The authors of [118] show an approach to RSS localization when this assumption is not met, by employing a neural network-based algorithm to identify the most likely value of the transmitter power from a set of finite values. Then, this value is fed into the algorithm that performs target trilateration and makes the UAVs converge around it.

Localization with Hybrid AoA and RSSI: In [117], the authors study the signal discovery and localization in a huge disaster scenario with the purpose of life detection. The proposed hybrid RSS/AoA algorithm is based on the triangulation from AoA while using RSS information to improve the estimate. The AoA measures are evaluated according to the actual measured RSSIs, giving more importance to measures in which the difference between the maximum and minimum RSSI is higher. The work presents an experimental test bed usable on typical terminals such as UE.

Other Types of UAV Based Localization: The use of UAVs for the particular scenario of a terrorist attack can also be extended to the role of a mobile sensor platform, which can be used, for example, to locate shooters as shown in [120]. In the paper, the authors show a shooter localization algorithm that uses data coming from an array of microphones mounted on a flying UAV. The technique is similar to the AoA approach, where rather than radio waves the estimation is done by using sound waves. While the authors show a successful shooter localization, several constraints of this approach pose some concerns during hostile attacks. The main issues arise from the possible absence of LoS condition that precludes reliable localization and from the noise introduced by the UAV rotors, which is one of the largest impairments affecting the SNR of the measurements.

3.2. *MAC Layer*

3.2.1. *Resource and power allocation schemes in centralized mode*

As previously indicated, D2D communication can be operated in two modes: centralized, which is controlled by the BS and decentralized mode, which is not assisted by the BS [121]. Contrary to the traditional cellular network, where cellular users (CU) communicate via BS, D2D provides direct communication between users regardless of the network status. So, D2D communication can reduce the traffic load to the BS and provide better system throughput. However, interference is generated by D2D users. Therefore, appropriate power allocation and efficient resource allocation schemes can play a vital role to reduce the interference level, thereby significantly improving the overall throughput of the system [122]. In Table 4, a summary of classical schemes for centralized D2D communication is presented.

Matching Based Scheme: In [123], a resource allocation technique is proposed to guarantee the QoS of D2D pairs and CUs at the same time, to improve the overall network throughput which improves the spectral efficiency. The authors proposed a three-step scheme. The first step is to determine the D2D pair for each CU by ensuring the QoS by verifying the minimum SINR requirements. The second step determines the power allocation for CU and its D2D pair with the constraints on the minimum SINR requirements. The third, and last, step is the resource allocation for all D2D pairs, which consists of finding the best CU partner by using a maximum weight bipartite matching based scheme. In this scheme, a set of D2D and a set of CU partners are considered as two groups of vertices in the bipartite graph. The performance of D2D communications can be influenced by the cell radius, D2D user locations, the maximum power limitation for the D2D pairs and, the numbers of active CUs and D2D pairs [124].

Mixed Integer Nonlinear Programming: During the downlink (DL) phase, CU could suffer from interference produced by the D2D transmitter. While during the uplink (UL) phase, the BS could face interference by the D2D transmitter when random

Table 4
Summary of classical schemes for centralized D2D communication in cellular network.

Proposed scheme	KPI	Network architecture		Achieved performance	Drawback
		Architecture	UL/DL		
Matching based scheme [123]	QoS, power control, resource allocation, spectral efficiency and energy efficiency	LTE	UL	System throughput is enhanced 60% and access rate 10% compared with random allocation	Computationally complex and expensive
Mixed integer nonlinear programming [125]	Resource allocation	LTE	UL/DL	System throughput is improved up to 7% compared with random D2D allocation	Power control
Proportional fair and heuristic algorithm [126]	Resource allocation and QoS	LTE	DL	System throughput is improved up to 30% compared with random allocation	Power control
Game framework [127]	Power control, energy efficiency and QoS	LTE	UL	System throughput is improved	Computationally complex and expensive
Lagrangian dual decompositioN [128]	QoS, resource allocation, energy efficiency and power control	LTE	UL	System throughput is improved up to 35%	Computationally complex and expensive
Water-filling algorithm [129]	Resource allocation, power control and Spectral efficiency	LTE	UL/DL	Spectral efficiency is enhanced	Computationally expensive

allocation is used for radio resources [130]. In [125], the authors propose a mixed-integer-nonlinear programming (MINLP) scheme for D2D radio resource allocation, where the SINR values of CU and D2D pairs are found separately for UL and DL, and RBs are allocated with respect to SINR values. Numerical simulations show that D2D throughput, cellular throughput, and system throughput are improved with the proposed algorithm compared to random allocation.

Proportional Fair Algorithm: In [126], the authors propose a proportional fair (PF) algorithm for resource allocation to CUs and a greedy heuristic algorithm for resource reuse of D2D users. The PF algorithm follows a greedy rule, wherein the CU with the minimum normalized transmission rate is selected as the best subcarrier each time. Further, the second heuristic algorithm first determines whether the D2D mode is suitable or not, by doing path loss comparison. The resource allocation will be initiated if the SINR values of both CU and the D2D pair meet the minimum requirement of the allowed SINR. The results show that D2D and system throughput will improve with the increase in the number of D2D pairs.

Game Theory Framework: The work [127] proposes a joint scheduling method, power control, and channel allocation for D2D communication using a game theory approach. A technique named Stackelberg game framework is used, where cellular and D2D UE are grouped in a pair with a leader–follower combination. The CU acts as a leader while the follower is the D2D UE who purchases resources of the channel from the leader. The leader charges some dues from the follower for channel usage. So, the D2D user chooses the optimal power by utilizing the price given by cellular UE. The results imply that the throughput performance for both the D2D and cellular UEs can be improved with proposed method [131].

Lagrangian Dual Decomposition: In [128], the authors propose a two-phases based resource sharing algorithm for D2D communication. The first phase determines the channel allocation for each D2D UE. QoS is considered for both CUs and D2D UEs by defining a combined channel gain factor to assign channels to each D2D UE. In the second phase, the Lagrangian function is used to determine the optimal power for D2D UEs.

Water-Filling Algorithm: Water-filling algorithm is used to allocate the power for the subcarriers assigned to each separate D2D pair. The rule of water-filling method is that the transmit power will be distributed among all assigned devices [132]. The power allocation is proportional to the CSI of the D2D link of the respective sub-carrier.

3.2.2. *Machine learning techniques for D2D communication*

In case of absence of initial information, the problem of resource and power allocation for D2D communication in cellular networks is solved using Machine learning (ML) methods as proposed in [133–135] and presented in Table 5.

Cooperative Reinforcement Learning Algorithm: In [133], the authors present a cooperative reinforcement learning (RL) algorithm for resource allocation in D2D communication to improve the system throughput, also called state action reward state action (SARSA). The cooperation is achieved by sharing the value function between UEs and a neighboring factor. A set of actions is considered based on the transmission power level of a particular resource block. The reward function is defined by SINR and channel gains. The accuracy of the learning algorithm is increased by defining a set of states with a suitable number of system-defined variables. Simulation results show that the system throughput is improved with the proposed learning method as compared to the distributed reinforcement learning method. The shared learning policies between devices help to converge faster. D2D throughput is enhanced around 7% comparing with distributed reinforcement learning. A trade-off can be seen in D2D and CU throughput by changing the transmit power; higher transmit power will provide higher D2D throughput. It is also shown that D2D and the system throughput will improve by increasing the number of D2D UEs but cellular throughput decreases.

Distributed Reinforcement Learning: The work in [134] suggests two RL methods, team-Q and distributed-Q learning, to improve power control in a D2D under-laying cellular network. In the team-Q learning algorithm where all agents keep the same Q-value table. The complexity level of this approach increases exponentially according to the increasing number of D2D UEs. A distributed Q-learning is introduced to solve this problem. Distributed Q-learning breaks one big Q-value table in team-Q into several small tables. Now each agent has its own local Q-value table. Actions are sampled constantly during the learning process. So the Q-values in a table will only be updated once the next Q-value is greater than the existing Q-value. The agents, states, and actions also used for distributed-Q learning. Simulation results

Table 5
Summary of ML schemes for centralized D2D communication in cellular network.

Proposed scheme	KPI	Network architecture		Achieved performance	Drawback
		Architecture	UL/DL		
Cooperative reinforcement learning algorithm [133]	Power control, resource allocation, energy efficiency and spectral efficiency	LTE	UL	D2D throughput is enhanced around 6.2% as compared to the distributed reinforcement learning	Computationally complex and expensive
Team-Q learning and distributed Q learning [134,135]	Power control, QoS and spectral efficiency	LTE	UL/DL	System throughput is improved and convergence speed is enhanced	Computationally expensive
Proportional fair and heuristic algorithm [136]	Power control and energy efficiency	LTE	DL	Same throughput as compared to conventional method	Computationally complex and expensive

show that distributed-Q learning converges the Q-value faster than team-Q learning algorithm. It can also be seen that D2D throughput is more improved with distributed-Q learning than team-Q learning, with the increasing number of D2D UEs.

Deep Learning: The authors of [136] suggested a distributed transmit power allocation scheme using deep learning for every D2D UE. Each D2D transmitter can decide its transmit power considering both the D2D throughput and interference to the cellular system. D2D UE uses only its location to determine the transmit power to maximize the D2D throughput. Each D2D UE learns how to decide the transmit power to achieve the optimal system throughput based on locations considering the interference to BS. Deep learning is applied for the learning process using a cost function to meet the constraints. The cost function can be considered as a linear function to decide the appropriateness of output. The results show that the proposed method is appropriated to cover the edge users. However, it provides almost same throughput as compared to conventional methods by operating completely on distributed manner, and it is also computationally expensive.

3.3. D2D Communication in a decentralized mode

For the first time in cellular network, D2D communication was introduced in LTE Release 12. D2D communication allows direct communication between two UEs. The term sidelink was introduced by the 3GPP for ProSe. In ProSe three different LTE D2D functionalities are defined, i.e., direct discovery, direct communication, and synchronization. Despite of establishing a communication link in ProSe, the direct discovery functionality permits the UEs to advertise and detect the services or devices. Without routing the data to base station, the communication functionality permits two UEs to communicate by establishing a direct link between them. However, the synchronization functionality gives the required approaches to UEs to settle on mutual system information and is able to decode LTE sidelink transmission [77].

According to 3GPP, three scenarios are offered to operate D2D functionalities regardless of the network position of the UEs, i.e. in-coverage, partial coverage and out-of-coverage. In in-coverage scenario, the D2D communication is BS assisted and can also use pre-configured parameters. In the out-of-coverage scenario, UEs use preconfigured parameters for D2D communication. Finally, the partial coverage scenario is a combination of other two scenarios, where UEs inside the coverage area share system information with those out-of-coverage [137]. In Table 6, a summary of D2D communication in decentralized mode is presented.

3.3.1. Direct discovery

Different service discovery strategies are described in [138]. In service discovery process, UEs are allowed to advertise and monitor the services. Initial devices are required to register to the ProSe function. After the registration, the application layer permits the UEs to start or monitor the ProSe. A discovery signal is transmitted in discovery resources by advertising UEs. There are two types of service discovery approaches, uncoordinated service discovery and coordinated service discovery. An uncoordinated service discovery approach is not assisted by the BS for monitoring the services. The monitor UE starts RF discovery by blind decoding on all RF discovery resources. This approach requires significant undesirable processing and power consumption. In a coordinated service discovery approach, a monitoring UE is assisted by ProSe function indicating either if a service is offered or not in the specific area. For the advertised service, the network gives the information about the RF discovery resources to monitor the respective service. This approach is efficient but can only be used for the in-coverage scenario.

An enhanced algorithm is proposed in [139] to improve the discovery performance by detecting the presence and removal of UEs by using dynamic configuration instead of static configuration. In a static configuration, each UE will keep the same record of other discovered UEs at the time they were discovered. Furthermore, all the UEs use the initial transmission probability, and it will be not updated according to the current situation during the whole discovery process. The proposed algorithm uses a dynamic configuration where each UE processes the received announcements to check different transmission probabilities and computes its own transmission probability, after the addition or removal of UEs in the discovery group. The approach is known as dynamic configuration due to the continuous upgrading of transmission probabilities. Presented results show that the proposed algorithm can improve the accuracy and required time for the discovery up to 15%.

In [140], D2D discovery mechanisms for 3GPP are investigated, in particular, w.r.t. energy consumption; in addition it is proposed a D2D discovery mechanism based on the concept of proximity area, i.e., a dynamic region wherein UEs activate their D2D capabilities, enabling UEs to perform D2D discovery only when there is a high probability to find other UEs for the same service.

Furthermore, the authors in [141] discuss some key requirements and solutions, including those regarding discovery, for enabling D2D communications in LTE in order to meet public protection, disaster relief, national security, and public safety services-related requirements. The contribution of the paper is based on a clustering approach integrating cellular and ad hoc operation modes depending on the availability of infrastructure nodes.

Table 6
Summary of D2D communication in decentralized mode.

Proposed scheme	KPI	D2D scenario	Achieved performance	Drawback
Uncoordinated service discovery [138]	Direct discovery	Out-of-coverage Partial coverage	Able to discovered the services	Undesired processing Power consumption
Enhanced discovery algorithm [139]	Direct discovery	Out-of-coverage Partial coverage	Detected the withdrawal of the UEs. Accuracy of the discovery, and the time required for discovery is improved up to 15%	It is not autonomous to tune the parameters depending on the group size
PSCCH resource pool arrangement [142]	Direct communication Synchronization	Out-of-coverage	Same throughout as compared to conventional method	Throughput could be Reduced
PSSCH resource pool arrangemen [143]	Direct communication	Out-of-coverage	Increased the transmission probability up to 11%	Throughput could be Reduced
Frequency hopping resource scheduling [144]	Direct communication Synchronization	Out-of-coverage Partial coverage	Improved the reliability up to 20%	Performance could be decreased by increasing the number of UEs
Enhanced HARQ process [145]	Direct communication	Out-of-coverage	Improved the reliability and latency up to 9%	Able to increase the Interference

3.3.2. Direct communication

LTE sidelink communication has two physical channels [139]. The physical sidelink shared channel (PSSCH), which carries the transmission data of UE and the physical sidelink control channel (PSCCH), which carries the sidelink control information (SCI) message to detect and decode the PSSCH of a receiving UE. A UE uses the PSSCH to send data to other UEs. First, a UE should advertise the transmission using the PSCCH channel to send a SCI message that informs the remaining UEs about the transmission occupying by the PSSCH resources [146].

- **PSCCH:** All control messages are sent twice in PSCCH in the same period with two different PRBs. The out-of-coverage UEs randomly choose PRB pairs from the PSCCH resource pool defined by the following pair of parameters: the number of subframes from the time domain, and that of PRBs from the frequency domain [144]. As two PRBs are used for each transmission, the number of accessible resources in the pool can be found as: number of subframes * [number of PRBs /2]. If the same PSCCH resource index is selected by two or more UEs, then their SCI messages will interfere with each other. If the SINR at the receiver UE is high enough, then it could be possible to decode one of the interfering messages. The message could also be lost because of the half-duplex nature of UE transmissions. SCI message could be missed by a UE from another UE if it utilizes its own SCI in the same pair of subframes. So, SCIs can be missed because of collisions or the half-duplex effect; UEs that lose the advertisements could not get the real sent data during the following occurrence of the PSSCH. However, the problem could be overcome if the PSCCH resource pool is appropriately dimensioned. In [142], the authors propose a scheme for out-of-coverage scenarios where the PSCCH resources can be selected by UEs autonomously. They did the distribution of UEs in the D2D category that could get a transmitted control message as a function of the PSCCH and the number of UEs in the group. This distribution is used to make performance metrics as the maximum number of UEs that could be supported above a preferred threshold for a given resource pool arrangement. The results show that arrangement of the resource pools has a vital impact on the performance. PSCCH performance could be enhanced by increasing the number of subframes. The transmission period is a ratio of the PSCCH to the PSSCH, so by decreasing the duration of the PSSCH will increase the length of PSCCH that will reduce the throughput.
- **PSSCH:** PRBs of PSSCH are periodically repeated after the PSCCH in the time domain. In PSSCH, the band of PRBs is distributed into Nsb sub-bands in the frequency domain, whereas the set of subframes is divided into multiple time resource patterns (TRPs) on the time domain and each TRPs has NTRP subframes. OOC UEs randomly select the resources in PSSCH, so there could be interference between them. The collision impact could be resolved by the hybrid automatic repeat request (HARQ) process. UEs do not give feedback for each HARQ transmission over the sidelink even not for the successful transmission. A transmitting UE over the PSSCH sends four redundant versions (RVs) of data; each RV has the information and error correction bits [144]. However, the HARQ mechanism will increase the time response and also decrease throughput. It is observed in [143] that increasing the number of sub-bands in the PSSCH enhances the probability of decoding the transmitted message of a UE up to 7%, but this decreases the throughput. It is also seen that the value of kTRP (number of subframes for each TRP utilized by UEs to send data) has a crucial influence on performance. The probability of decoding the message of a receiving UE increases with the lower values of kTRP, but also the throughput is reduced.

The D2D frequency hopping resource scheduling on PSSCH is extended over the LTE Uplink as described in [144]. Frequency hopping is divided into two types. The first type is constant frequency hopping and the second type is pseudo-random frequency hopping. Constant frequency hopping determines the starting resource block for the transmission occurring in odd or even subframe indexes using two predefined formulas from the standard. Pseudo-random frequency hopping for the resource schedule assignment is performed with a predefined pattern calculated by a pseudo-random generated binary sequence, a set of equations defined by 3GPP standard in [147]. It is shown in [144] that frequency hopping improves the LTE D2D communications by about 20% with a single link, while the results obtained from sidelink group communication reveal a limited performance enhancement when enabling the frequency hopping over the standard no-hopping sidelink schedule assignment. This is due to lack of resource scheduling coordination in out-of-coverage scenario and the interference between UEs. Overall constant hopping slightly outperforms pseudo-random hopping.

In [145], the authors analyzed the effect of various configuration settings of unsupervised D2D communication on system performance. The impact on different parameters, such as reliability and latency, is observed using a simulation approach by varying the PSCCH to PSSCH ratio. As HARQ process transmits the same data four times even packets are transmitted successfully because there is no feedback system. Thus, the re-transmission process is improved by adding the transmission probability to the HARQ process. Every re-transmission X is achieved with a probability P(X). It is shown that the reliability is increased with increasing HARQ probability and it is maximum for 100% HARQ probability (conventional HARQ process). But it can also be seen that the reliability is improved with more number of nodes even with lower HARQ probability. It is also analyzed that latency is reduced by decreasing the HARQ probability which is desirable for he highly loaded network. While reliability decreases with smaller PSCCH to PSSCH ratio because smaller PSCCH periods enhance communication overhead but increase the interference between the UEs.

3.3.3. Synchronization

Synchronization helps to establish effective sidelink communication and discovery. UEs are required to coordinate in frequency and time domain, and they must settle on the same system information utilized in the communication procedures such as subframe indication, bandwidth, etc. Therefore, the same synchronization reference (SyncRef) must be followed by two UEs. The BS is responsible for providing the SyncRef for in-coverage UEs. While for out-of-coverage UEs, predefined parameters are utilized for the synchronization process between UEs to settle down on shared SyncRef. A transmitting UE in the Sidelink communication becomes a SyncRef in an out-of-coverage scenario. After becoming a SyncRef, it sends sidelink synchronization signals (SLSS) periodically for sharing its synchronization info. SLSS use one time domain subframe and the six central RBs from the frequency domain. The periodic length of SLSS is 40ms [99].

An SLSS signal is further categorized into four elements as the primary sidelink synchronization signal (PSSS), the secondary sidelink synchronization signal (SSSS), the demodulation reference signals (DMRS), and the physical sidelink broadcast channel (PSBCH). The PSSS and SSSS are operated for frequency and time reference; together they identify the SyncRef by encoding the SLSS identifier (SLSSID). SLSSID has two subsets: the first is dedicated to the identification of the SyncRefs for in-coverage situations and the second is reserved for the out-of-coverage scenario. The PSBCH has the master information block-SL (MIB-SL), which carries the systematic information required for the arrangement of the synchronizing UE. The DMRSs have the information of the receiving UE for channel approximation, demodulation of the PSBCH, and measurement of sidelink reference signal received power (S-RSRP). The S-RSRP has the strength information of the SyncRef signal [99].

3.4. Network layer

Historically, at the network level routing was realized by conventional technologies such as mobile ad hoc networks (MANETs) and wireless sensor networks (WSNs). Emergency MANETs (eMANETs) are deployed in emergency cases to provide communication for emergency workers with intelligent devices such as smartphones and personal digital assistants (PDAs) [148]. Recently, integration of UAVs in D2D/MANETs for efficient routing named as UAV-NETs is proposed [149]. The authors in [150] provided a comprehensive survey of multi-hop routing protocols for different classes of MANETs and the integration of networking technologies for disaster response scenarios. Similarly, [151] highlighted the merits and demerits of MANETs and delay tolerant networks (DTNs) and further presented the case of integrated MANET and DTN for improving the performance in dynamic environments. This survey also highlights the lack of realistic simulations models for disaster environments. Kawamoto et al. present the case of hybrid MANET and DTN implementation [152]. However, a single technology is not able to provide a complete solution. Therefore, a fusion of MANET based technologies such as MANETs, vehicular ad hoc networks (VANETs), flying ad hoc networks (FANETs), WSNs, and DTNs are the suitable choices. The authors in [153] reiterate the fact that most of the research work is simulation-based. However, they have tried to present details of the real experimental work in this domain and concluded that it is feasible provided the interoperability issues are resolved. In [154], a survey of routing algorithms and mobility models proposed for MANETs, DTNs, VANETs, WSNs for communication under disaster scenarios is presented. It also highlighted the challenges, gaps between applications, protocols evaluations and mobility models. In another effort, dynamic routing in FANETs is discussed in detail for the case of self-organizing wireless networks [155]. The success of any networking technology is also dependent on the underlying access technology. These days, user devices are equipped with multiple access and network technologies that allow these to communicate on multiple interfaces. This makes it more feasible to enable and facilitate D2D communication. D2D communication allows (I) Single hop communication, (II) Two hop communication, and (III) Multi-hop communication. Single hop communication is the basic mode of communication and D2D standards support for two and multi-hop communications through relays. There are multiple uses of relays in multi-hop communications such as range extension, connectivity with infrastructure, and other devices. Multi-hop D2D communication is an important feature and requires coordination between multiple nodes. The coordination between nodes can be achieved through routing protocols and gives rise to a new routing paradigm called multi-hop D2D routing.

3.4.1. Multi-hop D2D routing for PSN

The authors of [156] gave a very comprehensive survey on multi-hop D2D routing. They have presented a taxonomy of the D2D communications systems, classification of routing protocols, application areas, comparative analysis, and future directions. The survey classified multi-hop routing into three main categories (I) multi-hop device to infrastructure (D2I) and infrastructure to device (I2D) communication, (II) Multi-hop D2D communication and (III) Ad hoc routing for D2D networks. Multi-hop D2D devices operate in two modes. In the first one, a BS, or another central entity, controls the routing decision, while, in the second one devices operate in a distributed manner. The broad categories identified by the authors for base station dependent multi-hop D2D routing protocols are incentive-based, security-based, content-based, location-based, and topology-based. Similarly, the broad categories for D2D ad hoc routing are incentive-based, topology-based, QoS-based, security-based, device-aware, and multipath coding based. In addition to the above classification, routing protocols can be further classified as reactive, proactive, hybrid, and adaptive. Based on more recent trends in multi-hop D2D routing a few new classifications are possible: mm-wave D2D multi-hop routing (for spectrum efficiency), cluster based multi-hop routing (for load balancing and energy efficiency) and social aware multi-hop routing (for reducing the overhead and improve energy efficiency). The important factors affecting multihop D2D routing are node mobility, dynamic network, and network fragmentation. Multi-hop D2D routing can further benefit from advanced techniques such as software-defined networking (SDN) and network function virtualization (NFV).

3.4.2. Software-defined networking for PSN

The Table 7, presents a summary of main SDN architectures and frameworks. In SDN, the control plane is decoupled from the data plane. The control plane is responsible for monitoring

Table 7
Summary of SDN Frameworks.

SDN architecture framework	Features	Achievement	SDN controller
D2D-SDN [157]	Data packets sent in more flexible and efficient way	Hierarchical control plane for scalability and reduce communication overhead	Centralized global controller and multiple local controllers
VARP [158]	Better security, lower routing overheads, and higher scalability	Centralized and distributed	Main SDN controller to manage sub SDN controllers
HSAW [159]	Splitting of network control and data forwarding by two separate frequency bands	Demonstrates the advantage of hybrid architecture, offers better scalbility and reliability	Centralized SDN controller
EHSD [160]	QoS parameters, handover mechanism, security and coverage area	Results in better QoS compared to legacy LTE, improved security	SDN controller, L7 switch, open flow controller and security is provided in user side
SEANET [161]	Energy harvesting, separate energy plane	Improves data traffic by reducing packet loss, energy saving by optimizing energy utilization	SD data and energy controller
Softnet [162]	Coverage and low decentralized mobility management	Low signaling overhead compared to LTE NA	Network controller consisting of SDN controller and Virtual Network Function (VNF) orchestrator
CROWD [163]	MAC layer reconfiguration, dynamic backhaul reconfiguration	Reduced signaling overhead	Regional controller and Local controller
SoftPSN [164]	Resource slicing, reliability and low latency	Priority based resource slicing to accommodate first responders	Virtual resource controller

flows and managing the resources of the network. The control plane has a broad view of the network topology and can be used for the dynamic allocation of resources [165]. Initially, SDNs were widely used for wired networks. However, recently, an increasing interest in deployment of SDNs for distributed and wireless networks has been observed [166,167]. This is mainly due to the flexibility of deployment offered by SDNs. Most of the current SDN based research is mainly limited to proposals, architectures, and frameworks. A survey of recent SDN related efforts in wireless networks such as cellular, sensor, mesh, and home networks is presented in [167]. It highlights the advantages of using SDNs and discusses further opportunities to improve the performance of wireless networks. The report [168] proposes the integration of modern technologies such as LTE with networking technologies like SDN and NFV for the PSNs. As per the studies conducted on earthquakes, the features of these networking technologies are suitable because of rapid deployment, reliability, security and resilience. It further summarizes the features of the frameworks published in the literature.

SDNs play an important role in providing central management to the D2D clouds. They make use of the global information such as link quality, battery life, routing, etc. of all the devices available. They also control device registration, authentication and provide information about reliable connections. This hierarchical architecture is well suited for public safety applications where infrastructure is partially or totally damaged [68]. A wireless network architecture that exploits multi-hop D2D controlled through SDN controller to provide effective and efficient communication between devices is presented in [169]. Usman et al. [170] proposed a hierarchical architecture composed of several domain controllers being monitored by a central controller. The central controller dynamically allocates resources and thus reduces the energy consumption and signaling.

D2D-SDN is a hierarchical SDN based architecture [157]. It uses two tier centralized controller to derive the network topology with the help of connectivity and conflict graphs. MAC performance of the architecture against time division multiple access (TDMA) and carrier sense multiple access (CSMA) is also demonstrated through a prototype. Virtual ad hoc routing protocol (VARP) [158] framework provides multi-hop D2D routing as an extended service to the cellular networks through routing virtualization and SDN. VARP has the main SDN controller and sub-controllers for each cell to allow scalability, independence and intelligent decision forwarding. Each UE can use both LTE and Wifi bands and acts as an end-user of the main network and a forwarding node for the controller. VARP-based source (VARP-S) performs topology discovery, route discovery and route maintenance using modified control packets. For performance comparison, a modified version of Hybrid SDN Architecture for WDNs (HSAW) [159] proposed earlier is used. This protocol has shown the advantage of using a hybrid architecture over centralized and distributed architectures. An architecture based on the integration of SDN and short-range UEs to achieve reliability and low latency is presented in [164]. This creates a virtual network of available resources and applies a resource slicing algorithm. There is a provision to use priority-based resource slicing for the cases when the traffic load is too high. An architecture using the SDN controller nearby base stations to extend coverage to dead nodes is proposed in [172]. This is possible as the SDN controller is at the core and can better monitor network issues. This also proposes a flow based routing using relays to extend coverage in the dead spots. The UEs acts as relay nodes, therefore, it is important to take into account their limited energy and computational resources. Software-defined energy harvesting IoT (SEANET) is a proposed architecture that takes into account energy issues of the network [161]. In addition to data and control plane, it introduces an energy plane for efficient energy utilization. This uses a central controller which also considers energy situation of the nodes. CROWD [163] presents a flexible architecture for dense networks that facilitates reconfiguration of wireless devices and links. This uses two-tier hierarchical SDN controller named local controller (for fast and short time decisions) and regional controller (for slower and long time decisions).

The authors in [173] proposed an SDN based routing protocol for wireless multi-hop networks. The centralized controller has a broad view of the whole network and can make better routing decisions compared to AODV and OLSR when realized in simulations. The OpenFlow controller is located outside the core wireless network and connected to UEs via OpenFlow switch component. A low-overhead D2D routing (LODR) is proposed and compared with other protocols in terms of convergence time and overhead. In [171] the authors have presented a centralized

Table 8
Summary of SDN based D2D Multi-hop Routing Protocols.

Proposed scheme	KPI	D2D scenario	SDN controller	Achieved performance	Drawback
SD-MANET [171]	Overhead, throughput, delay, packet delivery ratio	Ad Hoc	SDN controller on one of the nodes, local controllers on other nodes	Low routing and communication overhead, low average end to end delay, proactive routing	Not suitable for large networks
VARP-S [158]	Overhead,energy consumption	Multi-hop D2D	Main SDN controller responsible for sub controllers in BS in each cell	Source based scalable routing	Optimization of power control, traffic classification strategy, metric measurements
HSAW routing [158]	Overhead,energy consumption	Hybrid(multi-hop D2D and cellular)	Sub controller need to exchange information	N/A	Higher overhead due to sub controller information exchange
LODR [169]	Convergence time, Overhead	5G, data plane multi-hop D2D	Central OpenFlow controller supported by OpenFlow switch function at UEs	Low routing overhead, hybrid reactive and proactive approach	Single central controller
FINDER routing [172]	Overhead ratio, delivery probability, average residual energy	D2D coverage extension	SDN controller at core network	Reduced energy consumption in routing and increased network lifetime, hybrid ant colony optimization	Single SDN controller
SDN routing [173]	Hop count, residual energy	Ad hoc	Central controller	Better performance in terms of hop count and end to end delay	Single controller is not suitable for high node density

SDN based proactive routing protocol SD-MANET for MANETs. The SDN controller learns the network topology without location services and the performance is much better compared to OLSR for a network of 50 nodes. Clustering is a suitable option for large networks.

Software-defined decentralized mobile network (SoftNet) is an architecture that proposes a natural alliance of SDN and 5G. SofNet shows better performance compared to legacy LTE. 5G networks allow the use of different devices and protocols, therefore, mobility of these devices in different segments of the network is unavoidable. SoftNet mainly suffers from coverage and device handover issues. Exemplary handover scheme during (EHSD) D2D communication based on decentralization of SDN is a framework that combines D2D communication and 5G vertical handover. Handovers can introduce delays and security issues. EHSD uses OpenFlow controller to reduce delay, L7 switch to support load balancing and has a provision for security. The cost of enabling handover is extra signaling overhead. A summary of SDN based routing protocols is presented in Table 8. This section has provided a detailed description of the communication technologies supporting D2D communication. In the next section, we introduce various channels models in the context of D2D communication including UAVs.

3.5. *Jamming in mobile networks*

With the term jamming, it is denoted any transmission activity that is intended to have explicitly a negative impact on the communication between one or more legitimate transmitters and one or more legitimate receivers. It is also clear that the wireless propagation environment is inherently more vulnerable to malicious attacks, as intentional or unintentional jamming signals or also passive eaves-dropping for data interception. In the reference scenario of this survey, the systems involved in the scenario are (i) the base stations still active in the network, (ii) the terminals on the ground and (iii) the UAVs acting as temporary base stations or relays towards and from the network as described in our reference scenario; the technology is again LTE and Sidelink, with a particular emphasis on PSNs.

In the context of terrorist attacks, jamming techniques can be part of the terrorists' strategy and/or of the public authorities in order to disturb the terrorists' communications and/or take control or limit the access to the network infrastructure. From these two perspectives, we can state that jamming is one of the technical challenges to be faced in the context of PSNs in presence of terrorist activity.

1. Terrorist strategy:
    - causing the network failure for preventing persons involved in the area from calling and communicating in order to increase the advantage in terms of time and effectiveness w.r.t. public authorities;
    - decreasing the communication capability of the public authorities and first responders;
    - preventing the use of machines, including UAVs, controlled by remote devices.
2. Public authorities strategy:
    - decreasing or nullifying the communication capability of the terrorists in order to decrease their effectiveness;
    - preventing the use of controlled devices, including UAVs, and possibly containing explosives or dangerous items.

Jamming can operate thanks to techniques applied to different physical and transport channels of the attacked network; for a general introduction to this area, the reader can refer to [174, 175] for an introduction and classification of jamming and anti-jamming techniques in wireless networks. Concerning the terminology useful for the sequel of this section, we can distinguish among (i) *elementary jammers*, which are blind interfering signals transmitted without considering the nature of the network and its possible defenses, and (ii) *advanced jammers*, capable of more sophisticated strategies; elementary jammers can be further classified as *proactive*, operating independently from the network activity, or *reactive*, which transmit only after detecting a radio communication on the channels to be attacked. On the other hand, advanced jammers are typically capable of adapting to the behavior of the attacked network, with enhanced functions designed according to specific protocols and system specifications and possibly more sophisticated capabilities of intercepting the control channels of the network in order to increase the probability of causing a service outage.

In terms of general articles, moving closer to the LTE interface, we mention the tutorial in [176], which analyzes the physical layer resilience of orthogonal frequency division multiplexing (OFDM) communications, considering elementary noise-like forms of jamming, energy-efficient jamming attacks, and possible countermeasures. Then, in the context of the evolution towards the fifth generation, in [177] it is possible to find a methodology for classifying the attacks to security in mobile phone networks with its application to the digital network generations; in particular, the analysis is exploited for proposing defenses and suggestions for the 5G specifications, with the final aim of increasing the protection of users' privacy and network resistance even in multi-operator scenarios. In [178], after an overview of the security vulnerabilities and threats in wireless systems as Bluetooth, WiFi, WiMAX, and LTE, it is presented the state of the art of physical-layer security, which is a set of techniques for protecting wireless communications at the physical layer: several techniques are reviewed and compared w.r.t. the presence of different jamming attacks and it is also discussed the integration of physical-layer security into the current authentication and cryptography mechanisms. Finally, in the same context of physical layer security, in [179] it is observed that the cooperation among the legitimate devices in a network can significantly enhance the security w.r.t. an uncoordinated scenario; so the paper provides a survey of works on cooperative relaying and jamming techniques for securing wireless transmissions against eavesdropping nodes, which attempt to intercept the transmissions. Then, the challenges of cooperative security are discussed, including their application to device-to-device communication.

In the sequel, we divide the review of the recent literature (mainly since 2016) into three parts, (i) jamming techniques against LTE and PSN, (ii) techniques for contrasting jamming in LTE and PSN and (iii) jamming techniques against UAVs operations. These topics have been knowing a growing interest also due to the development of the 5th generation mobile network.

3.5.1. Jamming techniques in LTE and PS networks

The studies in this field can be divided primarily into contributions on the analysis of LTE vulnerability to jamming signals and the proposal of anti-jamming techniques. In this section, we are interested in the former group, with an emphasis on the contributions of PSNs. In general, LTE appears vulnerable both in uplink and downlink, especially in the synchronization and reference signals.

Vulnerability of LTE Physical Layer: in [180], it is investigated the vulnerability of all the physical layer channels to RF jamming, spoofing and sniffing, with an assessment of different threats; LTE appears highly vulnerable to jamming and, in particular, the weakest links are identified as the PSS (primary synchronization signal), PUCCH (physical uplink control channel), PCFICH (physical control format indicator channel), and PBCH (physical broadcast channel). In [181], it is possible to find results from practical laboratory tests, performed for measuring the jamming margins of LTE physical layer w.r.t. several jamming techniques. Then, in [182], the LTE downlink is analyzed w.r.t. each subsystem in order to identify the weakest parts of the system: the experimental results, obtained with an open-source system and a synchronized protocol-aware jammer, show that the synchronization signals (PSS/SSS) are robust while the weakest ones are the cell specific reference signals (CRS), at least under these test conditions. On the other hand, also [183] confirms that the impact of pseudo-CRS signals can be really severe on the performance of channel estimation and consequently on data demodulation. Then, also in, it is provided a set of measurements obtained with a software downlink LTE implementation, showing the high vulnerability of the system, especially for protocol-aware attacks, like those designed for RS (reference signals or pilots) and PCFICH signals. In the uplink (in particular the physical uplink control channel or PUCCH, the physical uplink shared channel or PUSCH and the access channel or PRACH), [184] and [185] provide useful results for understanding the critical points of the system, which appears fragile especially w.r.t. requirements of critical missions and infrastructures. The weakness of the uplink is confirmed also in [186], where the single carrier-frequency domain multiple access, used in the LTE uplink, is tested w.r.t. advanced jamming techniques towards the synchronization and channel estimation processes, so by means of attacks on the cyclic prefix and pilots in the signal slots.

Mission-Critical Communication: in [187], several test cases are defined and performed on the LTE subsystems involved in the mission-critical communications; the experiments confirm that one of the weakest points of the system is constituted by the synchronization signals. It is also discussed a method for detecting the specific radio frequency attack in order to be able to mitigate its impact.

Evolution to the 5th Generation: In [188], it is presented a study on the impact of jamming when the interference is localized on non-pilot blocks, which cause the pilot-aided channel estimates to be inaccurate; in addition, the results also show that this kind of attack can severely compromise low-latency applications, which are crucial in vehicle-to-vehicle (V2V) communications and other ultra-reliable low-latency applications. Then, in [189], it is analyzed the vulnerability of 5G to jamming and spoofing and some mitigation strategies are proposed; the weakest links appear to be the PSS and PBCH channels even if, compared to LTE, 5G NR seems definitively less vulnerable to jamming, also because of the removal of sparse control channels like the PCFICH.

3.5.2. Anti-jamming techniques for LTE and PS networks

In this section, we are reporting the contributions that are more focused on the techniques for contrasting jamming attacks in LTE networks, including PSNs.

Protection of LTE Physical Layer: in [190] it is considered the deployment of LTE in both licensed and unlicensed bands; the paper analyzes the effect of RF spoofing affecting devices during the initial cell selection process, a serious threat for uncoordinated unlicensed bands and licensed bands interfered by intentional jammers, and it proposes some mitigation techniques compatible with LTE networks. In [191], the authors propose some mitigation techniques for addressing the LTE weakness related to the jamming of control channels during the cell selection process. Moving to LTE for PSNs, in [192], it is presented an algorithm for timing synchronization, cell identity detection, and carrier frequency offset estimation that is robust against partial-band interference and/or jamming, thanks to a proposed, appropriate adaptive filtering of the jamming signal from the PSS. Then, in [193], it is observed how LTE networks resilience decreases under wideband multipath conditions; in this scenario, it is proposed an algorithm based on game theory for combating smart jamming attacks.

Jammer-Type Estimation: part of the techniques for mitigating the impact of jamming involves the necessity of detecting the attack and its type. In [194], a mechanism is proposed and validated for helping the network to estimate the type of jammer and computing a repeated-game strategy conditioned on this estimate; interestingly, the mechanism is autonomous since it does not require explicit feedback from the network users.

Physical Layer Security: in [195], in order to respond to the weakness of D2D communications to jamming, data modification and privacy violation, solutions based on the application-layer and physical-layer security are proposed and validated.

3.5.3. Jamming in UAV communications

In the recent literature, there is a wide selection of papers concerning the impact of jamming signals on the control of UAVs and several proposed countermeasures.

Jamming Impact: in [196], there is a study on the impact of jamming signals in the spectrum used for piloting signals, in particular for evaluating the efficiency of commercial LTE signal jammers as a countermeasure against the LTE UAVs. On the contrary, in [197], it is considered a scenario where the link between a legitimate ground user and a UAV is subject to several eavesdroppers UAVs; the proposed model and analysis provides an insight on the secure connection probability w.r.t. several parameters and propagation conditions.

Anti-jamming Techniques: among the countermeasures against jamming and eavesdropping, in [198] it is studied a secure millimeter wave (mmWave) communication assisted by multiple UAV-enabled relays and jammers; one peculiarity of the study is that a cooperative jamming scheme, generated by a part of the UAV relays, is designed to degrade the eavesdropping channels and enhance physical layer security. Then, in [199], the physical layer security mechanisms for the two case studies of a UAV as a flying base station and a UAV as an aerial node are investigated. In [200], it is proposed and studied a power allocation strategy for UAV transmission based on reinforcement-learning, in order to resist smart jamming attacks without knowing their type and the channel model in the dynamic game. The numerical results show that the proposed strategy can suppress the attack motivation of subjective smart attackers and increase the secrecy of the UAV communication. In [201] it is considered a scenario where ground devices can learn how to contrast intelligent jamming attacks coming from UAVs using the application of deep Q-networks; the problem is formulated as a dynamic game, which is analyzed and simulated. In [202], the work is devoted to a novel detection and response scheme, which operates at the UAV and ground station for detecting malicious anomalies in the network. The numerical results show that the proposed scheme has remarkable attack detection probabilities for the most known cyber-attacks for UAV networks, including jamming.

Beamforming: in [203], it is considered the problem of fast-moving jamming, which constitutes a real challenge for UAVs. Therefore, it is developed a robust adaptive beamforming technique capable of enhancing the navigation signal and suppressing the jamming efficiently.

Trajectory Design: an interesting research line has been considering the design of optimal trajectory and other parameters for contrasting efficiently jamming. In [204], it is proposed a maximization function for the average secrecy rate by jointly optimizing the UAV trajectory, transmit power in the presence of an eavesdropper, and avoiding specific no-fly zones. The sub-optimal solution allows an efficient computational implementation despite the general high complexity of this kind of problem. In [205], the scenario is constituted by an UAV under the threat of a malicious jammer; it is proposed a joint power and trajectory optimization method based on a game theory approach. Then, in [206], a tracking algorithm for a legitimate UAV is proposed to track the trajectories of some suspicious UAVs, by using eavesdropped packets, angle-of-arrival and received signal strength. Finally, in [207], the optimization of a UAV flight trajectory for a relay communication system in presence of a jammer is investigated; a performance gain is achieved by optimizing the UAV path for maximizing the signal-to-interference-plus-noise ratio of the link.

GNSS Jamming: also the global navigation satellite systems (GNSS) can be subject to jamming, causing problems to the UAVs flight under control during GPS jamming. In [208], it is analyzed the impact of off-the-shelf GPS jammers to UAVs and a countermeasure is described, implemented and tested in realistic conditions.

4. Channel models proposed for D2D communication

The architecture proposed for the COUNTER TERROR project, depicted in Fig. 4 shows the three different channel models that are required to obtain realistic performance: (i) the channel between two D2D users, given in [74]; (ii) the air-to-ground (A2G) channel between UAV and ground user, defined in [209]; and (iii) the UAV-to-UAV or air-to-air (A2A) channel, studied in [210]. The channel model characterization is done by defining large scale parameters (LSP) and small scale parameters (SSP). While the LSP include path-loss and shadowing effects, the SSPs take into account angular spread, delay spreads, and the Rician factor. To model these parameters, three different channel approaches can be adopted: stochastic, map-based, and hybrid. In the stochastic-based approach, the parameters are characterized by the data obtained using channel measurement campaigns. In the map-based (or deterministic) approach, environments are simulated using a radio propagation or ray-tracing software to obtain the channel parameters. The Hybrid-based approach is a mixture of the two, where LSPs are calculated using the map-based approach and the SSPs using the stochastic ones [211].

There exist surveys pertaining to channel characterizations for A2G, A2A, and D2D. In [212], the results of measurement campaigns are described for narrow and wide-band channel sounders, IEEE 802.11 transceivers and cellular-connected UAVs operating at either unlicensed frequency bands or respective bands according to the considered technology. Further, measurement results were shown for A2G and A2A characterization with LSP and SSP. In this area, reference [213] describes the difference and analysis of A2A and A2G aeronautical and UAV channel fading statistics, where aeronautical channels are clearly characterized by a flight altitude that is much higher than the UAV one, especially when UAV is used as a low altitude aerial platform (LAP). Then, a list of civil aircraft and UAV channel modeling campaigns is provided along with the link budget, channel impulse response metric, antenna diversity, spatial multiplexing and MIMO characteristics over rural, urban, and sea environments. Another relevant survey [214] describes in detail the impact of multipath channel propagation effects, including scattering and Doppler effects, in different types of environments. Furthermore, antenna configurations, channel sounding waveforms, effects of elevation angles are extensively elaborated. These surveys on A2G and A2A channels also provide open challenges in channel modeling for UAV aided wireless networks.

About D2D channel models, in [215], a comprehensive overview of the state-of-the-art D2D channel research is provided for different scenarios with a discussion on the associated parameters.

In the sequel, we present the details of the models elaborated and adopted in the COUNTER TERROR project.

4.1. D2D-to-D2D Channel model

The channel models defined by 3GPP for the link between D2D users were obtained from the stochastic approach and are classified for three different scenarios [74]. **Outdoor-to-Outdoor:** for this scenario the path-loss is modeled as

$$\mathrm{PL}_{tot}(d) = \max\{\mathrm{FSPL}(d), \mathrm{PL}_{B1}(d)\}, \tag{1}$$

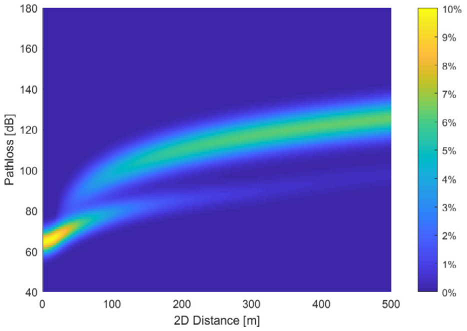

Fig. 10. Path-loss statistical modeling for the case of BS height equal to 25 m and UE height set to 1.5 m, operating frequency 1.9 GHz. A clear separation between LOS and NLOS conditions can be seen.

where max(·, ·) chooses the maximum of its two arguments, d is the distance, in meters, between the UEs establishing D2D communication, which is used to calculate both FSPL(d), the free space path-loss, and PL$_{B1}$(d), the path-loss in dB for Winner and channel model [216] in the urban microcell layout. The FSPL is computed as [217]

$$\mathrm{FSPL}(d) = 20\log_{10}(d) + 46.4 + 20\log_{10}\left(\frac{f_c}{5}\right), \quad (2)$$

where f_c is the system frequency in GHz. Similarly, PL$_{B1}$ is modeled as follows:

- $$\mathrm{PL}_{B1}(d) = (44.9 - 6.55\log_{10}(h_{UE}))\log_{10}(d) + 5.83\log_{10}(h_{UE}) + 16.33 + 26.16\log_{10}(f_c), \quad (3)$$
  for f_c in the range $0.45 - 1.5$ GHz;
- $$\mathrm{PL}_{B1}(d) = (44.9 - 6.55\log_{10}(h_{UE}))\log_{10}(d) + 5.83\log_{10}(h_{UE}) + 14.78 + 34.97\log_{10}(f_c), \quad (4)$$
  for f_c in the range $1.5 - 2$ GHz;
- $$\mathrm{PL}_{B1}(d) = (44.9 - 6.55\log_{10}(h_{UE}))\log_{10}(d) + 5.83\log_{10}(h_{UE}) + 18.38 + 23\log_{10}(f_c), \quad (5)$$
  for f_c in the range $2 - 6$ GHz.

In the equations h_{UE} is the height of the UE above the ground, usually taken as 1.5 m.

Indoor-to-Indoor: the path-loss modeled for this scenario is taken from [218],

$$\mathrm{PL}(d_{OI}) = 38.46 + 20\log_{10}(d) + 0.7d_{OI} + {} + 18.3n^{((n+2)/(n+1)-0.46)} + q\,L_{iw}, \quad (6)$$

where d_{OI} is the distance inside the house, n is the number of penetrated floors, q is the number of walls separating apartments between the two UEs and L_{iw} is the penetration loss of the wall, which is 5 dB.

Outdoor-to-Indoor: in this scenario, the model for path-loss is obtained from [218] as

$$\mathrm{PL}(d) = \max\left\{15.3 + 37.6\log_{10}d,\ 38.46 + 20\log_{10}(d) + 0.7\,d_{OI} + 18.3\,n^{((n+2)/(n+1)-0.46)}x + qL_{iw} + L_{ow}\right\}, \quad (7)$$

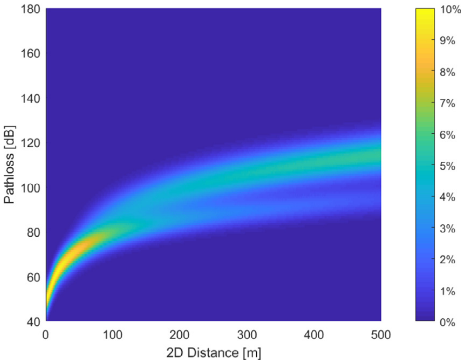

Fig. 11. Path-loss statistical modeling for the case of BS height equal to 25 m and UE height set to 20 m, operating frequency 1.9 GHz.

where L_{ow} is the penetration loss of an outdoor wall, which is 20 dB.

Furthermore, other channel parameters such as LoS probability and coefficient generation for fast fading effects are reported in [219]. The shadowing correlation is assumed to be independent and identically distributed, with a standard deviation of log-normal shadowing as 7 dB for outdoor-to-outdoor and outdoor-to-indoor scenario. For indoor-to-indoor scenario, 3 dB standard deviation is taken for LoS, 4 dB for NLoS and 10 dB if UEs are in different buildings, as reported in [74].

4.2. Air-to-ground channel model

The A2G channel model between UAVs and UEs, where UAVs act as low-altitude aerial platforms, can be inferred from [220, 221]. This channel is different from terrestrial and satellite links. The authors here have used the map-based approach and used the close-in reference path-loss model to characterize the path-loss effect. This model is given by

$$\mathrm{PL}_{LOS}(d) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10\eta_{LOS}\log_{10}(d) + X_{\sigma,LOS} \quad (8)$$

and

$$\mathrm{PL}_{NLOS}(d) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10\eta_{NLOS}\log_{10}(d) + X_{\sigma,NLOS}, \quad (9)$$

for LoS and NLoS, respectively. Here, η is the path-loss exponent, d is the distance between UAV and UE in meters, d_0 is the reference distance, taken as 1 m here. X_σ is the log-normal random variable with standard deviation σ that models the large scale shadowing. The average path loss is given by

$$PL(d) = P_{LOS}\cdot PL_{LOS}(d) + (1 - P_{LOS})\cdot PL_{NLOS}(d), \quad (10)$$

where P_{LOS} is the probability of having a LoS condition. The LoS probability is modeled as

$$P(LoS,\theta) = \frac{1}{1 + a\exp(-b[\theta - a])}, \quad (11)$$

where θ is an elevation angle between UAV and UE, a and b are parameters that depend on the type of environment, as indicated in ITU-R regulations.

The channel characterization for these models using a map-based approach is given in [221] at 2.4 GHz for environments defined according to ITU-R environment description. A comprehensive survey is also provided in [214] with several measurements and simulation campaigns to describe LSP, SSP, and MIMO channel characteristics.

A guide for channel modeling can be found also in the 3GPP specifications from 0.5 to 100 GHz in TR38.901 [222]. Of particular interest in our scenario is the modeling of urban macro-areas, defined for BS height of 25 m and variable user height. While this model is of limited applicability to the scenario that includes UAVs, it is nonetheless an important reference. Figures 10 and 11 show the probability distribution of the path-loss values depending on the 2D distance for different cases of UE height assuming that a UAV flies at 25 m of altitude. 3GPP has also provided a technical report for enhancing LTE support for aerial BSs [209], where channel characterizations are provided for uplink and downlink over different cell areas.

4.3. UAV-To-UAV channel model

The LSP and SSP for the UAV-to-UAV channel can be found in [210]. The approach is based on a ray-tracing or map-based approach in order to identify the channel parameters over a certain specific city environment and the sea at 2.4 GHz. A simple path-loss model was addressed, with attenuation and path-loss exponent measurements. Also, delay and Doppler dispersion were characterized.

5. Open challenges and discussions

5.1. Challenges faced by D2D in decentralized mode

D2D communication has attracted both academia and industry. The literature mostly focuses on D2D communication in a centralized mode. In emergency scenarios, the BS would be only partially available or completely damaged; however, only few works in the literature exist on D2D communication in a decentralized mode. Here, we describe some of the main challenges faced by D2D in decentralized mode.

- **Blind Discovery:** After advertising, the monitoring UE starts to discover the associated service/device by blind decoding on all RF resources in decentralized mode, which is undesirable for battery life of cellular phones because higher power consumption and computations are required.
- **Adaptive Resource Scheduling:** Various configurations are possible for sidelink communication by varying the PSCCH to PSSCH ratio and PSCCH period length according to D2D UEs. However, according to the best of our knowledge, there is no adaptive resource scheduling technique which could vary the configuration according to the required situation that would improve the reliability and throughput.
- **HARQ Process:** HARQ process, in sidelink communication, retransmits the data four times. Even if the data is sent successfully in the first attempt, the HARQ process will retransmit the same data although this is not required and desired because there is no technique to get feedback. So, the HARQ process could be improved having feedback to improve the latency and reliability.
- **Energy Consumption vs ProSe Performance:** Battery life of the UE is one of the most significant challenges in critical situations. This highly depends on the designed protocol for direct discovery and communication, for example, if the UE is forced to wake up by the protocol or to advertise the discovery frequently or to retransmit the data repeatedly. The trade-off between the energy consumption of UE and the performance of ProSe should be better analyzed.
- **Adaptive Tuning:** In emergency and critical scenarios it is likely that the BS is either partially available or completely damaged. To handle such situations, 3GPP defines pre-configured parameters [223]. Those are provisioned on ProSe enabled UE by the network operator before the deployment. To have efficient performance, it is required to develop an adaptive tuning at run time according to the specific and possibly dynamic situation.
- **Limited Resources:** There is no literature using experimental evaluation because chip-sets supporting LTE sidelink are not available on the market for the practical implementation; moreover, experimental equipment and test-beds are extremely expensive.

5.2. Challenges in beamforming for UAVs

When a beamforming system is installed on the UAV, the main issue is the relation between the array, with its steering properties, and the position and orientation of the UAV, which is a mobile system. In other words, the array is mounted on an object whose position and orientation in space is not fixed but, changes either as a result of a controlled flight or atmospheric/non-atmospheric disturbance factors like wind or the automatic corrections of the UAV flight control system. This dynamic behavior clearly increases the difficulty of controlling the beamforming, affecting and reducing the final accuracy of the system. Therefore, the main challenges can be summarized as:

- **Beamforming Management in a Dynamic Reference System:** This is the main issue, in which the dynamics of the UAV affects the position and orientation of the array, causing the necessity of managing beam steering, coordinates, and antenna mechanical tilt accordingly. The time constants associated with the UAV dynamics and electronic steering are different, and this could allow the decoupling of the two processes, flight control and beamforming control. However, in a real system, this remains one of the main issues to be addressed.
- **Impact of Flight Turbulence:** In the context of the flight dynamics, some disturbances can condition the stability of the UAV, also when it is supposed to transmit and receive in a fixed position. It is important to study the impact on the communication and localization performance of phenomena like wind, flight turbulence, transitory periods between flight commands and their actuation.
- **Energy Budget in Presence of Beamforming:** The energy budget could be affected by the presence of a beamforming system aboard since the electronic beam steering could be used for changing the flight trajectories and plans. Trade-off studies with given coverage and/or transmission quality requirements and experimental validation are surely another challenging point of research interest.

5.3. Challenges in UAV based localization

Many works have focused on utilizing the versatility of UAV anchors for performing localization. In most of them, the main challenges are represented by the energy and weight constraints the hardware and, while prominent, they are not the only challenges faced in the case of terrorist attacks.

- **Hardware Weight and Aerodynamic Constraints:** Some works in the literature focus on the introduction of massive MIMO into AoA localization [119]. These approaches are suitable for ground based BS that are already equipped with such hardware but they are unpractical for UAV based relays due to clear constraints on the size and weight of the antenna array, which calls for alternatives approaches.

- **Energy Budget Constraints:** Drones are battery-powered and low energy consumption is a fundamental requirement. Therefore, an emerging trend is to select RSS or hybrid RSS/AoA solutions due to their simplicity, reduced cost and energy consumption w.r.t. pure AoA or ToA/TDoA approaches, which would provide better accuracy but at the expense of higher energy costs.
- **Adversarial Activity:** On the one hand, moving the UAVs closer to, and, in LoS condition, the target certainly improves localization accuracy. On the other hand, in the case of terrorist attacks, it gives the terrorists the capability of damaging the drones by shooting them down. To the best of our knowledge, no study has attempted to address this problem, which remains an open issue.

5.4. Challenges in multi-hop routing

Many earlier works have focused on multi-hop D2D routing. However, due to the topology and application dependent nature of the networks, there is a lot of room to develop new routing protocols which can achieve spectral and energy efficiency.

- **DTN Based Routing:** Node mobility is one of the important factors affecting the performance of D2D routing. DTNs use the principal of store carry and forward to allow nodes to carry data and forward when a possible connection is available. For content distribution in disaster and post-disaster scenarios, inspiration from store carry forward can be derived to devise routing protocols for multi-hop D2D routing.
- **Security Based Routing:** As mentioned earlier security becomes a significant concern in multi-hop D2D. The interactions between different devices need some secure routing protocols to avoid malicious activities, which remains an open issue.
- **Energy Harvesting Based Routing:** Network lifetime is dependent on efficient utilization of energy resources. However, in public safety scenarios, energy is very critical in order to keep devices alive for tracking and content distribution. Devices provisioned with energy harvesting capability can further enhance their life. Devices can harvest energy from solar, radio frequency and other sources, which should be considered in routing algorithms.
- **Interference Aware Routing:** Interference is the main reason for performance degradation in multi-hop D2D networks. Interference aware routing strategies can improve performance and save energy.

5.5. Challenges in SDN

As discussed earlier in the paper, SDNs have a great potential to improve multi-hop D2D routing. Some of the open challenges in this domain are listed below:

- **Security:** Security is a major concern and is not catered in the majority of the architectures. It is important to have security provisions in D2D communications. However, central controllers result in delays and some security related tasks could be delegated to local controllers.
- **Wireless Channels:** Wireless channels are dynamic and require continuous monitoring of change in channel conditions. Having centralized controllers can result in delays. Therefore, it is desirable to design hierarchical (main centralized + multiple distributed) or distributed controllers to cater for dynamic nature of the channel and timely update to central controller.
- **Scalable Architectures:** Most of the existing architectures report scalability issues. Considering the increasing number of devices, it is desirable to target architectures which are scalable and support routing protocols which can accommodate a wide variety of devices.

5.6. Challenges in jamming techniques

The analysis of the recent literature has emphasized some clear weaknesses in LTE and potentially in the 5G against jamming attacks. We think that there is still a need for further research in this context.

- **PSNs Resilient to Jamming Attacks:** the context of terrorist attacks requires a specific resilience of the PSN to jamming in order to reach the devices in the area with a secure and reliable connectivity.
- **Jamming in D2D Communications:** this aspect seems not sufficiently addressed by the literature even if, in the scenario considered by this survey, D2D communication is one of the key technologies for overcoming the difficulties in an area without the full infrastructure support.

6. Conclusion

This article has provided a comprehensive survey for pervasive public safety communication technologies in public safety scenarios, especially in terrorist attacks. We have discussed different disaster scenarios, difference between natural and human-made disasters, technical challenges faced by PS services, existing architectures for PSNs along with the enhancements from 3GPP standardization on D2D, and importance to have reliable PSN to deal such disasters. Furthermore, various ongoing research projects have been summarized in the context of pervasive public safety communication. One of the important issues in such scenarios is how to reduce the response time. In order to reduce the time response, we briefly describe an architecture for disseminating the critical information. With this motivation, we have discussed the emerging technologies for PSN that could be critical in the context of emergency management, i.e. UAVs, localization techniques, weak signal detection methods, reliable routing, and jamming and anti-jamming in mobile networks. Finally, the article concluded with open challenges in each layer to highlight the possible future directions of the research in PSC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 3

III

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Experimental Characterization of ProSe Direct Discovery for Emergency Scenarios

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Abstract—**Device-to-device communication, as provided by the third generation partnership project standardization, can play a vital role in designing a reliable pervasive public safety network, which allows the user equipments to communicate directly with each other in emergency situations. In this paper, we present experimental results and evaluate the performance of proximity services-based direct discovery in terms of reliability and maximum range for outdoor and indoor emergency scenarios.**

Index Terms—**Device-to-device communication, public safety network, proximity services, direct discovery.**

I. INTRODUCTION

In emergency scenarios (e.g., terrorist attacks, earthquakes), the availability of the cellular base stations (BS) cannot be guaranteed; it is often unavailable due to e.g. physical damages, and thus people are not able to communicate with those who are outside of the disaster zone. Consequently, the first responders remain unable to take immediate actions to provide relief, even after many hours, due to unclear information such as the number of affected people, their locations and identity, etc. Consequently, the response time may become very long [1]. The main challenges in emergency scenarios are 1) to establish connectivity in the absence of a BS and share important information with the first responders [2], and 2) to maintain the network connectivity alive for several hours.

Device-to-device (D2D) communication supports both commercial and public safety (PS) scenarios. The application of PS is considered one of the most essential applications of D2D communication. D2D can provide connectivity between remote user equipments (UEs) in emergency scenarios to directly communicate with nearby UEs when the BSs are destroyed, non-functional, or unavailable due to disasters.

The third generation partnership project (3GPP) proposed proximity services (ProSe), initially in Release 12 and 13, to enable D2D communication (including PS scenarios) over a new interface called sidelink PC5 [3]. Later in Release 14 and 15, additional enhancements were proposed primarily for vehicle-to-everything (V2X) communication [4], while Release 16 proposed new radio sidelink enhancements such as additional physical resources, feedback channel, etc. Finally, in Release 17, 3GPP is planning to provide communication with a UE via another UE (UE-to-UE relay) to enhance ProSe services along with V2X services.

A. Related Work

Existing studies propose different schemes for D2D discovery, such as location-based D2D discovery with the help of BS [5], coordinated relay discovery approach [6], a neighbor discovery scheme through demodulation reference signals (DMRS) based on a power normalized correlation process [7], a discovery retransmission scheme with different discovery periods [8] to discover larger numbers of devices in proximity and to improve discovery accuracy and energy efficiency. In [9], the authors present the evaluation of network-assisted D2D discovery, in terms of the number of discovered devices, through a mathematical analysis using stochastic geometry model in indoor and outdoor environments. It is concluded that the discovery performance can be improved by reducing the in-band emission.

However, the above-mentioned schemes are not suitable for out-of-coverage emergency scenarios because 1) the solutions proposed in [5], [6] are only network-assisted, 2) the discovery protocol proposed by 3GPP is not followed by these schemes [10], and 3) the method suggested in [8] is not an energy-saving solution, contrary to what is needed for PS out-of-coverage scenarios.

PS communication is typically operated in sub 1 GHz frequencies [11] and existing studies lack in understanding the D2D communication in those frequencies; i.e., there is a need for investigating realistic communication ranges under various conditions, packet losses, and baseline network lifetime in those frequencies.

B. Contribution

To the best of our knowledge, this is the first empirical study that presents experimental measurements to characterize the ProSe direct discovery using the open-source software OpenAirInterface (OAI) and software-defined radio-based hardware platforms (USRPs). The experimental results are obtained in order to evaluate the baseline performance in terms of various operating frequencies (between 697 and 897 MHz), reliability of successful discovery message reception, and maximum discovery range in three different scenarios: 1) indoor (LoS), 2) indoor (NLoS), and 3) outdoor (LoS).

II. EXPERIMENTAL CHARACTERIZATION OF PROSE DIRECT DISCOVERY

ProSe supports two types of discovery mechanisms for PS use: partially network-assisted discovery and direct discovery. We consider the decentralized case when the BS is not available and our attention is focused on direct discovery. Direct discovery can identify and detect the other ProSe-enabled PS

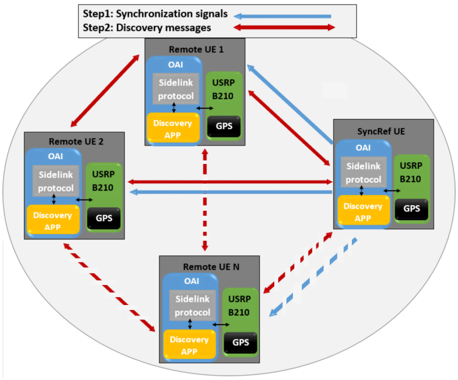

Fig. 1: Components and architecture for the ProSe direct discovery.

UEs located in proximity. Two models are introduced for PS direct discovery [12]: Model A ("I am here") and Model B ("Who is there?"). Model A uses only a single protocol message for discovery, i.e a ProSe-enabled UE periodically transmits the discovery messages, and the second ProSe-enabled UE monitors the discovery messages. On the other hand, Model B uses two protocol messages, i.e. A ProSe-enabled discoverer UE periodically transmits the solicitation messages, and a discoveree UE sends back a response message to the discoverer UE. The discovery and response messages contain information such as message type, discovery group ID, announcer info, monitoring UE info, ProSe UE ID, etc. More details about discovery and response messages can be found in [13]. In this study, we consider direct discovery with model A for the measurements in order to evaluate the performance of direct discovery in heterogeneous environments.

In practice, the main steps for the D2D discovery are summarized in what follows. Before announcing the discovery message, a synchronization reference (SyncRef) UE transmits the sidelink synchronization signals (SLSS) periodically each 40 ms to announce its synchronization information, in order to acquire the necessary timing and frequency information for performing the successive steps. After synchronization, the UE starts to announce the discovery message periodically and other UE(s) will monitor the discovery message to discover the announcing UE on the physical sidelink discovery channel (PSDCH) [13], as depicted by the arrows in Fig. 1.

A. *Experimental Setup*

The open-source software (OAI) and hardware platform (USRP) are used to performs the experiments and collect empirical data. In brief, the OpenAirInterface Software Alliance (OSA) is a non-profit association that encourages the research and industrial contributors for open source software and hardware development for the core network (EPC), access network, and user equipment of 3GPP cellular networks. The OSA is an initial work of Eurecom that creates OAI towards the development of 5G cellular stack on commercial-off-the-shelf hardware.

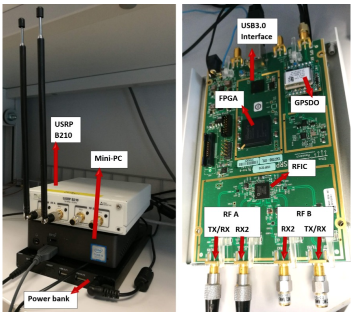

Fig. 2: Photos of a UE (hardware).

Our OAI/USRP based testbed consists of the following equipment:

Each UE is composed of:

- USRP B210 board used as the radio front-end hardware part of a UE. The main components of the USRP B210 are a Xilinx spartan 6 XC6SLX150 FPGA, AD9361 RFIC direct-conversion transceiver, CYUSB3014 USB 3.0 interface, four connectors for the antennas. The radio frequency part is based on the AD9361 chip, whose maximum output power is 8 dBm. After the AD9361, there is a PGA-102+ output amplifier (15.9 dB gain at 800 MHz). The available Tx gain and Rx gain are 89.8 dB and 76 dB, respectively and the noise figure of the receiver is 8 dB max.
- Board Mounted GPSDO (TCXO) module that provides a high-accuracy 10 MHz reference. All UEs in the network use the same reference clock for synchronization.
- Each UE is fitted with two telescopic antennas to transmit and receive the signals (one-channel configuration).
- Mini PC: used to run the software part of OAI. It runs the Linux operating system and the OAI protocol stack of 3GPP standard (Starting at LTE (Rel 8), including features from LTE-Advanced (Rel 10/11/12), LTE-Advanced-Pro (Rel 13/14), going on to 5G (Rel 15/16)). Each mini PC is linked with one USRP to configure it as one OAI-based UE. The implemented application for the direct discovery (D2D App (Sidelink protocol)) runs on top of the 3GPP layers.

An illustration of the architecture and components (except USB power banks) of the OAI-based UEs is shown in Fig. 1; corresponding hardware photos are shown in Fig. 2.

On the software side, an initial OAI prototype for LTE Sidelink publicly available from Eurecom[1] has been used as a starting point. The above initial setup is limited to two UEs in the network, transmitting one random discovery message; moreover, the UEs are to be connected with one OctoClock

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[1] https://gitlab.eurecom.fr/oai/openairinterface5g/-/tree/LTE-sidelink/

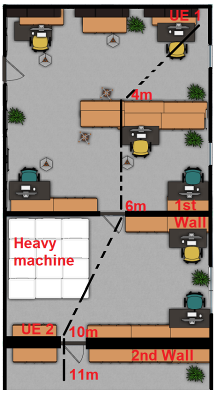

Fig. 3: UEs perform direct discovery in an indoor scenario.

(CDA-2990) device through SMA cables for synchronization. In our work, we expanded the setup up to 8 UEs in the network and installed a GPSDO (TCXO) module for synchronization on each UE in order to remove the OctoClock from the setup and allow moving the UEs easily.

B. Measurement Campaign

In this work, all the experiments were performed at the Tallinn University of Technology after obtaining the required permission (RF test license) for the measurement campaign. Up to 8 OAI-based UEs are used in this measurement campaign. The UEs are deployed in outdoor and indoor scenarios to analyze the performance of the direct discovery.

1) Indoor (NLoS): In the indoor NLoS scenario, UEs do not have a direct transmission path. Experiments are carried out in up-to three different labs where there are different obstacles between the UEs, such as shelves, electronics devices, heavy machine, concrete, and/or plaster, as shown in Fig. 3.
2) indoor (LoS): In the indoor LoS scenario, UEs have a direct transmission path between them without any obstacle. Experiments are performed in a long and straight corridor inside the university building, as shown in Fig. 4
3) Outdoor (LoS): Outdoor experiments are carried out on the rooftop of the university building where the UEs have a direct transmission path between them, as shown in Fig.5.

III. EMPIRICAL MEASUREMENT RESULTS

This section presents the empirical measurement results to examine the direct discovery in three different scenarios. The main goal of this analysis is to provide recommended values for sidelink direct discovery in critical scenarios when the BS becomes non-functional.

First, the impact of the carrier frequency, transmitter (Tx), and receiver (Rx) gains on direct discovery have been investigated in the indoor NLoS scenario. After observing the performance of ProSe direct discovery in terms of discovery reliability, the maximum discovery range is examined in the three described scenarios.

Fig. 4: Direct discovery in an indoor-LOS scenario.

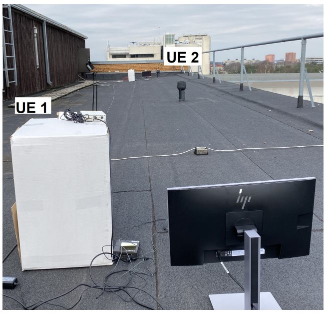

Fig. 5: UEs perform direct discovery in an outdoor scenario.

For the empirical results, the 700 MHz and 800 MHz bands have been examined as the spectrum within the 694-894 MHz has been allocated for PS communication in Europe, North America, and in many other countries [11]. A total number of 600 discovery messages are transmitted by two UEs to evaluate the performance of direct discovery. The first UE periodically transmits a discovery message each 500 ms and the second UE monitors it. After transmitting eight messages in one cycle, the second UE starts to transmit, and then the first UE monitors the discovery messages. Again after transmitting eight messages in the next cycle, the first UE starts to transmit without changing any parameter, and so on. Overall, 300 discovery messages are transmitted by each UE and eight discovery messages are transmitted in each cycle. To evaluate the performance of direct discovery in terms of reliability, we calculated the following three KPIs: average, maximum, and minimum discovery ratios.

The average discovery ratio, DR_{mean}, is defined as the total number of successful discovery messages received, $N_{received}$ by the monitoring UE over the total number of transmissions $N_{transmitted}$. (600 discovery messages are transmitted in total.) It is expressed as:

$$DR_{mean} = 100\frac{N_{received}}{N_{transmitted}} \tag{1}$$

The maximum discovery ratio, DR_{max}, shows the max-

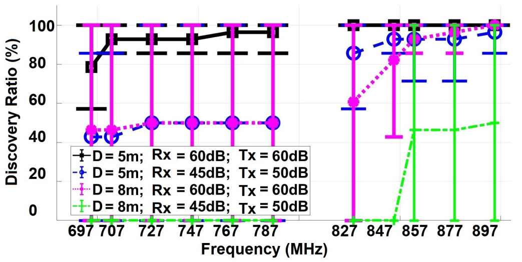

Fig. 6: Impact of the carrier frequency on the direct discovery in an indoor NLOS scenario.

imum of the total number of successful discovery messages received by the monitoring UE in any cycle, $N_{received\,per\,cycle}$. The total number of transmitted discovery messages in a cycle, $N_{transmitted\,per\,cycle}$, is set to eight discovery messages per cycle. It is expressed as:

$$DR_{max} = 100\frac{max(N_{received\,per\,cycle})}{N_{transmitted\,per\,cycle}} \tag{2}$$

The minimum discovery ratio, DR_{min}, shows the minimum number of successful discovery messages received by the monitoring UE in any cycle. It is expressed as:

$$DR_{min} = 100\frac{min(N_{received\,per\,cycle})}{N_{transmitted\,per\,cycle}} \tag{3}$$

The average discovery ratio is directly proportional to the reliability of direct discovery. A 100% discovery ratio signifies the best transmission conditions for direct discovery and the reliability of direct discovery decreases with a decreasing average discovery ratio. On the other hand, the minimum and maximum discovery ratios are indicated by the vertical short lines in the figures, which show the minimum and maximum value at each point. The higher this difference, the higher the randomness in the channel propagation, which generally means denser multipath and consequently less reliable connection. In the next subsections, we discuss the impact of frequency, amplification, distance, and number of UEs on the discovery ratio.

1) Discovery ratio as a function of the carrier frequency: Fig. 6 shows the impact of the carrier frequency on direct discovery in an indoor NLOS scenario. It can be noticed that as the carrier frequency increases, the discovery ratio improves as well; see for example when D = 8 m, Rx gain = 45dB and Rx gain = 50 dB, (shown as a magenta dotted line with '*' marker) in Fig. 6.

First, when the carrier frequency is 697 MHz, the average discovery ratio is 46%, and the maximum and minimum discovery ratios are 100% and 0%, respectively. The 46% average discovery ratio value indicates that 46 discovery messages are received by the monitoring UE out of 100 transmitted messages. The 100% maximum and 0% minimum discovery ratios indicate that a monitoring UE could receive all the transmissions or it could also miss all the transmissions from the announcing UE. This shows very poor settings for the direct discovery.

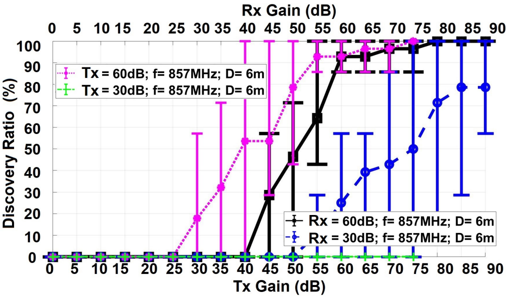

Fig. 7: The effect of Tx and Rx gains on the direct discovery in an indoor NLOS scenario

Next, the average discovery ratio increases when increasing the carrier frequency and it reaches 100%. A 897 MHz carrier frequency yields a 100% average discovery ratio and provides a very reliable and stable connection for direct discovery. It is also observed that the carrier frequencies set in the spectrum from 857 to 897 MHz provides reliable connectivity for direct discovery in all consider cases, even with low Rx and Tx gains.

Note that the selected frequencies were not being used for the other purposes as checked by a portable FSH4 spectrum analyzer, and the spectrum from 790 to 820 MHz has not been evaluated because it is occupied by mobile operators in Tallinn, Estonia.

2) Discovery ratio as a function of the Tx and Rx gains: As can be observed from Fig. 6, the Tx and Rx amplifier gains have an impact on the performance of direct discovery. In order to have a better understanding of this impact, Fig. 7 represents the effect of the Tx and Rx gains on the performance of direct discovery in the indoor scenario: here UEs are placed 6 m apart to announce discovery messages at 857 MHz. In fact, as can be seen in Fig. 6, carrier frequency from 857 MHz provides reliable connectivity for all the considered cases.

It can be observed that by increasing the Tx gain, the reliability of the direct discovery improves. When the Rx gain is set to 60 dB, shown as a black solid line with a square marker in Fig. 7, the average discovery ratio remains zero for Tx gains ranging from 0 to 40 dB. This shows that no discovery message is received by the monitoring UE. The average discovery ratio increases from 0 to 65% for Tx gains ranging from 40 to 55 dB. However, there is a large difference between the maximum and minimum discovery ratios that indicate poor connectivity. After that, the average discovery ratio increases very gradually from 93 to 100% for Tx gains ranging from 60 to 80 dB, and connectivity becomes stable and reliable for direct discovery. If instead of 60 dB, we set the Rx gain to 30 dB, even higher Tx gains do not provide a reliable discovery, as shown with a blue dotted line.

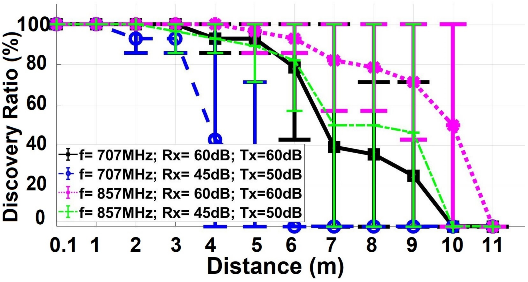

Fig. 8: The impact of distance between two UEs on the direct discovery in the indoor-NLOS scenario (labs).

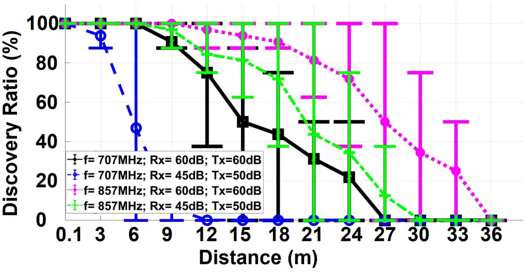

Fig. 9: The impact of the distance between two UEs on the direct discovery in the indoor-LOS scenario (corridor).

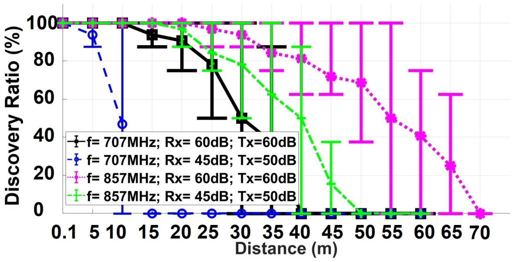

Fig. 10: The impact of the distance between two UEs on the direct discovery in the outdoor scenario (rooftop).

A similar behavior is observed when Tx has a fixed value. By increasing the Rx gain, the performance of direct discovery improves. For example, when the Tx gain is set to 60 dB, shown as a magenta dotted line with '*' marker in Fig. 7, the average discovery ratio is 93% when Rx gain is set to 55 dB. For Rx gain equal to or larger than 70 dB, the discovery ratio reaches 100% and provides a very stable and reliable direct discovery. Whereas, when the Tx gain is set to 30 dB, the discovery ratio remains 0% regardless of the Rx gain, shown as a green dashed line.

It can be seen from Fig. 6 and Fig. 7 that the reliable connectivity for direct discovery also depends on the distance between announcing and monitoring UEs along with carrier frequency, and Tx and Rx gains. It can be also observed that the average discovery ratio is more than 90% when $f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB, and the average discovery ratio is around 50% when $f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB in most of the considered cases. Therefore, we used these moderate gains and carrier frequencies and considered the following four cases to analyze maximum discovery range for direct discovery in three different scenarios: case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), case 2 ($f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB), case 3 ($f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB).

3) Discovery ratio as a function of a distance between two UEs in the indoor-NLOS: Fig. 8 shows the impact of the distance between announcing and monitoring UEs on the direct discovery in the indoor NLOS scenario. The case, referred to as Case 3, that provides the best connectivity and maximum distance for the direct discovery as compared to the other three cases, shown as a magenta dotted line with '*' marker in Fig 8. It can be seen that the average discovery ratio remains 100% when the distance is up to 4 m between two UEs. The discovery ratio decreases gradually to 84% with increasing distance up to 7 m regardless of the first concrete wall at 6 m.

It is also interesting to observe the behavior with Case 1 and Case 4 after the first concrete wall (i.e. after 6 m). The average discovery ratio decreases swiftly, and reaches 0% after the radio signal meets an obstacle (a heavy machine) at 10 m. Whereas the average discovery ratio decreases gradually regardless of the obstacles until 10 meters in Case 3, but it decreases swiftly after the second concrete wall and becomes zero at 11 m.

Finally, for Case 2 with low gains and carrier frequency, the average discovery ratio reaches 0% at 6 m, as shown with a blue dashed line in Fig. 8.

4) Discovery ratio as a function of a distance between two UEs in the indoor-LOS: Fig. 9 shows the impact of the distance between two UEs on the direct discovery in the indoor LOS scenario. Case 3, shown as a magenta dashed line in Fig. 9, provides the best connectivity and maximum range for direct discovery with the highest discovery ratio. It can be observed that the average discovery ratio remains 100% when the distance is up to 9 meters between two UEs. The discovery ratio decreases gradually and reaches 0% at 36 meters. A similar trend can be seen in Case 4 and Case 1, the average discovery ratio remains 100% until 6 m in both cases, and the maximum discovery range is 24 and 27 m respectively. On the other hand, in Case 2, the UEs could not discover each other after only 9 m with low gains and carrier frequency, as shown with blue dashed line in Fig. 9.

5) Discovery ratio as a function of the distance between two UEs in outdoor (LOS) scenario: Fig. 10 shows the

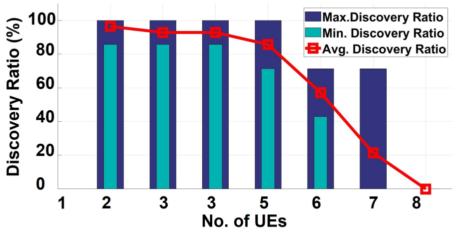

Fig. 11: Impact of increasing the number of UEs on direct discovery in the indoor-NLOS scenario.

measurements for the outdoor scenario. A similar behavior can be observed in Fig. 10 as compared to the indoor LOS (Fig. 9). Once again, Case 3 provides the highest discovery ratio, reliable connectivity, and maximum distance for direct discovery as compared to the other three cases. It can be observed that the average discovery ratio remains 100% when the distance is up to 20 m between two UEs, and it decreases gradually and reaches 0% when the distance is 70 m. However, the maximum discovery range is 35 and 45 m in Case 4 and Case 1, respectively. On the other hand, in Case 2, the UEs configured with low gains and frequency could not discover each other beyond 15 m.

6) Discovery ratio as a function of the number of UES: Finally, Fig. 11 shows the impact of the increase in the number of UEs in a group on the performance of direct discovery in the indoor-NLoS scenario, where D = 5 m, f = 857 MHz, Rx gain = 60 dB, Rx gain = 60 dB. It can be seen that the discovery ratio decreases gradually when increasing the number of UEs in the network. Our OAI-based direct discovery can support up to 5 UEs in a group with up to 90% discovery ratio. After adding the sixth UE in the group, the average discovery ratio decreases swiftly (down to 60%). It can be seen that a maximum of 7 UEs can be discovered in one group but with a low average discovery ratio of only 20%. As according to the 3GPP system, sidelink communication shall be able to support up to 5 UEs in a group, and NR sidelink communication shall be able to support up to 19 UEs in a group [14].

IV. CONCLUSION AND FUTURE WORK

To our best knowledge, this is the first empirical study in the open literature that presented experimental results in heterogeneous environments and suggested suitable gains and frequency which provide reliable direct discovery. Furthermore, the coverage analysis performed can help the first responders to deploy the unmanned aerial vehicles and/or command centre to cover the affected area for reliable communication. In the future, we aim to investigate other parameters such as mobility, air-to-ground and air-to-air channels, interference, and discovery time to fully characterize the ProSe direct discovery in emergency scenarios.

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Appendix 4

IV

Ali Masood, Muhammad Mahtab Alam, Yannick Le Moullec, Luca Reggiani, Davide Scazzoli, Maurizio Magarini, and Rizwan Ahmad. ProSe direct discovery: experimental characterization and context-aware heuristic approach to extend public safety networks lifetime. *IEEE Access*, 9:130055–130071, 2021

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ProSe Direct Discovery: Experimental Characterization and Context-Aware Heuristic Approach to Extend Public Safety Networks Lifetime

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ABSTRACT Device-to-device communication, as provided by the third generation partnership project standardization, can play a vital role in designing a reliable pervasive public safety network, which allows the user equipment (UEs) to communicate directly with each other in emergency situations. In this paper, we analyze the performance of direct discovery, one of the features introduced by proximity services. This is examined in heterogeneous environments using the OpenAirInterface open-source software and USRP hardware platform. The experimental results highlight the suitable values for different gains and frequencies of the UEs for performing reliable baseline direct discovery in out-of-coverage scenarios. We evaluate the performance of direct discovery in terms of reliability and maximum range in outdoor and indoor scenarios. Furthermore, we propose a context-aware energy-efficient heuristic algorithm for direct discovery with the aim of extending the network lifetime in emergency scenarios. This heuristic yields significant improvements in UE lifetime (20-52%) and reduces redundant transmissions of discovery messages compared to the baseline approach.

INDEX TERMS Device-to-device communication, public safety network, proximity services, direct discovery.

I. INTRODUCTION

Predictable emergency scenarios (e.g. floods, hurricanes) are typically less challenging than unpredictable emergency scenarios (e.g. earthquakes, terrorist attacks). In the former, the first responders can foresee and get enough time to prepare for estimated incidents and take proper actions to provide quick relief. In contrast, unpredictable emergency scenarios are unexpected incidents, and therefore, the first responders do not have enough time for disaster prevention. In such a situation the main goal is to provide rescue services as rapidly as possible and reduce the response time. A major challenge is that response time cannot be improved without having basic information about the affected area [1].

In unpredictable emergency scenarios, the availability of the cellular base stations (BS) cannot be guaranteed and is often unavailable due to disasters; thus, people are not able to communicate with the outside of the disaster zone. Consequently, the first responders remain unable to take immediate actions to provide relief, even after many hours, due to unclear information such as the number of affected people, their locations and identity, etc. Consequently, the response time may become very long [2], [3]. The main challenges in such emergency scenarios are (i) to establish connectivity in the

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absence of a BS and (ii) share important information with the first responders [1], and second to maintain the network connectivity alive for several hours.

Device-to-device (D2D) communication supports both commercial and public safety (PS) scenarios. The application of public safety is considered one of the most essential applications of D2D communication. In emergency scenarios, D2D can provide connectivity between remote user equipments (UEs) to allow their direct communication when the BSs are destroyed, non-functional, or unavailable due to disasters. The third generation partnership project (3GPP) proposed proximity services (ProSe), initially in Releases 12 and 13, to enable D2D communication (including public safety scenarios). A new interface, known as sidelink PC5, was introduced [4]. Later in Releases 14 and 15 additional enhancements were proposed, primarily for vehicle-to-everything (V2X) communication [5], while Release 16 proposed new radio sidelink enhancements such as increased physical resources, feedback channel, etc. A more detailed description of the evolution of D2D communication is provided in Section II.

For D2D communication using sidelink PC5 interface, mainly there are three steps, i.e., synchronization, direct discovery, and direct communication. In unpredictable emergency scenarios, the most critical information is about the number of users (e.g., trapped persons), their IDs, and locations. To conserve the energy of the devices and consequently to prolong the network connectivity, we propose to confine the three steps to only synchronization and discovery by accommodating the light-weighted application payload in the discovery message.

Aiming at such an optimization, in this paper we focus on ProSe-based direct discovery. In particular: i) we carry out an empirical measurement campaign to characterize ProSe direct discovery in different out-of-coverage scenarios, and ii) we propose a context-aware novel heuristic algorithm to improve the lifetime of UEs in the network to share critical information with the first responders in emergency scenarios to speed up the rescue process.

A. RELATED WORK

Existing studies mainly focus on D2D sidelink communication in in-coverage scenarios to reduce the network burden, improve the spectrum efficiency, and energy efficiency [6]–[10], as well as improve cellular coverage through multi-hop D2D communication [11], [12]. These studies propose different schemes for joint scheduling and resource allocation [6]–[8], interference-aware resource allocation [9], and distributed power control [10] for D2D sidelink communication.

However, there is only a relatively low number of studies on D2D sidelink discovery in the literature. Existing studies propose different schemes for D2D discovery, like location-based D2D discovery with the help of BS [13], [14], coordinated relay discovery approach [15], neighbor discovery scheme through demodulation reference signals (DMRS) based on a power normalized correlation process [16], [17], discovery retransmission scheme with different discovery periods to discover more devices in proximity, improve discovery accuracy and energy efficiency [18]. In [19], the authors present the evaluation of network-assisted D2D discovery, in terms of number of discovered devices, through a mathematical analysis using stochastic geometry model in indoor and outdoor environments. It is concluded that the discovery performance can be improved by reducing the in-band emission.

However, the above-mentioned schemes are not suitable for unpredictable emergency scenarios because the solutions proposed in [13]–[15] are only network-assisted. In contrast to the discovery protocol proposed by 3GPP, it is not followed by these schemes [16], [17], and the method suggested in [18] is not an energy-saving solution, contrary to what is desired in PS out-of-coverage scenarios.

In addition to the above research efforts, developments related to long-term evolution (LTE) sidelink for PS communications around the world include e.g. Device-to-Device System for Public Safety (DDPS) in the United States [20], Project 1B (Basic UE functionality) in France [21], Experimenting with Flexible D2D communications over LTE (FLEX-D) in Greece [22], and COmmUNication in conTExt Related to Terror Attacks (COUNTER-TERROR) in Estonia [23], [24]. More details and many other completed or ongoing projects related to PS communication can be found in [1]. However, most of the available information is about their use-cases and does not give full descriptions of their implementations. Furthermore, the performance evaluation of the direct discovery in heterogeneous out-of-coverage scenarios is still missing in the literature.

The operation of PS communication is typically in the sub-1 GHz band [25] and existing studies lack in understanding the D2D communication at such frequencies e.g., realistic communication ranges under various conditions, packet losses, and baseline network lifetime. This work addresses these gaps by analyzing experimentally the connectivity behavior and then proposing a new energy conservation strategy for UEs to enhance their lifetime and prolong network connectivity.

B. CONTRIBUTION

The main contributions presented in this paper are:

- Experimental measurements carried out to characterize the ProSe direct discovery using the open-source software OpenAirInterface (OAI) and software-defined radio-based hardware platforms (USRPs). New experimental results are obtained in order to evaluate the baseline performance in terms of various operating frequencies (between 697 and 897 MHz), reliability of successful discovery message reception, and maximum discovery range in three different scenarios: i) indoor line-of-sight (LoS), ii) indoor non line-of-sight (NLoS), and iii) outdoor (LoS).

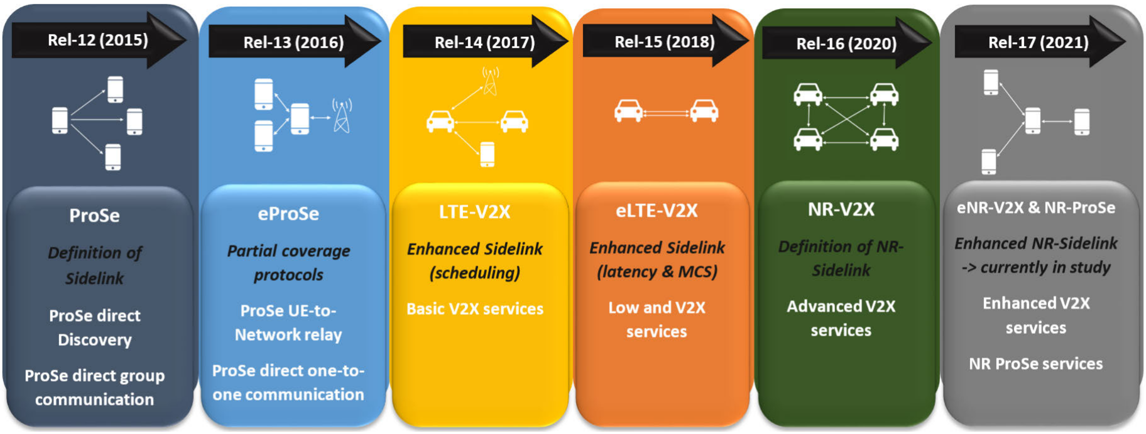

FIGURE 1. The evolution of D2D communication in 3GPP.

- In emergency scenarios, we suggest to include the coordinates of a UE in the discovery message, but periodic discovery messages, carrying redundant information (e.g., same location, ID, etc.), will lead to energy wastage. In order to improve the baseline lifetime and maintain reliable up-to-date information transfer via direct discovery, a new heuristic algorithm is proposed to avoid redundant transmissions of discovery messages by keeping track of the change of actual information (e.g. location) and context awareness. This algorithm significantly enhances (20-52%) the UEs' lifetime compared to the baseline direct discovery approach without compromising the transmission of critical information.

To the best of our knowledge, this is the first empirical study that presents experimental results concerning the performance of ProSe direct discovery as a function of the operating frequency, transmitter (Tx) and receiver (Rx) gains, the distance between transmitter and receiver in different out-of-coverage scenarios. In addition, our proposed heuristic approach improves the network lifetime and provides more up-to-date information in a heterogeneous emergency environment.

C. ORGANIZATION OF THE PAPER

The remainder of this paper is organized as follows. A detailed evolution of D2D communication is provided in Sect. II. In Sect. III, we discuss the methodology to characterize ProSe direct discovery: in Sect. III-A, we discuss our experimental setup to perform empirical measurements. Different indoor and outdoor scenarios are discussed in Sect. III-B to carry out the measurement campaign. The empirical measurement results are presented in Sect. III-C to analyze the performance of ProSe direct discovery in different scenarios. Next, in Sect. IV, we propose a context-aware energy-efficient approach for sidelink direct discovery in emergency scenarios. The description of the proposed approach is given in Sect. IV-A, and its performance evaluation is presented in Sect. IV-B. Concluding remarks are given in Sect. V.

II. PROXIMITY SERVICES AND EVOLUTION OF 3GPP RELEASES SUPPORTING D2D COMMUNICATION

In some contexts, pervasive public safety networks (PSN) can play a significant role to save lives and infrastructure. However, from the information and communication technology point of view, classical PSNs are not designed to deal effectively with first responders during emergency scenarios when BSs may not be available. Indeed, current communication systems like land mobile radio systems (LMRS) [26], M-Urgency, SafeCity [27], [28], and social media websites like Twitter and Facebook are facilitating [29] affected people to share information and live video streaming during disaster situations. However, a proper network infrastructure is required for them to operate.

In order to standardize PSN on cellular networks, the 3GPP standardization provides D2D communication that can be a key enable feature to design reliable PSNs. D2D communication allows UEs to communicate directly with each other using a new transmission link known as sidelink PC5 interface [4]. D2D communication can operate in three different scenarios: in-coverage, partial coverage, and out-of-coverage. In the in-coverage scenarios, UEs are inside the radio coverage of a BS and they are assisted by that BS to perform D2D communication. The BS assigns the resources and shares the synchronization signals with the UEs. Network-assisted D2D communication decreases the interference and improves the quality of service (QoS), but increases the burden on the BS. In a partial coverage scenario, an out-of-coverage or remote UE is assisted by another UE within the radio coverage of a BS to perform D2D communication. Finally, in an out-of-coverage scenario, UEs are outside the radio coverage of a

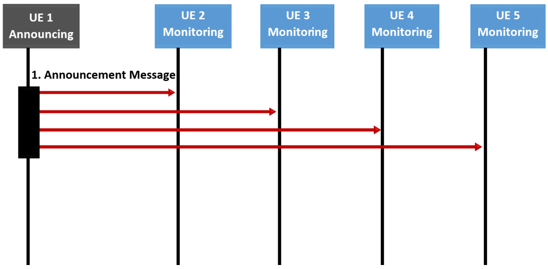

FIGURE 2. ProSe D2D direct discovery with Model A.

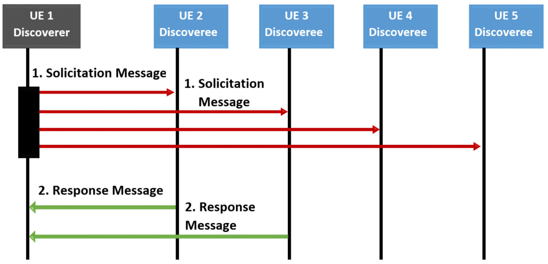

FIGURE 3. ProSe D2D direct discovery with Model B.

BS. Remote UEs use pre-configured parameters to perform D2D communication [30].

The evolution of D2D communication in 3GPP is shown in Fig. 1. In cellular networks, the concept of D2D communication was initially introduced in Release-12 of the 3GPP LTE standardization, referred to as ProSe [4]. Only ProSe-enabled UEs can support the ProSe functionalities. ProSe provides two main functions using the sidelink interface: ProSe discovery and direct communication. ProSe discovery is a process that identifies services and detects other UEs in their proximity. Direct communication allows a UE to transmit data to another UE located in proximity. Although Release 12 enabled out-of-coverage UEs to directly communicate with each other, it is required to access the BS if it is available. Release 13 enhanced ProSe services and introduced UE-to-network reply in the ProSe. This allows out-of-coverage UEs to access the BS using the sidelink interface with another in-coverage UE located in its proximity [31].

Starting from Release 14, the 3GPP platform further evolved for the automotive industry to support the basic road safety services, and such type of D2D communication is referred to as LTE-based V2X services. Vehicles based UEs share cooperative awareness messages (CAM) and decentralized environmental notification messages (DENM) to exchange their information (such as speed, position, and heading) with other neighboring vehicles, pedestrians, and roadside units (RSUs) using the downlink, uplink, and sidelink interfaces [32]. Release 15 further expanded the LTE V2X services and enhanced sidelink communication by including new features such as sidelink carrier aggregation (CA), transmission diversity, and 64 quadrature amplitude modulation (QAM) to improve throughput and latency [33], [34].

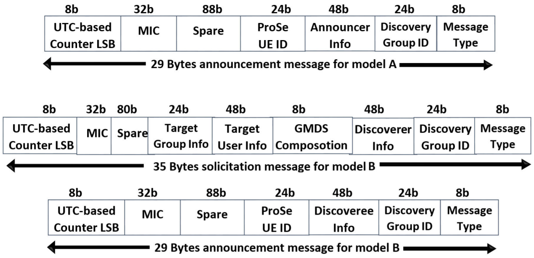

FIGURE 4. PC5 interface discovery messages for model A and model B.

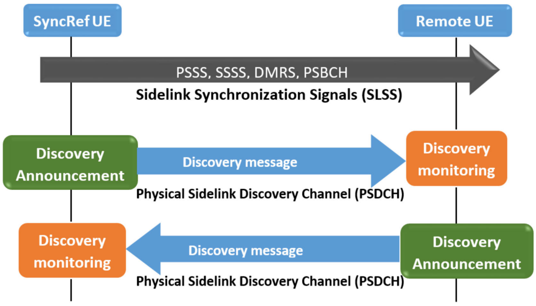

FIGURE 5. Overall procedure for the ProSE direct discovery.

In Releases 12-15, the D2D communications are based on the LTE network. Then Release 16 introduced the new radio (NR) sidelink to fulfill the requirements of the fifth-generation (5G) mobile network. Release 16 has defined the NR sidelink transmission and added new use cases for NR V2X services. The use cases are advanced driving, vehicle platooning, exchange of extended sensor information, and remote driving [35]–[37].

Release 17 is expected to provide several key features in V2X communication, e.g. coverage enhancements, power-saving and reliability improvements, and a new use case for ProSe services, i.e. UE-to-UE relay [38].

III. EXPERIMENTAL CHARACTERIZATION OF ProSe DIRECT DISCOVERY

ProSe supports two types of discovery mechanisms for public safety use: partially network-assisted discovery and direct discovery. We consider the decentralized case when the BS is not available and we focus on direct discovery. Direct discovery can identify and detect the other ProSe-enabled public safety UEs located in proximity. Two models are introduced for public safety direct discovery [31]: Model A (''I am here'') and Model B (''Who is there?''). Model A uses only a single protocol message for discovery, i.e. a ProSe-enabled public safety UE periodically transmits the discovery messages and the second ProSe-enabled public safety UE monitors the discovery messages, as shown in Fig. 2. On the other hand, Model B uses two protocol messages,

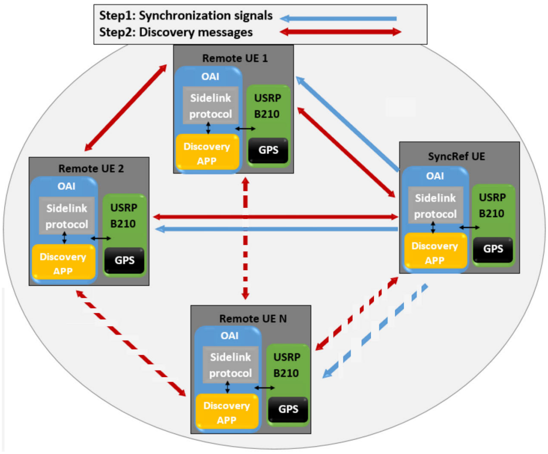

FIGURE 6. **Components and architecture for the ProSe direct discovery.**

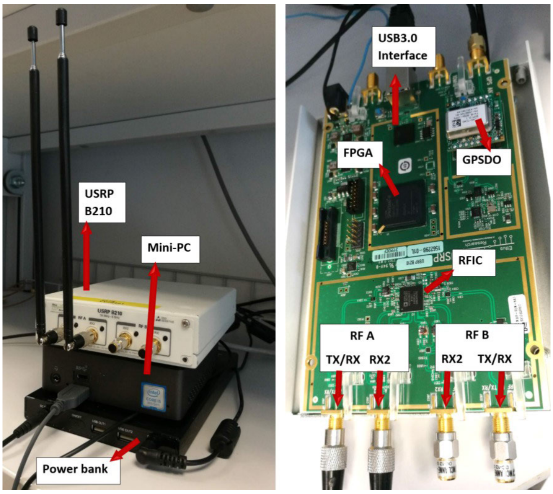

FIGURE 7. **Photos of a UE. Left (from top to bottom): USRP B210 radio front-end including GPSDO, Gigabyte Brix GB-BRi5-8250 mini-PC, Sandberg 420-23 power bank. Right: close-up of the USRP B210 board.**

i.e. A ProSe-enabled discoverer UE periodically transmits the solicitation messages and a discoveree UE sends back a response message to discoverer UE, as shown in Fig. 3. The discovery and response messages contain information such as message type, discovery group ID, announcer info, monitoring UE info, ProSe UE ID, etc., as shown in Fig. 4. More details about discovery and response messages can be found in [39]. In this study, we consider direct discovery with model A for the measurements in order to evaluate the performance of direct discovery in heterogeneous environments. Further, we examine both Model A and Model B when adding the coordinates of a UE in the discovery message as part of our suggested approach for improving the network lifetime of a UE, which will help first responders to locate and trace the affected UE in emergency scenarios.

A. EXPERIMENTAL SETUP

The OAI open-source software and USRP hardware platform are used to perform the experiments and collect empirical data. In brief, the OAI Software Alliance (OSA) is a non-profit association that encourages the research and industrial contributors for open source software and hardware development for the core network (EPC), access network, and UEs of 3GPP cellular networks. The OSA is an initial work of Eurecom that creates OAI towards the development of 5G cellular stack on commercial-off-the-shelf (COTS) hardware.

Our OAI/USRP based testbed consists of the following equipment.

Each UE is composed of:

- USRP B210 board used as the radio front-end hardware part of a UE. The main components of the USRP B210 are a Xilinx Spartan 6 XC6SLX150 FPGA, Analog Devices AD9361 RFIC direct-conversion transceiver, Cypress Semiconductor CYUSB3014 USB 3.0 interface, four connectors for the antennas (Rx and Tx, two channels each). The radio frequency (RF) part is based on the AD9361 chip, whose maximum output power is 8 dBm. After the AD9361, there is a PGA-102+ output amplifier (15.9 dB gain at 800 MHz), which makes that the maximum Tx power of the USRP B210 board can be up to 24 dBm. The available Tx gain and Rx gain are 89.8 dB and 76 dB, respectively and the maximum noise figure of the receiver is 8 dB max [40].
- Board Mounted GPSDO (TCXO) module that provides a high-accuracy 10 MHz reference. All UEs in the network use the same reference clock for synchronization.
- Two telescopic antennas to transmit and receive the signals (one-channel configuration on RF A).
- Mini PC used to run the software part of OAI. It runs the Linux Ubuntu operating system and the OAI protocol stack of 3GPP standard (Starting at LTE (Rel 8), including features from LTE-Advanced (Rel 10/11/12), LTE-Advanced-Pro (Rel 13/14), going on to 5G Rel (15/16)). Each mini PC is linked with one USRP to configure it as one OAI-based UE. The implemented D2D application for the direct discovery, based on sidelink protocol, runs on top of the 3GPP protocol stack.

For convenience, each UE (composed of the above elements) can be powered by a Sandberg 420-23 20000 mAh/74Wh power bank. A diagram of the architecture and components (except power bank) of the OAI-based UE are shown in Fig. 6; corresponding hardware photos are shown in Fig. 7.

The main steps for the D2D discovery are summarized in what follows. Before announcing the discovery message, the first step is to synchronize the UEs in order to acquire the necessary timing and frequency information for performing the successive steps, including message transmis-

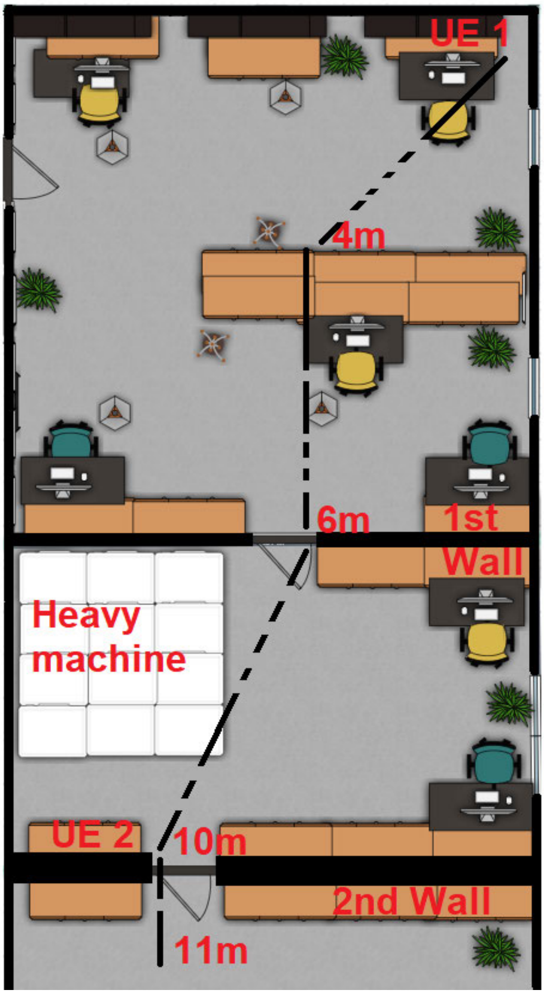

FIGURE 8. UEs perform direct discovery in an indoor NLoS transmission path (laboratories).

FIGURE 9. UEs perform ProSe direct discovery in an indoor LoS transmission path (corridor).

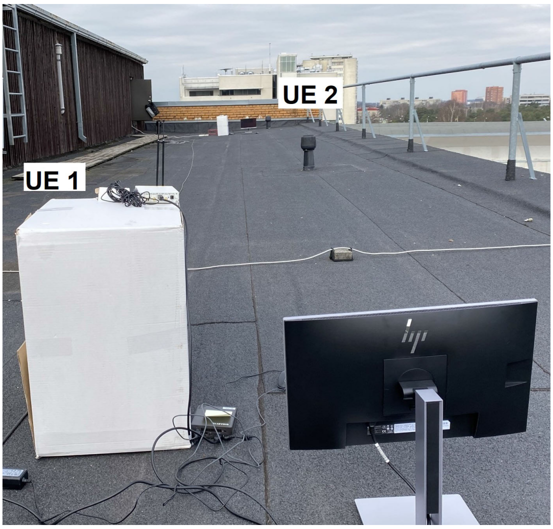

FIGURE 10. UEs perform direct discovery in an outdoor LoS transmission path (rooftop).

sion or reception. A synchronization reference (SyncRef) UE transmits the sidelink synchronization signals (SLSS) periodically each 40 ms. This synchronization process is performed by using the SLSS signals: the primary sidelink synchronization signal (PSSS), the secondary sidelink synchronization signal (SSSS), the DMRS signals, and the physical sidelink broadcast channel (PSBCH).

After synchronization, the UE starts to announce the discovery message periodically and the other UE(s) will monitor the discovery message to discover the announcing UE on the physical sidelink discovery channel (PSDCH) [39], as depicted in Fig. 5.

On the software side, an initial OAI prototype for LTE Sidelink publicly available from Eurecom[1] has been used as a starting point. The initial setup was limited to two UEs in the network, transmitting one random discovery message. The UEs were connected with one OctoClock (CDA-2990) through SMA cables for synchronization. In our work, we expanded the setup to up to eight UEs in the network and installed a GPSDO (TCXO) module for synchronization on each UE in order to remove the OctoClock and be able to move the UEs easily. Other details about the initial setup are discussed in Section IV.

B. MEASUREMENT CAMPAIGN

In this work, all the experiments were performed at Tallinn University of Technology after obtaining the required permission (RF test license) for the measurement campaign. Up to eight OAI-based UEs are used in this measurement campaign.

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[1] https://gitlab.eurecom.fr/oai/openairinterface5g/-/tree/LTE-sidelink/

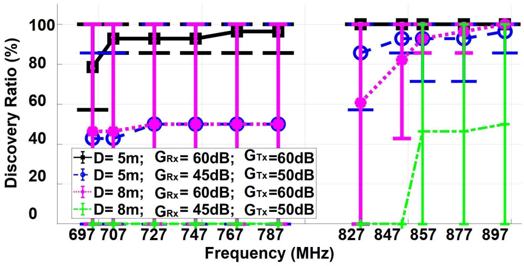


FIGURE 11. **Impact on the direct discovery due to frequency in an indoor NLoS scenario.**

The UEs are deployed in outdoor and indoor scenarios to analyze the performance of the direct discovery.

1) Indoor (NLoS): in the indoor non-line-of-sight (NLoS) scenario, UEs have not a direct transmission path. Experiments are carried out up-to three different labs where UEs have different obstacles between them, shown in Fig. 8.
2) Indoor (LoS): in the indoor LoS, UEs have a direct transmission path between them without any obstacle. Experiments are performed in a long and straight corridor of the university building, as shown in Fig. 9.
3) Outdoor (LoS): outdoor LoS experiments are carried out on the rooftop of the university building where UEs have a direct transmission path between them, as shown in Fig. 10.

C. EMPIRICAL MEASUREMENT RESULTS

This section presents the empirical measurement results to examine the direct discovery in the three different scenarios. The main goal of this analysis is to provide recommended values for sidelink direct discovery in critical scenarios when the BS becomes non-functional.

First, the impact of the carrier frequency and of the Tx and Rx gains on direct discovery have been investigated in the indoor NLoS scenario. After observing the performance of ProSe direct discovery in terms of discovery reliability, the maximum discovery range is examined in the three described scenarios.

For the empirical results, the 700 MHz and 800 MHz bands have been examined as the spectrum within the 694-894 MHz allocated for PS communication in Europe, North America, and in many other countries [25]. A total number of 600 discovery messages are transmitted by two UEs to evaluate the performance of direct discovery as a reference. The first UE periodically transmits a discovery message each 500 ms and the second UE monitors it. After transmitting eight messages in one cycle, the second UE starts transmitting, and then the first UE monitors the discovery messages. Again after transmitting eight messages in the next cycle, the first UE starts transmitting without changing any parameter, and so on. Overall, 300 discovery messages are transmitted by each UE and eight discovery messages are transmitted in each cycle as a reference. To evaluate the performance of direct discovery in terms of reliability, we calculated the following three key performance indicators (KPIs): average discovery ratio, maximum discovery ratio, and minimum discovery ratio.

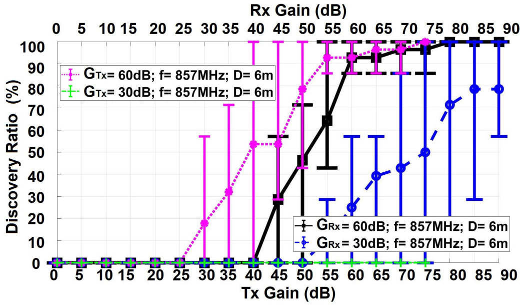


FIGURE 12. **The impact of Tx and Rx gains on the direct discovery in an indoor NLoS scenario.**

The average discovery ratio, DR_{-mean}, is defined as the total number of successful discovery messages received, $N_{-received}$, by the monitoring UE over the total number of transmissions $N_{-transmitted}$. (600 discovery messages are transmitted in total.) It is expressed as:

$$DR_{-mean} = 100\frac{N_{-received}}{N_{-transmitted}} \tag{1}$$

The maximum discovery ratio, DR_{-max}, shows the maximum of the total number of successful discovery messages received by the monitoring UE in any cycle, $N_{-received\ per\ cycle}$. The total number of transmitted discovery messages in a cycle, $N_{-transmitted\ per\ cycle}$, is set to eight discovery messages per cycle. It is expressed as:

$$DR_{-max} = 100\frac{max(N_{-received\ per\ cycle})}{N_{-transmitted\ per\ cycle}} \tag{2}$$

The minimum discovery ratio, DR_{-min}, shows the minimum number of successful discovery messages received by the monitoring UE in any cycle. It is expressed as:

$$DR_{-min} = 100\frac{min(N_{-received\ per\ cycle})}{N_{-transmitted\ per\ cycle}} \tag{3}$$

The average discovery ratio is directly proportional to the reliability of the direct discovery. A 100% discovery ratio signifies the best transmission conditions for direct discovery; the reliability of direct discovery decreases with a decreasing average discovery ratio. On the other hand, the minimum and maximum discovery ratios are indicated by the vertical short lines in the figures, which show the minimum and maximum value at each point. The higher difference between the minimum and maximum values mean denser multi-path and consequently less reliable connection. In the next subsections, we discuss the impact of frequency, amplification, distance, and number of UEs on the discovery ratio.

TABLE 1. The effect of Tx gains on the output power and SNR values of transmitted signals.

	SLSS		PSDCH	
Tx Gain (dB)	Output power (dBm)	SNR (dB)	Output power (dBm)	SNR (dB)
89,75	-42,4	23	-42,6	22
84,75	-47,3	23	-47	22
79,75	-51,9	23	-51	21,7
74,75	-58,1	22,5	-60,7	21,7
69,75	-62,4	21,5	-61,6	20,8
64,75	-68	21	-69,2	20,8
59,75	-72,4	20,4	-71,4	19,6
54,75	-79,8	12,5	-78,3	10,6
49,75	-83,7	8,2	-83,9	9,8
44,75	-86,7	4,4	-88,1	5,6
39,75	-89,8	1,1	-91,5	2,2
34,75	-92	0,5	-92,4	1,7
29,75	-92	0,5	-92,4	1,7
24,75	-92,6	0,2	-95,2	0,3
19,75	-92,6	0,2	-95,2	0,3
14,75	-92,6	0,2	-95,2	0,3
9,75	-92,6	0,2	-95,2	0,3
4,75	-92,6	0,2	-95,2	0,3
0	-92,6	0,2	-95,2	0,3

1) IMPACT ON THE DIRECT DISCOVERY DUE TO THE CARRIER FREQUENCY

Figure 11 shows the impact of the carrier frequency on direct discovery in an indoor NLoS scenario. It can be noticed that as the carrier frequency increases, the discovery ratio improves as well (see, for example, the curve associated with D = 8 m, Rx gain = 45 dB and Tx gain = 50 dB, shown as a magenta dotted line with '*' marker, in Fig. 11.

For the carrier frequency of 697 MHz, the average discovery ratio is 46%, and the maximum and minimum discovery ratios are 100% and 0%, respectively. The 46% average discovery ratio value indicates that 46 discovery messages are received by the monitoring UE out of 100 transmitted messages. The 100% maximum and 0% minimum discovery ratios indicate that a monitoring UE could receive all the transmissions or it could also miss all the transmissions from the announcing UE. This shows very poor settings for the direct discovery.

Next, the average discovery ratio increases by increasing the carrier frequency and it reaches 100%. The carrier frequency of 897 MHz yields a 100% average discovery ratio and provides a very reliable and stable connection for direct discovery. It is also observed that carrier frequencies set in the spectrum from 857 to 897 MHz provide reliable connectivity for direct discovery in all the considered cases, even with low Rx and Tx gains.

These results can be explained looking at the specific characteristics of the selected NLoS propagation environment; nevertheless, the most interesting aspect revealed by the experimentation is that carrier frequency can have a remarkable impact on discovery performance even in the most favorable range of frequency carriers for mobile systems, i.e. below 1 GHz.

Note that the selected frequencies were not being used for the other purposes as also checked by a portable FSH4 spectrum analyzer. Furthermore, the spectrum from 790 to 820 MHz has not been evaluated because it is occupied by mobile operators in Tallinn, Estonia.

2) IMPACT ON THE DIRECT DISCOVERY DUE TO THE TX AND RX AMPLIFIER GAINS

As can be observed from Fig. 11, the Tx and Rx amplifier gains have an impact on the performance of direct discovery. In order to have a better understanding of this impact, Fig. 12 represents the effect of the Tx and Rx gains on the performance of direct discovery in the indoor scenario: here UEs are placed 6 m apart to announce discovery messages at 857 MHz. In fact, as can be seen in Fig. 11, carrier frequency from 857 MHz provides reliable connectivity for all the considered cases.

It can be observed that by increasing the Tx gain, the reliability of the direct discovery improves. When the Rx gain is set to 60 dB, shown as a black solid line with a square marker in Fig. 12, the average discovery ratio remains zero for Tx gains ranging from 0 to 40 dB. This shows that no discovery message is received by the monitoring UE. The average discovery ratio increases from 0 to 65% for Tx gains ranging from 40 to 55 dB. However, there is a large difference between the maximum and minimum discovery ratios that indicate poor connectivity. After that, the average discovery ratio increases very gradually from 93 to 100% for Tx gains ranging from 60 to 80 dB, and connectivity becomes stable and reliable for direct discovery. If instead of 60 dB, we set the Rx gain to 30 dB, even higher Tx gains do not provide a reliable discovery, as shown with a blue dotted line.

The effects of Tx Gains on ProSe discovery can be better understood from Table 1 (measured by means of a portable FSH4 spectrum analyzer, see Appendix and Fig. 27). As it is explained in Sect. III, the UEs have to synchronize using SLSS signals before transmitting the discovery messages. Otherwise, UEs will not able to discover each other. Therefore, output transmitted power and signal-to-noise ratio (SNR) values of both SLSS signals and PSDCH channel against Tx gains are presented in the table. An FSH4 spectrum analyzer is used to measure the output power and SNR values. It can be seen from the table that the output power of both SLSS and PSDCH remains approximately -92 dBm for Tx gains ranging from 0 to 34.75 dB. After that, the output power increases gradually from $-89{,}8$ to -42 dBm for Tx gains ranging from 39.75 to 89.75 dB.

On the other side, the SNR value remains less than 10 dB for the TX gains of less than 50 dB for both SLSS and

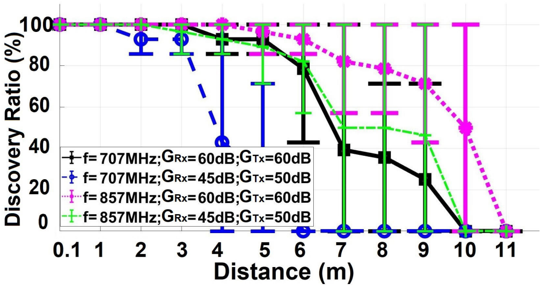


FIGURE 13. The impact on the direct discovery due to the distance between two UEs in the indoor-NLoS scenario (labs).

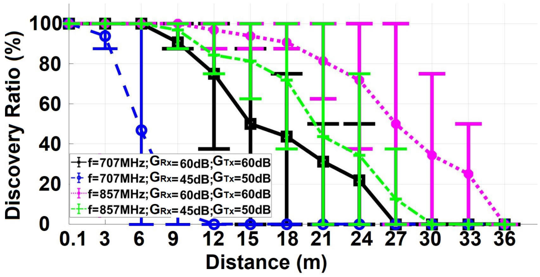


FIGURE 14. The impact on the direct discovery due to the distance between two UEs in the indoor-LoS scenario (corridor).

PSDCH. Such low SNR values give very poor discovery ratios, as shown in Fig. 12, 46% average discovery ratio with 60 dB Rx gain and 0% with 30 dB Rx gain. The SNR improves significantly around 10 dB to 20 dB for Tx gains ranging from 49.75 to 59.75 dB. The discovery ratio also improves to 93% with 20 dB SNR. Then SNR improves gradually up to 23 with maximum Tx gain and the direct discovery becomes very reliable with a 100% discovery ratio. A similar behavior is observed when Tx has a fixed value. By increasing the Rx gain, the performance of direct discovery improves. For example, when the Tx gain is set to 60 dB, shown as a magenta dotted line with '*' marker in Fig. 12, the average discovery ratio is 93% when Rx gain is set to 55 dB. For Rx gain equal to or larger than 70 dB, the discovery ratio reaches 100% and provides a very stable and reliable direct discovery. Whereas, when the Tx gain is set to 30 dB, the discovery ratio remains 0% regardless of the Rx gain, shown as green dashed line.

It can be seen from Fig. 11 and Fig. 12 that the reliable connectivity for direct discovery also depends on the distance between announcing and monitoring UEs along with carrier frequency, and Tx and Rx gains. It can be also observed that the average discovery ratio is more than 90% when $f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB, and the average discovery ratio is around 50% when $f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB in most of the considered cases. Therefore, we used these moderate gains and carrier frequencies and we considered the following four cases to analyze maximum discovery range for direct discovery in three different scenarios: case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), case 2 ($f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB), case 3 ($f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB).

3) DISCOVERY RATIO AS A FUNCTION OF A DISTANCE BETWEEN TWO UEs IN THE INDOOR-NLoS

Figure 13 shows the impact of the distance between announcing and monitoring UEs on the direct discovery in the indoor NLoS scenario. The case, referred to as case 3, that provides the best connectivity and maximum distance for the direct discovery as compared to the other three cases is with both Rx and Tx gains set to 60 dB and the carrier frequency set to 857 MHz ($f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), shown as a magenta dotted line with '*' marker in Fig 13. It can be seen that the average discovery ratio remains 100% when the distance is up to 4 m between two UEs. The discovery ratio decreases gradually to 84% with increasing distance up to 7 m regardless of the first concrete wall at 6 m (Fig 8).

It is also interesting to observe the behavior with the case 1 ($f = 707$ MHz, Rx gain = Tx gain = 60 dB) and case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB) after the first concrete wall (i.e. after 6 m). The average discovery ratio decreases swiftly, and reaches 0% after the radio signal meets an obstacle (a heavy machine) at 10 meters. Whereas the average discovery ratio decreases gradually regardless of the obstacles until 10 meters in case 3, but it decreases swiftly after the second concrete wall and becomes zero at 11 meters.

Finally, for case 2 with low gains and carrier frequency ($f = 707$ MHz, Rx gain = 45 dB, Tx gain = 50 dB), the average discovery ratio reaches 0% at 6 meters, as shown with the blue dashed line in the Fig. 13.

4) DISCOVERY RATIO AS A FUNCTION OF A DISTANCE BETWEEN TWO UEs IN THE INDOOR-LoS

Figure 14 shows the impact of the distance between two UEs on the direct discovery in the indoor LoS scenario. Case 3 ($f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB) shown as a magenta dashed line in Fig. 14 provides the best connectivity and maximum range for direct discovery with the highest discovery ratio. It can be observed that the average discovery ratio remains 100% when the distance is up to 9 meters between two UEs. The discovery ratio decreases gradually and reaches 0% at 36 meters. A similar trend can be seen in case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB) and case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB), where the average discovery ratio remains 100% until 6 meters in both cases, and the maximum discovery range is 24 and 27 meters respectively. On the other hand, in Case 2, the UEs could not discover each other after only 9 m with low gains and carrier frequency ($f = 707$ MHz, Rx gain = 45 dB,

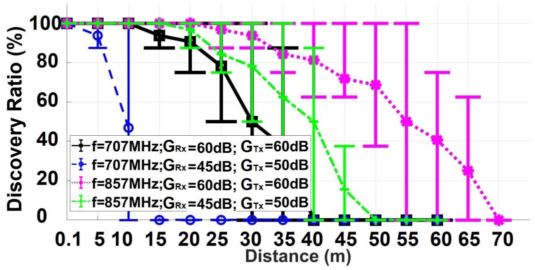


FIGURE 15. The impact on the direct discovery due to the distance between two UEs in the outdoor scenario (rooftop).

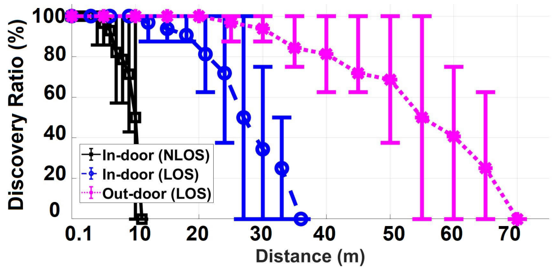


FIGURE 16. The impact on the direct discovery due to the distance between two UEs in all three scenarios where $f = 857$ MHz, Rx gain = 60 dB, Tx gain = 60 dB.

Tx gain = 50 dB), as shown with the blue dashed line in the Fig. 14.

5) DISCOVERY RATIO AS A FUNCTION OF A DISTANCE BETWEEN TWO UEs IN THE OUTDOOR (LoS)

Figure 15 shows the measurements for the outdoor scenario. A similar behavior can be observed in Fig. 15 as compared to the indoor LoS (Fig. 14). Once again, Case 3 ($f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB) provides the highest discovery ratio, reliable connectivity, and maximum distance for direct discovery as compared to the other three cases. It can be observed that the average discovery ratio remains 100% when the distance is up to 20 meters between two UEs, and it decreases gradually and reaches 0% when the distance is 70 meters. However, the maximum discovery ranges are 35 and 45 meters in case 4 ($f = 857$ MHz, Rx gain = 45 dB, Tx gain = 50 dB) and case 1 ($f = 707$ MHz, Rx gain = 60 dB, Tx gain = 60 dB) respectively. On the other hand, in Case 2 ($f = 707$ MHz, Rx gain = 45 dB, Rx gain = 50 dB), the UEs configured with low gains and frequency could not discover each other after 15 meters.

6) THE IMPACT ON THE DIRECT DISCOVERY IN ALL THREE SCENARIOS

It can be confirmed that case 3 with maximum amplification and frequency ($f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB) provides the best connectivity and maximum range for a reliable direct discovery as compared to the other three cases. The impact on the direct discovery due to the distance between two UEs in all three scenarios is shown in Fig. 16.

It is important to appreciate the performance gap between the three significant propagation scenarios, which can be measured numerically by the different slopes of the curves as a function of the distance.

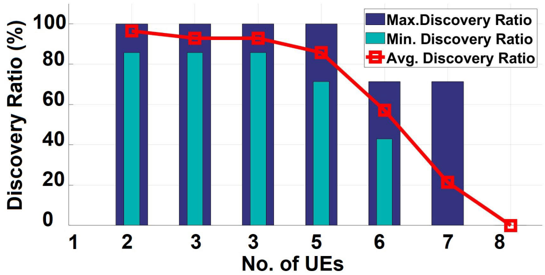


FIGURE 17. The Impact on direct discovery due to Increase in number of UEs in the indoor-NLoS scenario where D = 5 m, $f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB.

7) DISCOVERY RATIO AS A FUNCTION OF THE NUMBER OF UEs

Finally, Fig. 17 shows the impact on the number of UEs in a group on the performance of direct discovery in the indoor-NLoS scenario, where D = 5 m, $f = 857$ MHz, Rx gain = 60 dB, Rx gain = 60 dB. It can be seen that the discovery ratio decreases gradually when increasing the number of UEs in the network. Our OAI-based direct discovery can support up to 5 UEs in a group with up to 90% discovery ratio. After adding the sixth UE in the group, the average discovery ratio decreases swiftly (down to 60%). It can be seen that a maximum of 7 UEs can be discovered in one group but with a low average discovery ratio of only 20%. According to the 3GPP system, sidelink communication shall be able to support up to 5 UEs in a group, and NR sidelink communication shall be able to support up to 19 UEs in a group [41].

In this section, the performance of direct discovery has been evaluated in terms of discovery reliability and maximum range of discovery in three different environments. In the next section, we propose an algorithm for direct discovery to improve the lifetime of UEs and of the network in critical situations.

IV. CONTEXT-AWARE ENERGY-EFFICIENT PROPOSED HEURISTIC APPROACH FOR SIDELINK DIRECT DISCOVERY IN EMERGENCY SCENARIOS

In a decentralized case when the BS is not available, a ProSe-enabled UE transmits the discovery messages with a fixed period. Periodicity could be up to 10 seconds [42]. A UE keeps transmitting discovery messages although it has already been discovered by the neighboring UEs, first responder, or UE does not have new information to transmit. For instance, when a discovery message has been received

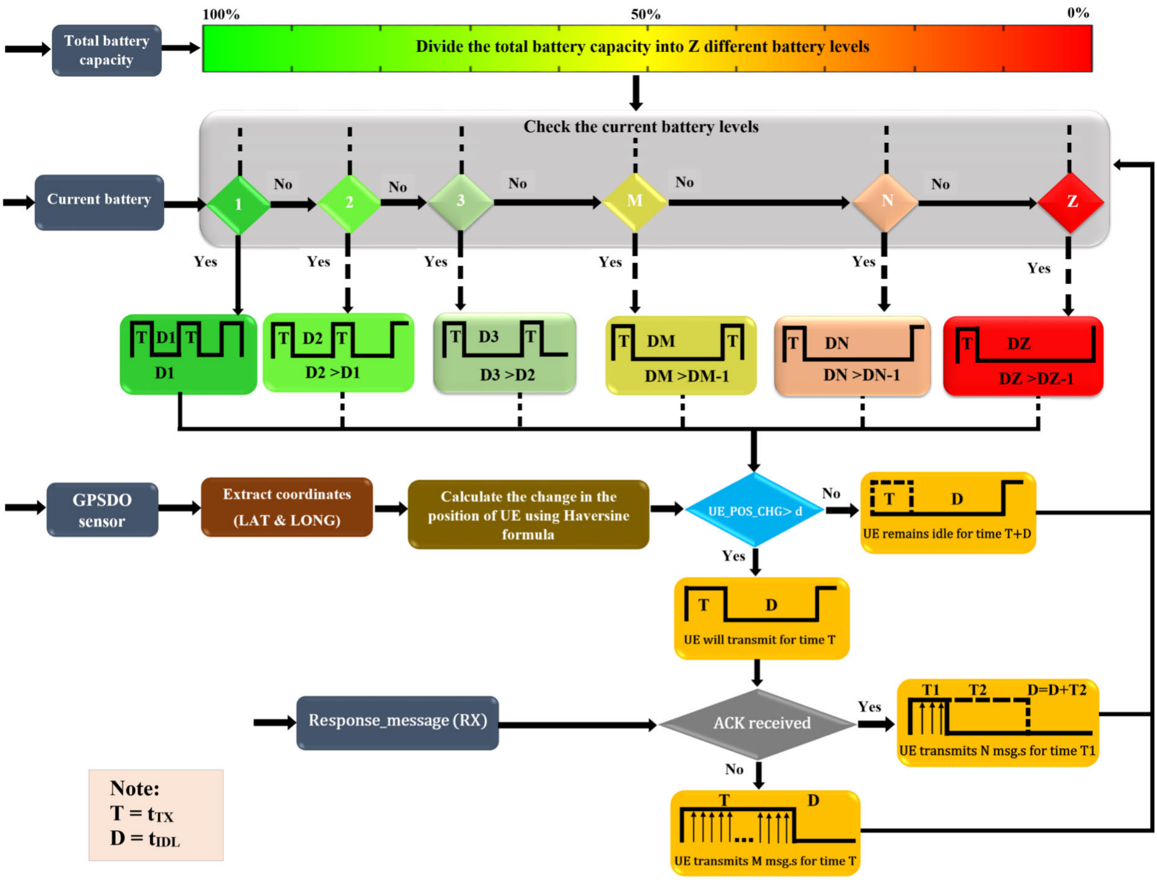


FIGURE 18. **Steps involved in the proposed approach.**

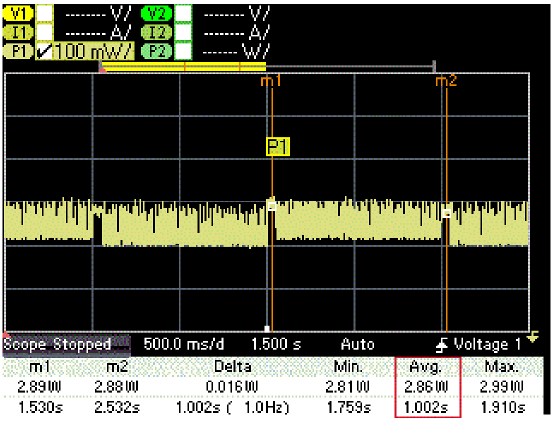
by the first responder and the UE is not changing its position then there is no need to re-transmit the discovery message. However, if a UE transmits redundantly it will consume more energy, and eventually, it will die out swiftly in the network. As a dead node, a UE could increase the delay to obtain the rescue services. In a critical situation, it is very important to stop redundant transmissions of discovery messages in order to keep the UE alive in the network for a longer time and increase the probability to get relief from the first responders.

A. DESCRIPTION OF THE PROPOSED APPROACH

In this paper, we propose a self-aware D2D discovery approach based on the current position and battery level of a UE in emergency scenarios (Algorithm 1). The suggested approach aims to improve significantly the lifetime of UEs by decreasing their number of redundant discovery messages transmissions. Our proposed approach has two main phases. The first phase defines the periodicity for discovery transmissions; there are two stages in each periodicity: transmission stage and idle stage. In the transmission stage, a UE can transmit N (up to eight) discovery messages in a time t_{TX}, and in the idle stage, a UE remains idle for a time t_{IDL}. The second phase determines either to transmit the optimal number of discovery messages in the transmission stage, or to remain idle for time t_{TX}. The steps involved in the proposed approach are shown in Fig. 18.

1) FIRST PHASE OF THE PROPOSED APPROACH

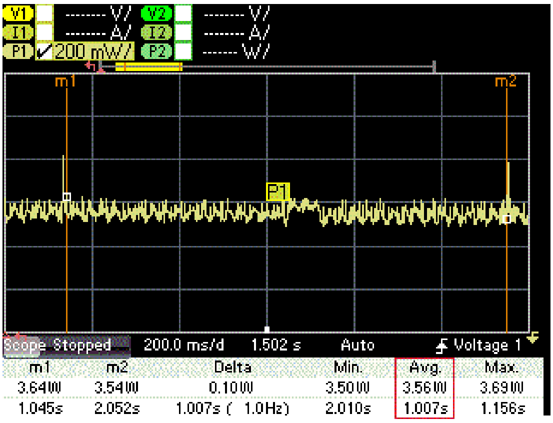
The first phase defines the periodicity for discovery transmissions according to the current battery level of a UE. Therefore, we consider battery capacity of a UE in our application for simulation purposes. Modern smartphones have 15.04 Wh battery capacity (i.e. 3957.9 mAh at 3.8 V) on average [43]. As a reference, we consider one half of this capacity, i.e. 7.52 Wh or 27072 Ws, as the total battery capacity of a single UE in our application. Further, we divide the battery capacity into seven levels, denoted from one to seven, to indicate the status of the battery. The one to seven battery levels indicate



Scope Stopped 500.0 ms/d 1.500 s Auto Voltage 1

m1	m2	Delta	Min.	Avg.	Max.
2.89W	2.88W	0.016W	2.81W	2.86W	2.99W
1.530s	2.532s	1.002s (1.0Hz)	1.759s	1.002s	1.910s

FIGURE 19. **Baseline power consumption of a ProSE UE implemented with OAI/USRP.**



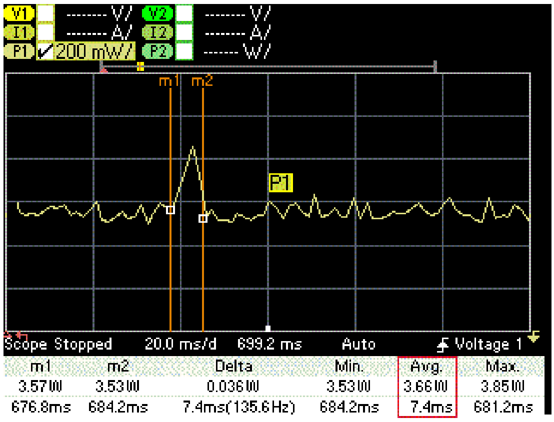
Scope Stopped 200.0 ms/d 1.502 s Auto Voltage 1

m1	m2	Delta	Min.	Avg.	Max.
3.64W	3.54W	0.10W	3.50W	3.56W	3.69W
1.045s	2.052s	1.007s (1.0Hz)	2.010s	1.007s	1.156s

FIGURE 20. **Power consumption in the idle stage of a ProSE UE implemented with OAI/USRP.**

when the remaining battery is between 100-97%, 96-88%, 87-75%, 74-50%, 49-25 24-10%, and 9-0%, respectively. Each battery level has a different but fixed periodicity to transmit the discovery messages. In this work, time t_{TX} for the transmission stage remains fixed for all battery levels (1 s). Time t_{IDL} for the idle stage increases with decreasing battery values over time, as shown in Fig. 18. We assign different periods for the idle stage i.e. $t_{IDL} = 2$ s, 3 s, 9 s, 29 s, 59 s, and 299 s for battery levels one to six, respectively. In the last battery level (less than 10%), a UE will remain idle and can transmit up to eight messages before dying.

This heuristic approach saves a substantial amount of energy consumption by reducing the redundant transmissions of discovery messages. A UE in a decentralized case consumes energy in both idle and transmission stages. In this work, we also provide energy consumption values of a UE in both stages using the keysight N6705C power analyzer. Our main objective was to measure the energy consumption by a UE in the transmission and idle stages. Therefore, the power consumed by the USRP board and Mini PCs is considered as the baseline power (2.86 W), as shown in Fig. 19. A UE consumes 0.7 W (3.56 − 2.86) for one second in the idle stage as shown in Fig. 20. A discovery transmission consumes an additional 0.1 W (3.66 – 3.56), as shown in Fig. 21. A UE consumes 0.8 W if it transmits a single discovery message in one second. The energy comparison is shown in Fig. 22 when a UE transmits up to eight discovery messages or remains idle for one second.



Scope Stopped 20.0 ms/d 699.2 ms Auto Voltage 1

m1	m2	Delta	Min.	Avg.	Max.
3.57W	3.53W	0.036W	3.53W	3.66W	3.85W
676.8ms	684.2ms	7.4ms(135.6Hz)	684.2ms	7.4ms	681.2ms

FIGURE 21. **Power consumption of a discovery messages in the transmission stage of a ProSe UE implemented with OAI/USRP.**

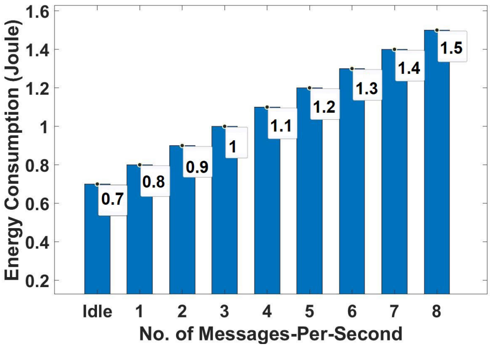


FIGURE 22. **Energy consumption comparison of a UE when it transmits N number of discovery messages or it remains idle.**

2) SECOND PHASE OF THE PROPOSED APPROACH

The second phase has two further steps to determine the optimal number of discovery messages for the transmission stage. In the first step, a UE will take a decision based on its mobility, i.e. either it will transmit for time t_{TX} or remain idle. Once an announcing or affected UE in emergency situations is already discovered by the first responders and this UE does not change its position, there is no need to keep transmitting the discovery messages because the first responder already

Algorithm 1: Proposed Heuristic Algorithm

```
Input: Tot_battery_cap, Curr_battery_cap,
UE_coordinates, response_message (Rx)
Output: Transmit a discovery message (TX)
Divide the Tot_battery_cap into Z different battery levels
while ($Curr\_battery\_cap \neq 0$) do
    Check the Curr_battery_level
    i = {1,2,3,...,Z} $\leftarrow$ $dependsonCurr\_battery\_level$
    for ($i; i \leqslant Z; ++i$) do
        Calculate a distance coved by a UE using
          Haversine formula:
        a = $\sin^2(\frac{\phi_2-\phi_1}{2}) + \cos(\phi_1)\cos(\phi_2)\sin^2(\frac{\lambda_2-\lambda_1}{2})$
        c = $2\arctan 2(\sqrt{a}, \sqrt{1-a})$
        UE_POS_CHG= $R * c$
        if ($UE\_POS\_CHG > Threshold$) then
            if ($Response == 1$) then
                while ($ACK \neq True$) do
                    Transmit a discovery message in
                      time $t_{TX}$
                    TX_counter $+= 1$
                end
            else
                UE Transmits N no. of discovery
                  messages for time $t_{TX}$
                TX_counter $+=$ N
            end
        else
            UE will remain idle for time $t_{TX}$;
        end
        UE remains idle for $t_{IDL} \leftarrow t_{IDL} = \{t_{IDL}1, t_{IDL}2,$
          $\ldots, t_{IDL}Z\}$ & $(t_{IDL}1 < t_{IDL}2, .., < t_{IDL}Z)$ }
        NW_lifetime $+= t_{TX} + t_{IDL}$
    end
end
```

received the updated information. However, whenever a UE changes its position it is important to transmit the discovery messages. This will benefit the first responder to keep track of the updated information and to keep tracking the affected UE. Given that a UE can move continuously, we set a threshold on the position change equal to 5 m based on our application requirements. Thus, a UE can only transmit the discovery messages in the transmission stage when a change in the position of a UE is more than 5 m. A GPSDO module is used to get the coordinates of a UE in real-time. A distance covered by a UE is calculated from the haversine formula using the current coordinates (point A) and the coordinates of a UE at the previous transmission (point B), as explained in the proposed algorithm (Algorithm 1), where ϕ_1, ϕ_2 are the latitude of point A and latitude of point B, respectively and λ_1, λ_2 are the longitude of point A and longitude of point B, respectively. All the angles are in radians and R is the radius of earth in meters. If an affected UE initiates the discovery transmission, for the first time, it will not follow this step and directly goes to the second step of the second phase.

The second and last step of the second phase is to determine the optimal number of re-transmission of discovery messages in the transmission stage. A UE can re-transmit up to eight discovery messages per second in the transmission stage. It was observed after the measurement campaign in different scenarios that the reliability of network connectivity depends on the channel conditions and distance between two UEs. It is further shown in Sect. IV-B that when the channel condition is good, a monitoring UE or the first responder can discover the announcing or affected UE with a single transmission. On the other hand, in poor channel conditions, an affected UE has to re-transmit multiple discovery messages to be discovered. Therefore, we add a response message in our proposed approach (see Sect. III), so that an affected UE will keep re-transmitting the discovery messages until it receives a response message from the first responder. Our proposed heuristic approach provides a reliable D2D discovery and significantly improves the UE lifetime in a critical scenario.

B. PERFORMANCE EVALUATION OF THE PROPOSED APPROACH

After evaluating the performance of direct discovery in terms of reliability and maximum range of direct discovery in heterogeneous environments (see Section III-A), we proposed the above-described heuristic approach to improve the UE lifetime in a network by stopping the redundant discovery transmissions and to provide a reliable direct discovery in critical situations. When a BS is unavailable, a UE will redundantly transmit discovery messages with a fixed period even although it is discovered by the rescue services and not changing its position. Normally, the periodicity could be up to 10 seconds [42]. As a baseline, we consider different periodicity periods (P) for discovery transmission, i.e. $P =$ 125 ms, 160 ms, 250 ms, 500 ms, in other words, a UE transmits 8, 6, 4, 2 messages-per-second (MPS), respectively. With the proposed approach, a UE considers two factors before performing discovery transmission: the current battery level of a UE and the distance covered by a UE. The current battery level of a UE defines the periodicity period for discovery transmission, whereas the distance covered by a UE determines to either transmit the optimal number of discovery messages in the transmission stage or remain idle, as fully explained in Section IV-A.

It can be seen from Fig. 23 that the proposed approach significantly improves the UE lifetime in the network compared to baseline discovery transmissions. A UE lifetime has been prolonged by 128, 219, and 329 minutes when compared to fixed periodicity periods for discovery transmission where $P =$ 2, 4, and 8 MPS, respectively. The proposed approach also stops the redundant transmissions and only transmits 1.72%, 1.05%, and 0.72% of discovery messages compared to fixed periodicity periods where $P =$ 2, 4, and 8 MPS, respectively. A 100% fully charged battery is considered for this result. However, on-scene available devices have different charging levels in real-life scenarios. Therefore, in what follows, we consider 30 UEs with different charging

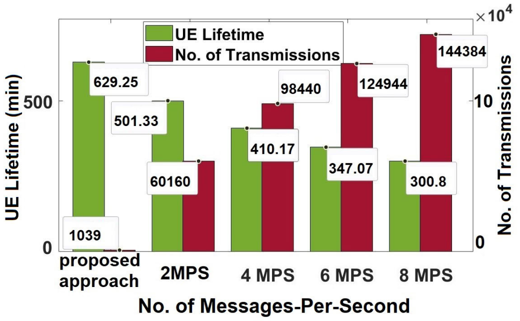


FIGURE 23. Comparison of the lifetime of a UE in the NW between our proposed approach (without response message) and fixed numbers of messages per second.

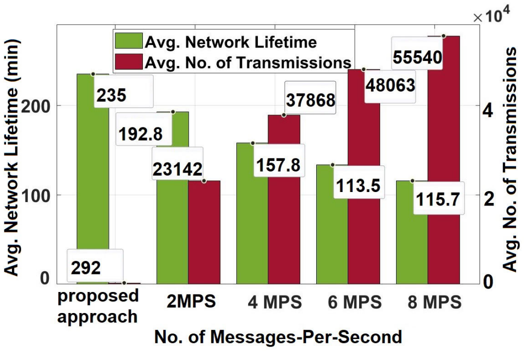


FIGURE 24. Comparison of the Avg. NW lifetime with 30 UEs between our proposed approach (without response message) and fixed numbers of messages per second.

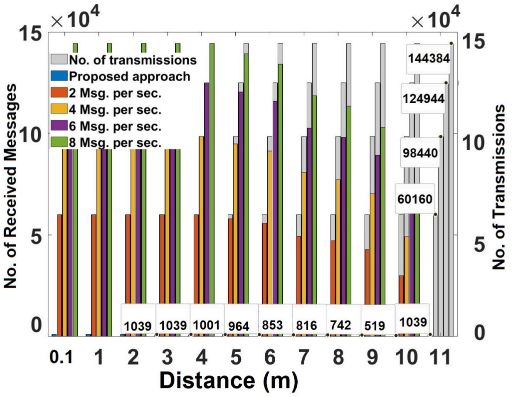


FIGURE 25. Comparison of the discovery ratio in the indoor-NLoS scenario between our proposed approach and fixed numbers of messages per second.

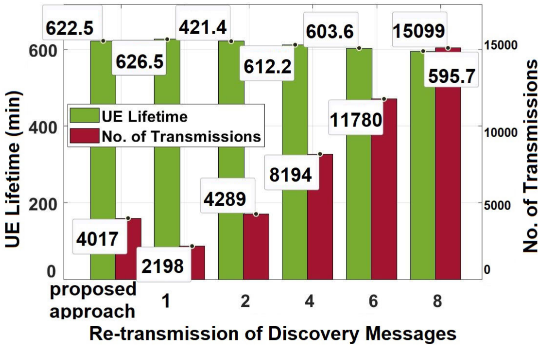
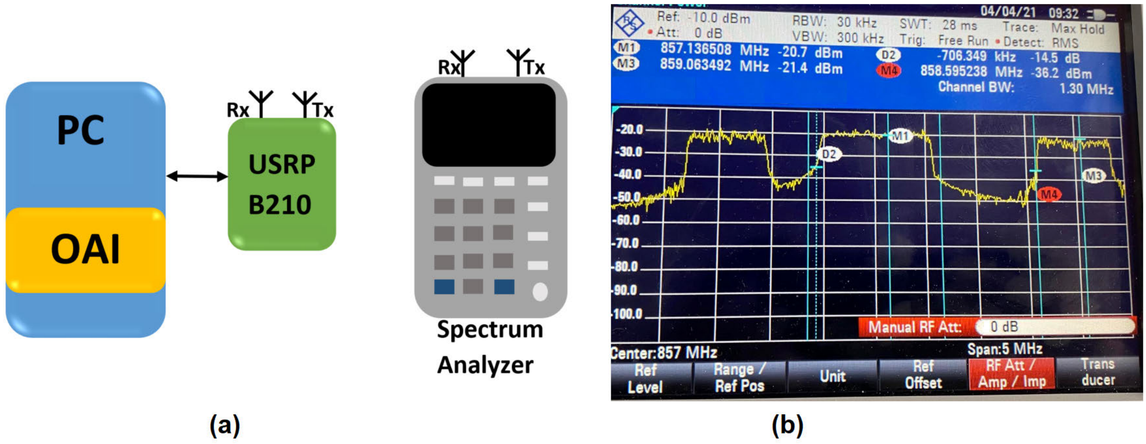


FIGURE 26. Comparison of the number of re-transmissions between our proposed approach (with response message) and fixed numbers of messages per second.

levels to analyze the average network lifetime, as shown in Fig. 24. A similar behavior is observed in network lifetime and number of transmissions of discovery messages. Our proposed approach outperforms baseline transmission for direct discovery thanks to the self-awareness strategy of a UE, based on its current battery level indication and context-awareness, before transmitting the discovery message. For the results shown in Figs. 23 and 24, we consider a very good channel condition with a 100% reliable connection; therefore, a UE transmits a single discovery message in the transmission stage to be discovered.

However, it is not feasible to always have a 100% reliable connection in critical situations. This depends on the channel conditions between the announcer and the monitoring devices. As it has been observed from the experimental results, a reliable direct discovery depends on the operating frequency, RX and TX gains, distance between transmitter and receiver, and different environments. Fig. 25 shows a very revealing result where we use the number of messages transmitted in Fig. 23 and average discovery ratio in the indoor-NLoS scenario to show the comparison between transmitted versus received number of discovery messages. It can be seen that all the transmitted messages are received when the distance is up to 4 m between two devices and a 100% reliable direct discovery is achieved. The number of received messages or discovery ratio decreases with increasing the distance. It is important to note that when the discovery ratio is low, there is a higher probability that a monitoring device can receive a discovery message with more re-transmissions. However, the challenge is "what could be an optimal number for re-transmitting the discovery messages in the transmission stage?". Thus, our proposed approach suggests that an announcing device should keep transmitting the discovery messages until a response message is not received from the monitoring device. This approach provides a highly reliable direct discovery and improves the UE lifetime in heterogeneous environments, as shown in Fig. 26. A UE lifetime is just 4 minutes shorter as compared to a fixed single transmission in the transmission stage. Our proposed approach outperforms all fixed numbers of discovery re-transmissions



Ref: -10.0 dBm RBW: 30 kHz SWT: 28 ms 04/04/21 09:32
Att: 0 dB VBW: 300 kHz Trig: Free Run Trace: Max Hold Detect: RMS
M1 857.136508 MHz -20.7 dBm D2 -706.349 kHz -14.5 dB
M3 859.063492 MHz -21.4 dBm M4 858.595238 MHz -36.2 dBm
Channel BW: 1.30 MHz
Manual RF Att: 0 dB
Center:857 MHz
Span:5 MHz

FIGURE 27. **A: an FSH4 spectrum analyzer-based setup to measure output transmitted power and SNR values of both SLSS signals and sidelink discovery channel. B: spectrum analyzer with markers to measure different power levels.**

in the transmission stage except a single transmission. However, a fixed number of discovery re-transmission is not a reliable solution in critical and heterogeneous environments, as discussed before.

V. CONCLUSION AND FUTURE WORK

To our best knowledge, we have presented the first experimental study in the open literature with results characterizing ProSe public safety direct discovery in heterogeneous environments. The OAI open-source software and USRP hardware platform are used to perform the experimental activity to evaluate the performance of ProSe public safety direct discovery in terms of discovery ratio, reliability, and maximum range of direct discovery in three different scenarios. The experimental results give suggestions on suitable gains and frequencies that are required for a reliable direct discovery. Furthermore, the coverage analysis can help the first responders to deploy the unmanned aerial vehicles and/or command center to cover the affected area for reliable communication and reveal the importance of these factors even at frequencies below 1 GHz. Furthermore, our context-aware energy-efficient heuristic approach could improve the UE lifetime and provide more reliable up-to-date information to first responders to reduce the time response in emergency scenarios. In future, we aim to investigate other parameters such as mobility, air-to-ground and air-to-air channels, interference, and discovery time to fully characterize the ProSe direct discovery in emergency scenarios.

APPENDIX

SPECTRUM ANALYZER-BASED SETUP APPENDIX

See Figure 27.

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Appendix 5

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Direct Discovery-based Cooperative Device-to-Device Communication for Emergency Scenarios in 6G

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Abstract—**Device-to-device (D2D) enables direct communication between two-user equipment (UEs) with or without the involvement of a base station (BS). D2D communication is a vital paradigm to design a reliable public safety network (PSN) and support several services in the sixth generation (6G) systems such as target monitoring, emergency search and rescue, etc. In this experimental study, we demonstrate a cooperative D2D communication system in an emergency scenario to disseminate important information (e.g., the number of people, their IDs and current location) from an affected zone to a deployed command centre in the absence of a BS. We suggest context-aware proximity services-based direct discovery along with unmanned aerial vehicles (UAVs) as a possible solution to implement the future PSN in 6G. Furthermore, we characterize the performance of direct discovery in terms of connectivity reliability and latency in emergency scenarios. Our results show that the discovery ratio is always higher than 90% for SNR values above 20 dB and reaches 100% for SNR values of 23 dB. The end-to-end delay is a low as 18 ms when there is no relay node between two UEs, and increases linearly with the number of hops. Under specific emergency scenarios, the impact of this work is that it is possible to deploy the equipment, establish connectivity, and pass information from the affected zone to deployed command centre in approximately one minute and forty seconds in a real-time lab environment, and four minutes and thirteen seconds in the tested real-life outdoor scenario.**

Index Terms—**Device-to-device communication, B5G, 6G. public safety network, proximity services, direct discovery, unmanned aerial vehicles.**

I. INTRODUCTION

Device-to-device (D2D) communication allows direct communication between two user equipment (UEs) in proximity regardless of the availability of a cellular base station (BS). D2D communication can play a significant role to design future public safety networks (PSNs) in sixth generation (6G) communication systems [1]. Such a technology can support first responders (police, fire department, etc.) in emergency scenarios (fires, earthquakes, terrorist attacks, etc.) to provide important information and speed up the rescue process [2].

A vision of a possible 6G architecture is outlined in [3]. It is envisioned that D2D communication in 6G network will be highly intelligent, markedly context-aware, extremely heterogeneous, and exceptionally energy efficient. D2D communication will have features such as clustering, UE-UE-relay communication, multi-hop, etc. [1], [4]. D2D communication can operate in in-coverage, partial coverage, and out-of-coverage scenarios, depending on the network condition of the UE. In an in-coverage scenario, communication is controlled by the BS; in a partial coverage scenario, a remote UE gets assistance from an in-coverage UE and connects to a BS; finally, in an out-of-coverage scenario, remote UEs fall outside the BS coverage and use pre-configured parameters for direct communication [5].

For the first time, the third generation partnership project (3GPP) proposed proximity services (ProSe) to enable D2D communication in Releases 12 and 13 [5]. A new interface has been introduced for D2D communication, called sidelink. The ProSe services were introduced primarily for public safety scenarios. Later, 3GPP proposed new services particularly for vehicle-to-everything (V2X) communication in Releases 14, 15, and 16 [6]. Finally, 3GPP is planning to introduce new features in ProSe services along with V2X services and to propose UE-to-UE relay communication to enhance ProSe services in fifth generation (5G) and beyond.

It is observed that in emergency scenarios, the BS are often unavailable due to physical damages. Thus, people who are stuck inside an affected zone cannot communicate with first responders. The first responders do not obtain the basic but important information such as the number of affected people, their locations and identity, etc. Due to unclear information, the first responders remain unable to take immediate actions to provide relief, even after many hours. Consequently, the response time may become very long [7]. The main challenges for the first responders in such incidents are to establish connectivity in the absence of a BS and obtain important information from the affected zone [2].

In recent times, unmanned aerial vehicles (UAVs) have been proposed in cellular networks for public safety (PS) scenarios. The UAVs can be used as a relay to connect the emergency zone with the nearest BS [8]. Recently, UAVs have been deployed as a portable BS to provide cellular connectivity to crowded events. The expected time to deploy a fixed BS is up to 90 days whereas setting up a portable BS on an UAV platform reduces this time to approximately 90 minutes. Additionally, unlike a fixed BS, the UAV provides the freedom to move the deployed BS and change its position according to the requirements [9].

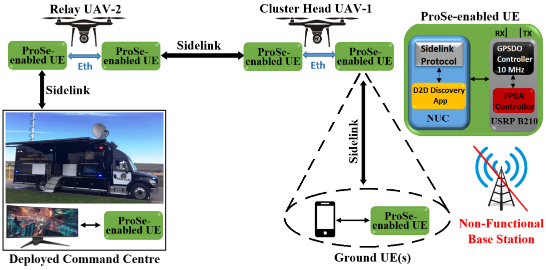

Fig. 1: Suggested novel architecture for UAV and D2D communication assisted public safety network for emergency scenarios wherein cellular BS are non-functional. The ProSe-enabled UEs are able to communicate with the deployed command centre via the multi-hop sidelink connectivity over UAVs.

A. Related Work

Existing communication technologies for PSNs, such as M-Urgency, mission-critical push-to-talk (MC-PTT), social media applications like Twitter and Facebook, etc., are not able to cope with the first responders during disaster situations and reduce the response time [2], [10]. Although these technologies allow people who are in a disaster zone to do e.g. live streaming, they need access to a core network to do so.

On the other hand, D2D communication is a promising paradigm to support new services in 5G and 6G systems. D2D communication can reduce network load, improve capacity per area, enhance spectral efficiency, increase energy efficiency, and reduce latency in a cellular network [11]. D2D communication can also extend cellular coverage of a BS using relaying [12], multi-hop [1] and clustering [13] techniques in PS scenarios.

Hence, we have previously suggested a novel architecture based on D2D communication along with UAVs, as shown in Fig. 1. Not only it can disseminate the important information from the affected zone to the external deployed command centre, but also speed up the rescue process and reduce the response time [2], [14]. Afterwards, we analysed the performance of D2D communication in terms of reliable connectivity and maximum range in real-life heterogeneous environments [15]. Furthermore, we proposed a context-aware energy-efficient heuristic approach which can improve both UE and network lifetime, avoid redundant transmissions, reduce response time, and provide more reliable context-aware communication to the first responders in PS scenarios [16].

In this paper we present key aspects and results of the demonstrator underpinning the implementation of the above-mentioned work.

B. Contribution

To our best knowledge, this is the first paper that presents an empirical demonstration of cooperative D2D communication in a PS scenario in the absence of cellular infrastructure. We propose the application for technologies such as clustering, UE-UE-relay, UAVs and context-aware D2D communication, and summarize the characteristics of the proposed architecture for future PSNs in 6G to share important information (such as the number of affected people, their identities and locations, etc.) with the first responders and reduce the response time in emergency scenarios. We implement a prototype and test it in a real-life scenario. Furthermore, we analyse the performance of implemented prototype in terms of reliable connectivity and latency. To deploy the equipment, establish connectivity, and pass information from the affected zone to deployed command centre, it takes approximately one minute and forty seconds in a real-time lab environment, and four minutes and thirteen seconds in the tested real-life outdoor scenario.

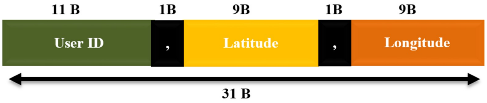

Fig. 2: The discovery payload contains information about user ID and current location.

II. CHARACTERISTICS OF SIDELINK-BASED PROTOTYPE

The ProSe provides mainly two services to enable D2D communication over sidelink interface: direct discovery and direct communication. Direct discovery allows devices to detect other devices and identify services located in their proximity. Direct communication allows two devices to share data with each other in proximity [17].

ProSe direct discovery only allows PS-enabled devices to detect and identify other PS-enabled devices in proximity for PS. ProSe direct discovery supports two models in emergency scenarios: model A and model B. Model A ("I am here") protocol uses only a single message for discovery. A PS-enabled UE periodically transmits the discovery message, and other PS-enabled UEs monitor the discovery messages but do not send an acknowledgement message back to the announcing UE. Model B ("Who is there?") protocol follows two messages for discovery. A PS-enabled UE periodically transmits the discovery message and other PS-enabled UEs send back an acknowledgement message to the announcing UE after receiving the discovery message. These messages can contain different information such as discovery type, information about announcing and monitoring UEs, application-layer identity, etc. A UE uses the physical sidelink discovery channel (PSDCH) to perform ProSe discovery, more detailed information can be found in [18].

Before performing ProSe direct discovery, all UEs have to synchronize to get the necessary timing and frequency information in order to perform successful transmission and/or reception. In an out-of-coverage scenario, when BSs are unavailable, a UE which is called synchronization reference (SyncRef) periodically transmits the sidelink synchronization signals (SLSS) after every 40 ms [17]. The other UEs, which

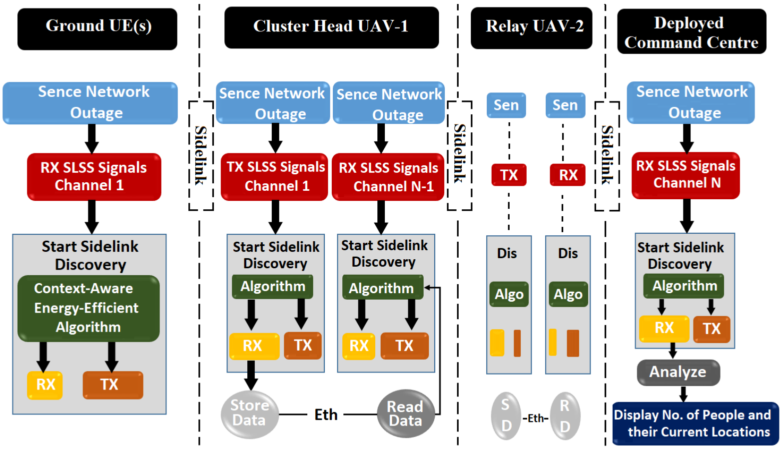

Fig. 3: High-level process flow diagram of the implemented prototype. The green boxes depict the implemented context-aware and self-aware intelligent algorithm for minimizing energy consumption while maintaining the necessary information transmission.

are called remote UEs, receive these SLSS signals to get synchronized with the SyncRef UE in order to start the direct discovery and direct communication. The synchronization subframe has six physical resource blocks (PRBs) and four types of synchronization signals: demodulation reference signals (DMRS), secondary sidelink synchronization signal (SSSS), primary sidelink synchronization signal (PSSS), master information block SL (MIB-SL) composed in the physical sidelink broadcast channel (PSBCH) more details can be found in [17].

Our demonstrator implements the architecture we proposed for PSNs in [2], [14], as shown in Fig. 1; we consider the emergency scenario where the BS is non-functional. UAVs with ProSe direct discovery features have been deployed to cover the emergency zone and provide connectivity to the ground or remote UEs. UAVs operate as SyncRef UEs and transmit the synchronization signals. PS-enabled UEs with ProSe direct discovery features receive those signals and establish connectivity. A UE shares its important information, such as ID and current location, with the UAV. A UAV sends back an acknowledgement to the announcing UE. UEs use the direct discovery protocol to send this information through the sidelink interface. The payload frame format of direct discovery with all the information can be seen in Fig. 2.

In Figure 3, UEs used for ground UE(s), cluster head UAV-1, relay UAV-2, and deployed command center all perform self-aware intelligent transmissions based on current battery level and position, as per the algorithm we proposed in [16] and implemented in this paper for future PSNs.

The implemented context-aware and self-aware intelligent algorithm minimizes energy consumption while maintaining the necessary information transmission. When a UE changes its current position, it transmits N number of discovery messages depending on the channel conditions. This approach does not only avoid redundant transmissions and improve the lifetime of a UE, but also provides updated information to the first responders. The UAV acts as a cluster head and gathers information from all the UEs inside the coverage area. The UAV passes this information to the next UAV. The second UAV sends this received information to the external deployed command centre (architecture shown in Fig. 1). Both UAVs and the deployed command centre use the same discovery protocol to transmit and receive information over the sidelink interface. The second UAV also has both functionalities; it acts as a cluster head to provide connectivity to ground UEs, and as a relay node to pass information to the command centre. In our demonstrator, the second UAV is used only as a relay node. Thanks to the developed system, the external deployed command centre collects all the important information (number of affected people, their identities, current locations inside the emergency zone). This information at the deployed command centre can help first responders to plan their strategies and speed up the rescue process.

A. *Experimental Setup*

The OpenAirInterface software (OAI) and USRP-based hardware platforms are used to develop our prototype. We consider an out-of-coverage emergency scenario when the BS is not available; therefore, all devices are configured as UEs. Each UE has the same components. The following types of equipment are used in our OAI/USRP-based prototype.

- USRP B210: The USRP board is used as the radio front-end hardware part of a UE. Each USRP has two telescopic antennas to transmit and receive the signals.
- Board Mounted GPSDO (TCXO): Each USRP board has a GPSDO module to get a high-accuracy 10 MHz reference clock; all UEs are synchronized with the same

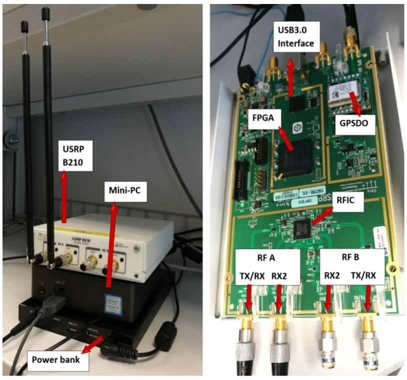

Fig. 4: Developed ProSe-enabled UE prototype.

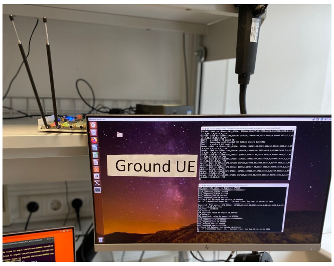

Fig. 5: Deployed ground (or remote) UE in indoor lab environment.

reference clock. A GPSDO module is also used to obtain the satellites information to get coordinates of a UE.

- Mini PC: The next unit of computing (NUC) (or “mini PC”) is used for running the software part of a UE. It operates the OAI software having a 3GPP protocol stack, starting from LTE (Rel 8) and going up to 5G (Rel 16). Furthermore, it runs our implemented application for direct discovery which is context-aware and energy-efficient. Each OAI-based UE has both mini PC and USRP board connected over USB 3.0 (see Fig. 4).
- Unmanned aerial vehicles: Two UAVs (DJI Matrice 600 Pro) are used to carry on implemented OAI-based UEs. Each UAV can provide connectivity to ground UE as a SyncRef UE, and gather information from ground UEs as a cluster head. After receiving information from the ground UEs, the UAV sends it to the next UAV or external deployed command centre. A system-level architecture of the prototype can be seen in Fig. 3.

The OSA provides an open-source OAI software for ProSe communication, publicly available on Eurecom’s GitLab repository[1]. Out-of-the-box, the above-mentioned setup has limitations. Each USRP board has to connect with one Octo-Clock (CDA- 2990) through SMA cables to get synchronized with the same reference clock. Therefore mobility of UEs is a major issue. Moreover, the above setup has only two UEs in the network who transmit one random discovery message over sidelink. As a starting point, we have used the same setup and introduced new enhancements. In our expanded setup, we have solved the mobility issue by installing a GPSDO module on each USRP board to remove the need for the OctoClock. Furthermore, we have developed an application for self-aware ProSe direct discovery which provides reliable, context-aware and energy-efficient communication in public safety scenarios; more details can be found here [16].

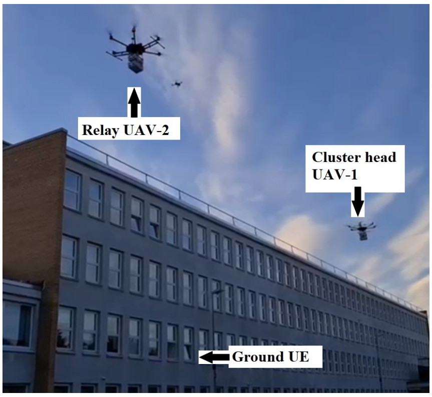

Fig. 6: Deployed UAVs in outdoor environment provide connectivity, collect and pass information to the command centre.

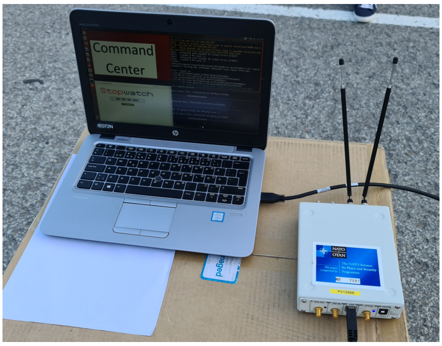

Fig. 7: Deployed command centre in outdoor environment.

B. Deployment in real-life scenario

The demonstration was prepared at Tallinn University of Technology. All the required permissions have been obtained to carry out these activities, for example, RF test license, permit to fly drones, etc. Six OAI-based UEs and two UAVs are used in the real-life demonstration.

1) Ground UE: One ProSe-enabled UE is deployed as a ground UE in the indoor lab environment on the second floor at an altitude of 6 m. A ground UE searches for the

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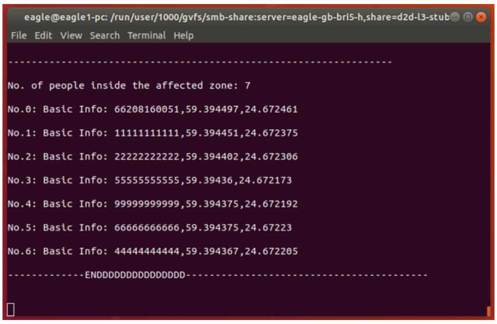
[1] https://gitlab.eurecom.fr/oai/openairinterface5g/-/tree/LTE-sidelink/



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No. of people inside the affected zone: 7

No.0: Basic Info: 66208160051,59.394497,24.672461

No.1: Basic Info: 11111111111,59.394451,24.672375

No.2: Basic Info: 22222222222,59.394402,24.672306

No.3: Basic Info: 55555555555,59.39436,24.672173

No.4: Basic Info: 99999999999,59.394375,24.672192

No.5: Basic Info: 66666666666,59.394375,24.67223

No.6: Basic Info: 44444444444,59.394367,24.672205

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Fig. 8: Screenshot of some of the information received at the deployed command centre.

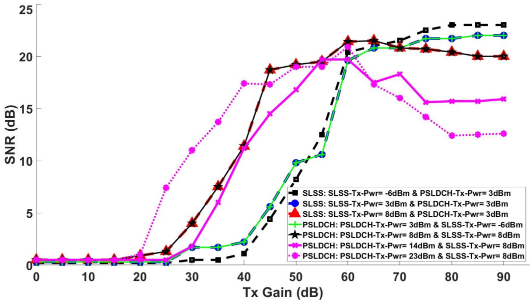

Fig. 9: SNR as a function of transmission power (values inset) and transmission gain (X-axis) of SLSS signals and PSDCH channel.

synchronization signals from an external deployed UAV to start communication. A ground UE has a non-line-of-sight (NLoS) transmission path with a UAV, which can be seen in Fig. 5.

2) UAVs: Two UAVs are deployed in the outdoor environment to provide connectivity to ground UE(s) and relay the information to the deployed command centre. Both UAVs have a direct transmission path between them, as shown in Fig. 6. The first UAV is configured as a cluster head to provide connectivity to ground UE(s), discover the ground UE(s), and send data to the next UAV. The first UAV has two ProSe-enabled UEs (i.e. two mini-PCs and two USRP boards). The first UE communicates with ground UE(s) and collects information using one channel. The second UE is used to enable communication between UAVs and transmit the received information to the next UAV using another channel to extend the range. Both UEs mounted on a UAV communicate with each other over an Ethernet cable, as shown in Fig. 3. We have the same setup on a second UAV with the same functionalities. Which receives data from the first UAV and relays it to the external deployed command centre.

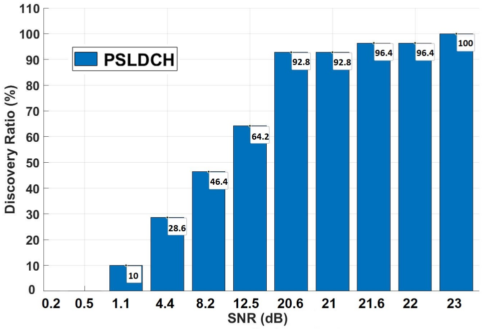

Fig. 10: Direct discovery ratio as a function of SNR.

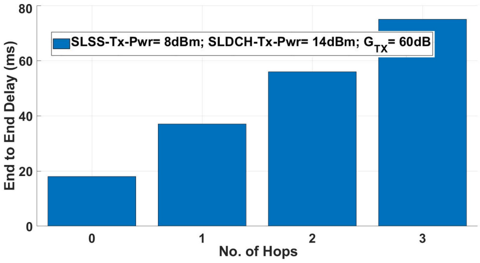

Fig. 11: The average time (end-to-end delay) to discover the UE in PS scenarios as a function of number of hops.

3) External Command Centre: One ProSe-enabled UE is configured as the external command centre and deployed in the outdoor environment, as shown in Fig. 7. The command centre receives all the information (such as the number of affected people, their identities and current locations in a disaster zone) and displays it in real-time.

III. PERFORMANCE EVALUATION

Our previous results [16] show that a reliable direct discovery is a combination of carrier frequency (f), transmitter and receiver amplification gains (G_{Tx}, G_{Rx}), distance between transmitting and receiving devices (D), and different environments. Therefore, it has been made sure to use the best parameters to establish a reliable communication link, i.e., f = 857 MHz, G_{Tx} = 60 dB, G_{Rx} = 60 dB. More details can be found in [16].

Before deploying our prototype in a real-life scenario, we have investigated it first in a lab environment. A demonstration video[2] illustrates that it took one minute and forty seconds to establish a network and relay data from the affected zone to the command centre. Afterwards, the prototype has been deployed in a real-life outdoor scenario[3], as explained in Section II-B. The response time is approximately four minutes and thirteen seconds to deploy the UAVs, establish connectivity, and pass

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[2] https://bit.ly/3GDyVMk

[3] https://bit.ly/3A6KDfX

information from the affected zone to deployed command centre. Fig. 8 shows the information received at the deployed command centre. It can be seen that the command centre has critical information such as the number of people inside the affected zone, their IDs and current locations. This real-time information can help the first responders to trace the affected UE and speed up the rescue process.

Furthermore, we have carried out additional experiments in a lab environment to fully characterize the ProSe direct discovery. In addition to our previous findings [2], [14], we investigate the impact of the transmission power of SLSS signals (SLSS-Tx-pwr) and PSDCH channel (PSLDCH-Tx-pwr), and G_{Tx} gains on ProSe direct discovery: Here f = 857 MHz and D = 6 m. Fig. 9 shows the effect of the transmission power of SLSS signals and PSDCH channel on the signal-to-noise ratio (SNR). It can be observed that SNR values improve by increasing the G_{Tx} gain except if the values of SLSS-Tx-pwr and PSLDCH-Tx-pwr go above 8 dBm and 3 dBm, respectively. The maximum SNR (23 dB) value is obtained when G_{Tx} = 90 dB, SLSS-Tx-pwr = -6 dBm and PSLDCH-Tx-pwr = 3 dBm, shown as a black dashed line with a square marker in Fig. 9. A strong interference can be noticed between SLSS and PSDCH with high values of power and gain. The SNR value improves 0 to 20 dB for G_{Tx} gains ranging from 20 to 60 dB when the value of SLSS-Tx-pwr is 14 or more than 14 dBm, shown as magenta lines with asterisk and cross markers.

The SNR is directly related to direct discovery. It can be observed from Fig. 10 that as the SNR value increase, the discovery ratio improves as well. The discovery ratio is always more than 90% for SNR values ranging from 20 to 22 dB. When the SNR value is 23 dB, it provides a 100% discovery ratio and the best network connectivity.

The average time to discover the UE (end-to-end delay) is the same in both indoor and outdoor scenarios after establishing a 100% reliable connectivity for direct discovery. Fig. 11 shows that end-to-end delay depends on the no. of hops. When there is no relay node between two UEs, the end-to-end delay is 18 ms. The end-to-end delay increases linearly with the number of hops.

IV. CONCLUSION

To the best of our knowledge, this is the first experimental study that suggests technologies such as clustering, UAVs, D2D and relay communication for future PSNs in 6G and demonstrates it in a real-life scenario. Such PSN can help the first responders to establish reliable connectivity and get critical information in emergency scenarios. Which can eventually speed up the rescue process and reduce the response time. Our demonstration videos illustrate that it takes approximately one minute and forty seconds to deploy the equipment, establish network connectivity and relay critical information from the affected zone to deployed command centre in a real-time lab environment, and four minutes and thirteen seconds in the tested real-life outdoor scenario.

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2016–2017	University of Burgundy, France, MSc in Advanced Electronic Systems Engineering
2011–2015	University of Bradford, United Kingdom, BEng Electrical and Electronic Engineering

4. Language competence

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6. Voluntary work

Guiding students, Collecting donations, Donating blood

7. Computer skills

- Operating systems: Linux, Windows
- Document preparation: MS Word, Latex, MS Power Point, MS Excel
- Programming languages: MATLAB, C, C++, Assembly, FPGA (AHDL, VHDL)

- Hardware Instruments: USRP boards (B210, N310), Microcontrollers (Arduino, PIC 18F4520/16F690/16F84A), FPGA board (Nexys 3 Xilinx Spartan-6 LX16), ARM 7TDMI, Power Analyzer, Spectrum Analyzer, Signal Generator, DMM, Oscilloscope, etc.
- Software: OpenAirInterface, Xilinx ISE, Altera Quartus, Mplab, Source Boost, Proteus, Express PCB, EAGLE, PSIM, PSpice
- Transferable skills: Project Management, Problem Solving, Self-motivation, Goal-oriented, Team Work, Adaptability

8. Honours and awards

- 2021, Won the Man of the Series award at the International Cricket Tournament in Cyprus
- 2018, Awarded the IT Academy Scholarship by the Tallinn University of Technology for PhD Studies
- 2016, Awarded a merit based scholarship by the University of Burgundy for master's degree
- 2013, Leading a team in RoboSrpint2013, got third position in all Pakistan competition
- 2011, Awarded a merit based scholarship by Punjab Group of Colleges to pursue my college studies

9. Defended theses

- 2017, SYNCHRONIZATION OF TR-NEWS BASED ACOUSTO-MECHANICAL IMAGING OF EX VIVO SKIN: INSTRUMENTATION AND SIGNAL PROCESSING, MSc, supervisor Prof. Serge Dos Santos, University of Burgundy, France

10. Field of research

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- Public Safety Networks
- Acousto-Mechanical Imaging
- Embedded Systems
- Real-time Systems

11. Scientific work

Papers

1. Masood, A., Alam, M. M., Le Moullec, Y. Direct Discovery-based Cooperative Device-to-Device Communication for Emergency Scenarios in 6G. In 2022 European Conference on Networks (EuCNC) and Communications 6G Summit (Accepted). IEEE, 2022.
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5. Ghorbel-Feki, H., Masood, A., Caliez, M., Gratton, M., Pittet, J. C., Lints, M., Dos Santos, S. (2019). Acousto-mechanical behaviour of ex-vivo skin: Nonlinear and viscoelastic properties. Comptes Rendus Mécanique, 347(3), 218-227.

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7. Dos Santos, S., Masood, A., Lints, M., Arruga, D., Nardoni, G. Towards standardization of nonlinear ultrasound for future nondestructive testing. Meeting of the Non Linear, 126.

8. Dos Santos, S., Masood, A., Furui, S., Nardoni, G. (2018, October). Self-calibration of multiscale hysteresis with memristors in nonlinear time reversal based processes. In 2018 16th Biennial Baltic Electronics Conference (BEC) (pp. 1-4). IEEE.

9. Dos Santos, S., Masood, A., Lints, M., Salupere, A., Kozena, C., Kus, V., ... Gratton, M. (2018, July). MULTISCALE MEMRISTIVE PROPERTIES OF SKIN INDUCED BY MEMORY EFFECTS OF CYCLIC STRESS-RELAXATION LOADINGS: DATA FUSION FROM GROUND TRUTH NONLIN-EAR ACOUSTO-MECHANICAL TESTING. In 25th International Congress on Sound and Vibration (ICSV25).

10. Dos Santos, S., Masood, A. Ultrasonic transducers self-calibration of nonlinear time reversal based experiments using memristor. Proceedings of 12th ECNDT, Goetheburg-Sweden-2018.

11. Dos Santos, S., Lints, M., Masood, A., Salupere, A., Pittet, J. C., Gratton, M., Caliez, M. (2017, June). Acousto-mechanical instrumentation of multiscale hysteretic memristive properties of the skin with nonlinear time reversal imaging. In 2017 Cosmetic Measurements And Testing (COSMETIC) (pp. 1-4). IEEE.

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13. Pardy, T., Rang, T., Tulp, I., Kremer, C., Rashid, M. H., Koel, A., ... Alam, M. M. 2018 16th Biennial Baltic Electronics Conference (BEC) Invited Talks.

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- Document preparation: MS Word, Latex, MS Power Point, MS Excel
- Programming languages: MATLAB, C, C++, Assembly, FPGA (AHDL, VHDL)

- Hardware Instruments: USRP boards (B210, N310), Microcontrollers (Arduino, PIC 18F4520/16F690/16F84A), FPGA board (Nexys 3 Xilinx Spartan-6 LX16), ARM 7TDMI, Power Analyzer, Spectrum Analyzer, Signal Generator, DMM, Oscilloscope, etc.
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8. Autasud

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- 2016, Awarded a merit based scholarship by the University of Burgundy for master's degree
- 2013, Leading a team in RoboSrpint2013, got third position in all Pakistan competition
- 2011, Awarded a merit based scholarship by Punjab Group of Colleges to pursue my college studies

9. Kaitstud lõputööd

- 2017, SYNCHRONIZATION OF TR-NEWS BASED ACOUSTO-MECHANICAL IMAGING OF EX VIVO SKIN: INSTRUMENTATION AND SIGNAL PROCESSING, MSc, supervisor Prof. Serge Dos Santos, University of Burgundy, France

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- Public Safety Networks
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