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MODELING OF CARRIER SENSE MULTIPLE ACCESS WITH COLLISION AVOIDANCE IN THE CONTEXT OF WIRELESS BODY AREA NETWORKS

Master's Thesis

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KOLLISIOONIDE VÄLTIMISE MODELLEERIMINE CSMA/CA-PÕHISTES KONTAKTIVABADES KEHAVÕRKUDES (BAN)

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

Wireless networking is often considered as the fastest growing segment of the networking industry. Recent and current improvements in sensing devices and wireless networking have allowed the proliferation of so-called wireless sensor networks. These wireless sensor networks are capable of both monitoring and controlling environments. These find some potential applications in many domains including the medical industry; one of the most primary applications herein is body area network (BAN). Although BAN is deemed able to reform the patient monitoring system, there remain several challenges in the design of these systems, among other things because they need to provide a right formation of network performance metrics, reliable data delivery in a timely manner, and adequate throughput. Thus, quality of service is an important issue in the design and implementation of wireless sensor networks.

This MSc thesis focuses on some of the technical aspects underlying the quality of service issue; in particular, it reviews and presents an understanding of access techniques used in medium access control (MAC) protocol for wireless body area networks (WBANs) standards proposed by the institute of electrical and electronics engineers (IEEE), namely IEEE 802.15.6. The work lays emphasis on the carrier sense multiple access with collision avoidance (CSMA/CA) and carries out an assessment of access techniques utilized as a part of MAC Protocol for WBANs, i.e. frequency division multiple access (FDMA), time division multiple access (TDMA), and CSMA/CA mechanisms. The execution measurements utilized for examination are throughput (T), delay (D), offered load (G), reliability (R), and user dissatisfaction probability (UDP) by comparing the different metrics with different number of nodes using MATLAB simulation tool. The experimental results illustrate how G and the number of nodes impact T, D, R, and UDP.

In addition, this work can be well thought-out as the starting point for the development of a more elaborate mechanism to optimize the performance metrics obligation in order to attain the performance imposed by BAN-based applications.

Keywords: CSMA/CA, FDMA, TDMA, delay, throughput, reliability, UDP, offered load, wireless body area networks, MAC protocol.

This thesis is written in English language and is 63 pages long, including 4 chapters, 17 figures and 6 tables.

Annotatsioon

Kollisioonide vältimise modelleerimine CSMA/CA põhistes kontaktivabades kehavõrkudes (BAN)

Traadita võrkusid peetakse sageli kõige kiiremini kasvavaks segmendiks võrgu-tööstustes. Viimased ja praegused sensorite ja traadita võrgu täiustamised lubavad nn traadita andurite võrgustike levikut. Need traadita andurite võrgustikud suudavad teostada järelevalvet ja kontrolli, võimalike rakendustega paljudes valdkondades, sealhulgas meditsiinis on üks esmane rakendus keha ala võrgud (BAN). Kuigi BAN võib reformida patsiendi jälgimise süsteeme, on veel mitmeid arenduse väljakutseid. Need süsteemid peavad muu hulgas tagama õige võrgu tulemuslikkuse meetrika, usaldusväärset ja õigeaegset andmete edastust piisava läbilaskevõimega. Seega, teenuse kvaliteet on traadita andurite võrgustike arenduse teemaks,

See magistritöö keskendub mõnedele tehnilistele aspektidele, mis on aluseks teenuse kvaliteedi küsimuses. Eelkõige vaadeldakse meediale juurdepääsu tehnoloogiaid (MAC) traadita kehaala võrkude (WBANs) protokolli osas ja vastavaid Elektri- ja Elektroonikainseneride Instituudi (IEEE) kavandatud standardeid, muuhulgas IEEE 802.15.6.

Töö pannakse rõhku rõhku mitmese juurdepääsuga kandva äratundmisega kollisioonide vältimisega (CSMA/CA) protokollile ja hinnatakse side-meediale juurdepääsu meetodeid, kasutada MAC protokolli osa WBAN-s, muuhulgas sageduse ühispöördustehnikat (FDMA), ajalise ühispöördusega (TDMA) ja CSMA/CA mehhanismide puhul. Jõudluse mõõtmiseks kasutatakse seost tootlikkusega (T), viivitusega (D), koormusega (G), töökindlusega (R) ja kasutaja rahulolematuse tõenäosust (UDP), võrreldes erinevaid meetrikaid erinevate sõlmede arvu puhul, kasutades MATLAB simulatsiooni vahendeid. Eksperimendi tulemused näitavad, kuidas G ja sõlmede arv mõjutab suurusi T, D, R, ja UDP.

Lisaks saab see töö hästi läbimõeldud lähtepunktiks põhjalikumaks arendustööks, et optimeerida meetrikaid, et saavutada soovitud tulemuslikkust BAN-põhistes rakendusteks.

Märksõnad: CSMA / CA, FDMA, TDMA, viivitus, jõudlus, töökindlus, UDP, koormus, traadita kehaala võrkude MAC protokoll.

Lõputöö on kirjutatud Eesti keeles ning sisaldab teksti 63 leheküljel, 4 peatükki, 17 joonist, 6 tabelit.

List of Abbreviations and terms

WSN	Wireless Sensor Network
MAC	Medium Access Control
PHY	Physical Layer
NB-PHY	Narrowband PHY
UWB-PHY	Ultra-wideband PHY
HBC	Human Body Communications
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WIMAX	Worldwide Interoperability for Microwave Access
TDMA	Time Division Multiple Access
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
FDMA	Frequency Division Multiple Access
UDP	User Dissatisfaction Probability
MIC	Message Integrity Code
MAP	Manage Access Phase
CAP	Contention Access Phase
RAP	Random Access Phase
EAP	Exclusive Access Phase
ID	Identification
QoS	Quality of Service
SF	Superframe
UP	User Priority
FCS	Frame Check Sequence
BER	Bit Error Rate
DTMCs	Discrete Time Markov Chains
RTS	Request To Send
SIFS	Short Inter Frame Space
ACK	Acknowledgment

CTS	Clear To Send
AMPS	Advanced Mobile Phone Service
RF	Radio Frequency
D	Delay
T	Throughput
R	Reliability

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1 Introduction

1.1 General Overview

Wireless Sensor Networks (WSNs) created a growing significance from industrial and research viewpoints at the start of the 21st century [1]-[5]. A WSN is usually defined as a network of nodes that cooperatively sense and would maybe control the environment, enabling interaction between people or computers and also the close environs [6]. On the other hand, new applications are supported by WSNs and as a consequence new potential markets have emerged; then again, new paradigms were called for because the design is influenced by quite a few setbacks that raises research and engineering challenges. In fact, the activity of sensing, processing, and communication under energy constraints erupts a cross-layer design technique usually for the most part requiring the thought of distributed signal/data processing, medium access control, and the corresponding communication protocols [7].

Wireless communication technology, network protocol, and application of sensor technology are joint in WSN, which delivers new enhancement design to the recent computer wireless networks. Ward monitoring system is an example that tells that the WSNs have a tendency to be connected in areas which contain substantial measure of information and are perplexing. Despite that, there are numerous issues varying from design to application that need to be solved [8].

Serving as one of promising possibility for WSNs, IEEE 802.15.6 is a short-range wireless communication standard for body area network (BAN) applications. And the most vital feature of the standard is low power consumption. A number of performance metrics and experimental setups are intended to assess the performance of IEEE802.15.6 [8].

One of the essential issues in wireless BANs (WBANs) is energy efficiency; reducing energy consumption also increases the lifetime of the nodes/sensors, and therefore increases convenience for the user (less frequent recharging or replacement of the batteries); lower energy levels are also desirable in light of the fact that RF sensor nodes might harm human body tissue. Further, sensor nodes connected to the body are battery operated devices, and may have inadequate life time. Consequently, medium access control (MAC) protocols of wireless body area network (WBAN) should be energy efficient and supports medical applications and other applications. This allows the integration of low power intelligent sensor nodes, and they are utilized to stream biological information from the human body and transmit it to a control device called coordinator. This procedure is exceptionally useful while observing health of a person, and if there should arise an occurrence of crisis, giving appropriate medication. Another significant role played by MAC protocol is to determine the energy efficiency in WBANs. In enhancing throughput and bandwidth efficiency, traditional MAC protocols concentrate on these. Be that as it may, the most essential issue is that they lack energy conserving mechanisms. Idle listening, overhearing and packet overhead are the foremost sources of energy wastage. The network lifetime can be maximized by controlling these energy waste sources.

Furthermore, mobility of patient and autonomous observing of patient are one of the numerous advantages that WBANs have, which can deal with e.g. Wireless Local Area Networks (WLANs), Worldwide Interoperability for Microwave Access (WIMAX) or internet to reliably transmit data to a server which is looking into health issues. There are couple of necessities for the MAC protocol design to be utilized as a part of WBANs.

First of all, all of protocols must have high Quality of Service (QoS), second it must be trustworthy, and third it needs to support diverse medical applications.

Different medium access techniques are being utilized, and the significant techniques of MAC protocol for WBANs are A) Time Division Multiple Access (TDMA) and B) Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Frequency Division Multiple Access (FDMA) is very close to TDMA; on the other hand, it is not widely used due to difficulties in implementing its hardware. In realization of the ideal multiple access technique for MAC protocol design, there are quite a few difficulties.

1.2 Motivation

The motivation behind this thesis is the need to bring about the analyses and understanding of access techniques used in MAC protocol for WBANs and to carry out an assessment of access technique utilized as a part of MAC Protocol for WBANs between

TDMA, FDMA and CSMA/CA. The execution measurements utilized for examination are Throughput (T), Delay (D), offered load (G), Reliability (R), and User Dissatisfaction Probability (UDP).

1.3 Objectives

The fundamental objective of this thesis is to show which procedure gives most noteworthy throughput and lowest delay with increase in load. Theoretical analysis and simulations for various situations/scenarios and results are used to compare existing methods and implantations.

MATLAB is the software tool that is utilized for simulation.

Hence, the tasks defined in this thesis are:

1. To give an explanatory model to exploring the execution of the CSMA mechanism for IEEE 802.15.6;
2. To analyse medium access techniques in wireless body area networks;
3. To gain an understanding of access technique utilized as a part of Medium Access Control (MAC) protocol for wireless body area networks between Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA);
4. To analyse and compare an existing methods and implementations;
5. To evaluate/conclude about suitability of existing methods and implementations for WSNs/BANs.

1.4 Thesis Structure

This document is organized into four chapters. This chapter is the introduction and also contains a description of the background; a literature review with detailed descriptions of WSNs, BANs, CSMA, and IEEE802.15.6; a model for inspecting the performance of the CSMA mechanism of IEEE 802.15.6; and a CSMA/CA mathematical model.

Chapter II reviews the fundamentals of multiple access techniques mathematical modelling of throughput for multiple access techniques. Chapter III describes the definition of metrics used such as Reliability (R), throughput, delay, load, UDP and to compare existing simulation methods and implementations for various situations/scenarios. Chapter IV concludes the thesis by reviewing the results achieved and by suggesting future extensions to the studied approaches.

1.5 Overview of WSNs, BANs and CSMA

1.5.1 What is a WSN?

A WSN is defined as a network of devices, indicated as nodes, that is able to sense the environment and to convey the information collected from the monitored field (e.g., an object (possibly living), an area or volume) through wireless links [4]-[5]. The information is sent, potentially via multiple hops, to a sink (at times designated as controller or monitor) which can utilize it locally or is associated with other networks (e.g., the Internet) through a gateway. The nodes can be stationary or moving and they can be aware of their location or not. Also, they can be homogeneous or not.

This is a traditional single-sink WSN (see Figure 1. A). Almost all scientific papers in the literature deal with such a definition.

The lack of scalability is encountered by these single-sink circumstances: by increasing the amount of nodes, the measure of data gathered by the sink rises and once its capacity is attained, the network size cannot be further increased. Likewise, network performance cannot be regarded independent from the network size for motive related to MAC and routing aspects.

A broader situation includes multiple sinks in the network (see Figure 1.B, [11]). As stated in [11], "Given a level of node density, a bigger number of sinks will reduce the likelihood of isolated clusters of nodes which can’t convey their information owing to unsuccessful signal propagation conditions". On a basic level, a multiple-sink WSN can be scalable (i.e., even by an increment in the number of nodes, the same performance can be accomplished), while this is obviously not in force for a single-sink network. Moreover, a trivial extension of a single-sink case for the network engineer does not signify a multi-sink WSN. As per [11], "In many cases nodes send the information gathered to one of the sinks, chose among many, which forward the information to the gateway, toward the final user (see Figure 1.

B). From the protocol perspective, this implies that a selection should be possible, taking into account a suitable criterion that could be, for instance, minimum delay, maximum throughput, minimum number of hops, and so on". Along these lines, with respect to the single-sink case (assuming the same number of nodes is sent over the same area), the presence of multiple sinks guarantees better network performance; however, the correspondence communication protocols must be more complex and ought to be designed according to suitable criteria.

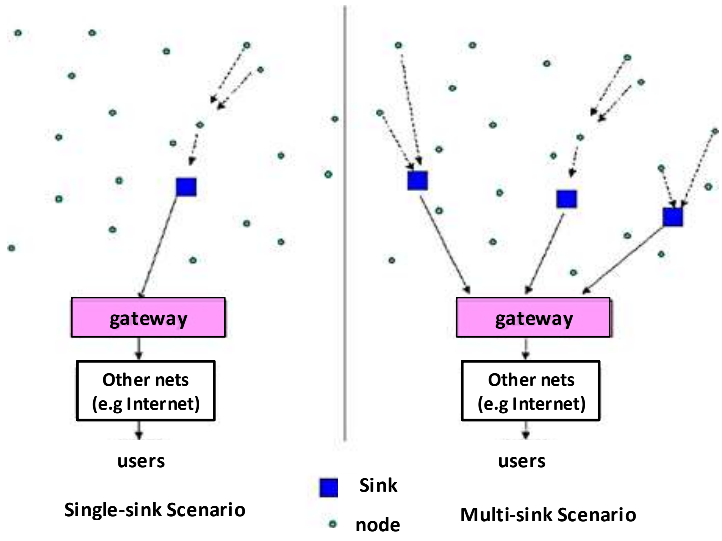


Figure 1. (a) single-sink WSN scenario, (b) multi-sink WSN scenario [11]

1.5.2 Applications of WSNs

The various applications of WSNs to this present world are basically limitless, from environmental monitoring [12], health care [13], to positioning and tracking [14], and logistic, likewise localization, and so forth.

It is mandatory to underline that the application impacts the choice of the wireless technology to be applied. Once the application requirements are set, truth be told, the designer has to choose the technology which let in to meet these requirements.

1.6 BANs

Body area network (BAN) is also known as body sensor networks (BSN) and wireless body area network (WBAN).

A WBAN consists of small smart devices attached on or implanted in the body, as shown in Figure 2, which are capable of establishing a wireless communication link. These devices deliver continuous health monitoring and real-time feedback to the user or medical personnel. And as a result, the measurements can be documented over a longer period of time, improving the quality of the measured data [15].

BANs are generally considered as an enabling technology for a diversity of applications, including health and fitness monitoring, emergency response and device control. Current innovations in solid-state electronics afford for the creation of low-power, low-profile devices that can be modularly interconnected in order to create unproven sensor nodes that consist of one or more sensor devices, a microcontroller unit (MCU), and a radio transceiver that removes the necessity for wires to communicate with the coordinator node in order to transfer the collected data.

The coordinator node functions either as a gateway to transfer data to an external electronic healthcare (eHealth) monitoring system or as a non-dependent node for local monitoring and control [15].

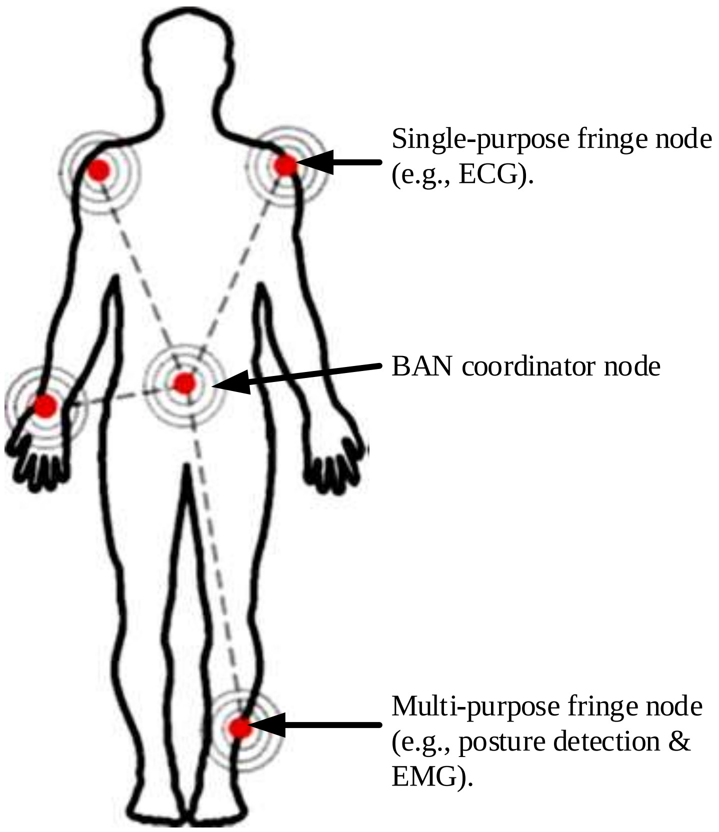


Figure 2. Placement of BAN nodes [16]

As a result, the existing literature repeatedly refers to BANs as wireless BAN (WBAN).

1.6.1 MAC protocols for WBAN

MAC protocols [17] used in WBAN must be low power consuming, accurate and with low latency. The utmost significant aspect is that the protocol should give good performance (i.e. sufficient throughput combined with low delays and low energy consumption) on varying traffic load. More or less popular protocols for WBAN are Timeout-MAC, Sensor-MAC, ZigBee MAC and Baseline MAC.

1.6.2 Characteristics of WBAN

Essentially, WBAN is a communication network between the humans and computers through wearable devices. In order to comprehend communication between these devices, techniques from WSN and ad hoc networks could be used. A distinctive sensor node in WBAN should make sure the accurate sensing of the signal from the body, perform low-level processing of the sensor signal and wirelessly transmit the processed signal to a local processing unit [18].

On the other hand, because of the typical properties of a WBAN, recent protocols designed for these networks are not always well appropriate to support a WBAN. To backing this fact, Table 1 summarizes the overall differences between a WSN and a WBAN as discussed elsewhere in [19] and [20]:

Table 1: Difference between WBAN and WSN. Summarized from [19], [20]

	WBAN	**WSN**
Development	The number of sensor nodes deployed by the user are similarly significant and only added when they are wanted for the application.	WSN is frequently deployed in places that may not be certainly accessible by operators which require more nodes to be placed to compensate for node failures.
Mobility	WBAN users may move around. WBAN nodes share the same mobility pattern.	WSN nodes are commonly considered stationary.

	WBAN	**WSN**
Data Rate	WBAN may occur in a more periodic manner and stable data rate.	WSN is employed for event-based monitoring where events can happen at irregular intervals.

1.6.3 Requirements of WBAN

In this work, we have characterized the requirements of WBAN into two categories i.e. systems and security. More details are described in the following subsection for only systems requirement.

1.1.1.1 System Requirements

This sub-section provides a short explanation of system requirements viewed in three different aspects, such as type of devices, data rate and energy, mostly based on [19]. Note that the following definitions are widely (re)used in the literature.

a) Types of devices

Sensor node: A device that responds to and gathers data on physical stimuli processes the data if required and reports this information wirelessly.

Gateway (Personal Device): It gathers all the information picked up by the sensor nodes and report to the users. This device is also known as a body control unit (BCU), body gateway, or a sink.

Monitoring Server: It comprises of a database for data storage and processing and examining software for delivering system intended services.

b) Data rates

The reliability of the data transmission is provided in terms of the required bit error rate (BER) that is used as a measure for the number of packets lost. For a medical device, the reliability is subject on the data rate. Low data rate devices can deal with a high BER even though devices with a higher data rate require a lower BER. The required BER is also dependent on the criticalness of the data. (I.e. some applications are less sensible to errors than others.)

c) Energy

Energy consumption can be divided into three domains: sensing, communication and data processing [21]. Nevertheless, the energy consumption for (RF-based wireless) communication is typically higher than for computation in WBAN. Additionally, higher security requirements typically correspond to increased energy consumption for cryptographic operations.

1.7 CSMA

“Carrier sense multiple access (CSMA) is based on media access control (MAC) protocol where a node checks the nonappearance of other traffic before transmitting on a shared transmission medium” [22].

Carrier sense implies that a transmitter attempts to decide whether or not another transmission is already in development, rather than establishing a transmission directly. That is, it tries to locate the presence of a carrier signal from another node instead of attempting to transmit directly. If a carrier is sensed, the node waits for the transmission in progress to end before initiating its own transmission. In different phases, CSMA is based totally on the principle "sense before transmit" or "listen before talk".

Multiple access implies that multiple nodes may send and receive on the medium. Transmissions with the aid of one node are generally obtained by way of all other nodes linked to the medium. One of the protocol modifications is CSMA with collision avoidance which will be discussed in the Section 2.1.

Some of the types of CSMA are Nonpersistent, 1-persistent, p-persistent [23], [24].

In a nonpersistent CSMA system, when the transmitting node is ready to transmit data, it senses the transmission medium for idle or busy. If idle, then it transmits straightaway. But, if busy, then it waits for a random period of time before repeating the whole logic cycle once more [23].

In a 1-persistent CSMA system, if the transmitting node is ready to transmit, it senses the transmission medium for idle or busy. If idle, then it transmits straightaway. But, if busy, then it senses the transmission medium continuously until it becomes idle, then transmits the message (a frame) unconditionally (i.e. with probability=1).

P-persistent CSMA is an approach between 1-persistent and non-persistent CSMA access modes. If a terminal senses that the channel is idle, the probability that it will transmit a packet is p. The probability that it will delay its transmission is (1-p) [24]. The p-persistent protocol is an improvement over the 1-persistent protocol, as the start of a terminal's transmissions can be randomly delayed, thereby reducing the likelihood of message collisions.

1.8 IEEE 802.15.6 Standard

The IEEE 802.15.6 standard is the most recent global international standard for Wireless Body Area Network (WBAN).

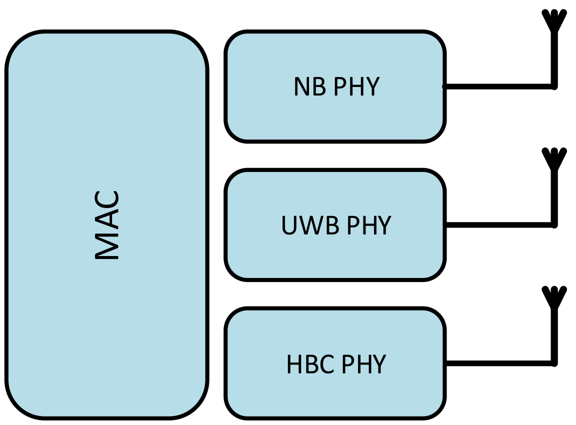


Figure 3. IEEE 802.15.6 MAC and PHY layers [25]-[26].

The IEEE 802.15.6 standard [25] describes a MAC layer that backs some physical (PHY) layers [26]-[28], which include Narrowband (NB), Ultra-wideband (UWB), and Human Body Communications (HBC) layers, of which UWB and HBC are compulsory, as represented in Figure 3. The best possible selection of PHYs or frequency bands has remained one of the essential issues to be considered in the improvement of WBANs [26], [32].

For the most part, the available frequencies for WBANs are regulated by communication authorities in various countries. Figure 4 shows the available frequency bands for WBANs [27].

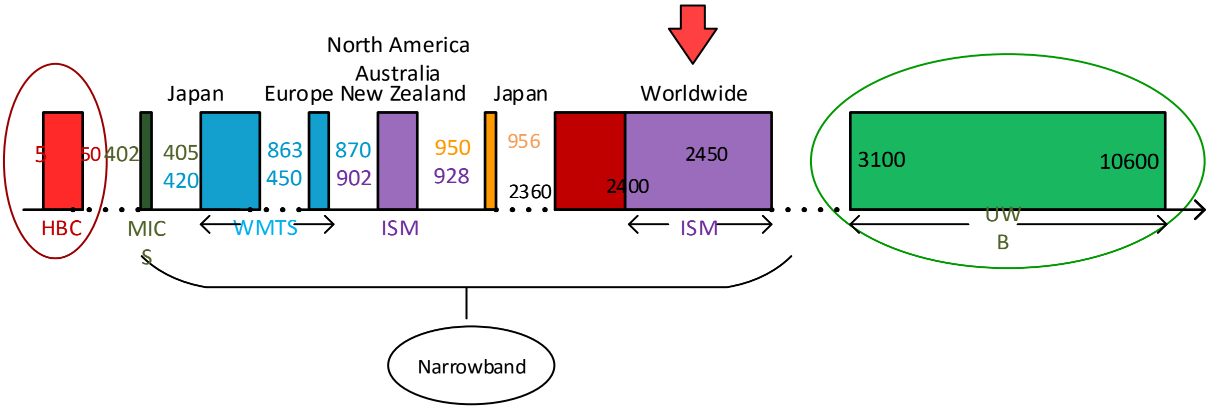


Figure 4. IEEE 802.15.6 frequency bands [23]-[27].

1.8.1 IEEE 802.15.6 MAC Specifications

Going by the IEEE 802.15.6 standard [26]-[32], the nodes are arranged into one- or two-hop star WBANs. A single coordinator or hub controls the whole operation of each WBAN. The WBAN must have one hub and a number of nodes, ranging from zero to n (where n is dependent upon the application area). In a two-hop start WBAN, a relay-capable node may be used to interchange data frames between a node and the hub. The standard splits the time axis or channel into beacon periods or superframes of the same length. Each superframe comprises a number of allocation slots that are used for data transmission. These slots have the same duration and are numbered from 0 to s, where $s \leq 255$. The hub transmits beacons to describe the superframe boundaries and allocate the slots. As for nonbeacon modes, the superframe boundaries where beacons are not used are utilized by polling frames. In general, the hub transmits beacons in each superframe with the exception of those that are inactive. The hub possibly will shift or rotate the offsets of the beacon periods, as a result shifting the schedule allocation slots.

The subsequent sections present the MAC frame format, communication modes, in addition to access mechanisms described in the IEEE 802.15.6 standard.

1.8.2 IEEE 802.15.6 MAC Frame Format

Figure 5 illustrates the general MAC frame format [29] made of a 56-bit header, variable length frame body, and 18-bit Frame Check Sequence (FCS). The frame body has a maximum length of about 255 octets. And 32-bit frame control has the MAC header, with an 8-bit recipient Identification (ID), sender ID of 8-bit and 8-bit WBAN ID fields. Together with the type of frame, the frame control field carries control information, i.e, beacon, acknowledgement, or other control frames. The recipient and sender ID fields comprise the address information of the recipient and the sender of the data frame, in that order. The WBAN ID contains information on the WBAN in which the transmission is active. The first 8-bit field in the MAC frame body carries message freshness information necessary for nonce construction and replay detection. Data frames are being carried by the frame payload field, and the last 32-bit Message Integrity Code (MIC) carries information about the legitimacy and reliability of the frame.

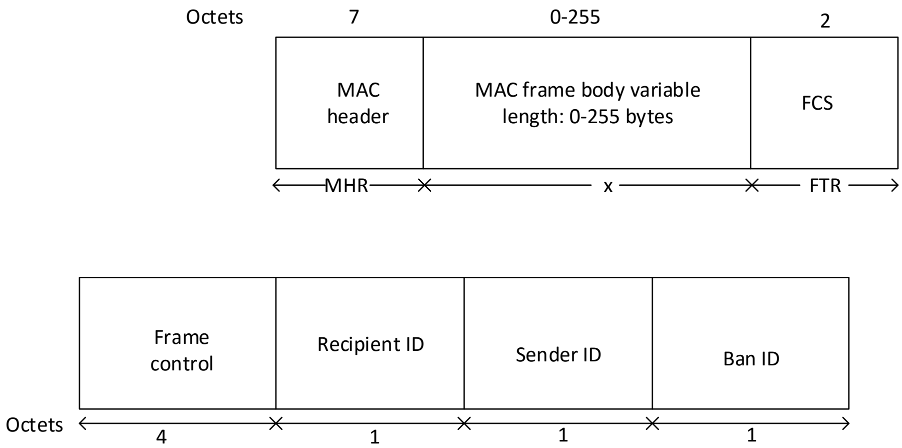


Figure 5: MAC frame format [29].

1.8.3 IEEE 802.15.6 Communication Modes

The IEEE 802.15.6 supports the following accompanying communication modes [27].

Beacon Mode with Superframe Boundaries

In this mode, the hub transmits beacons in active superframes, which may be followed by several inactive superframes at any time since there is no scheduled transmission. Figure 6(a) showed the superframe structure is divided into exclusive access phases (EAP1 and

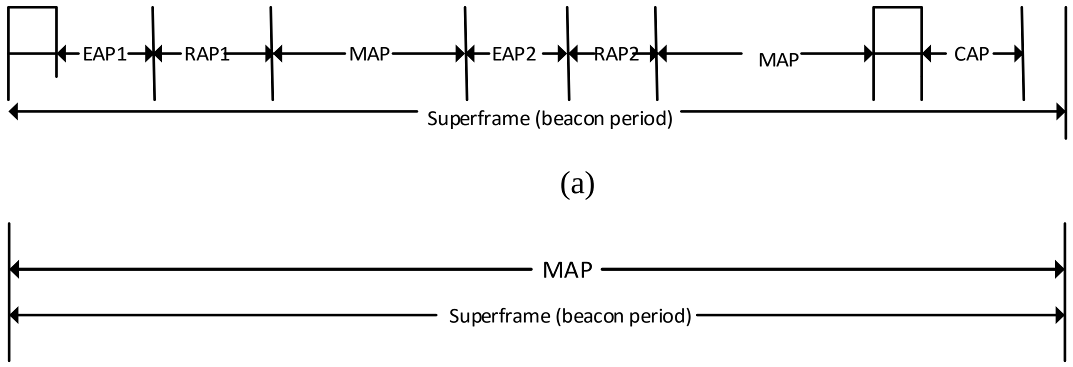
EAP2), random access phases (RAP1 and RAP2), a managed access phase (MAP), and a contention access phase (CAP). Transferring of high-priority or emergency traffic is done by the EAPs. For nonrecurring traffic, RAPs and CAP are used. The MAP period is used for scheduled and unscheduled bilink allocations, scheduled uplink and downlink allocations, and Type I (not Type II) polled and posted allocations. The length of Type I and Type II allocations is represented in terms of the transmission time and number of frames, respectively.

Nonbeacon Mode with Superframe Boundaries

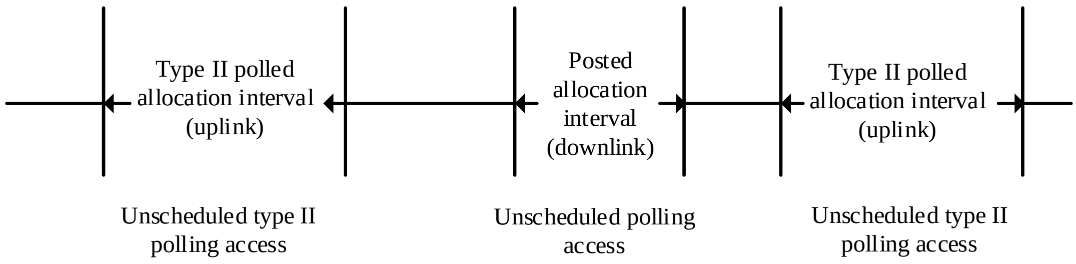
In this mode, as outlined in Figure 6(b), the hub functions during the MAP period only.

Nonbeacon Mode without Superframe boundaries

In this mode, as represented in Figure 6(c), the hub make available unscheduled Type II polled or posted allocations or a combination of both,



(b)



(c)

Figure 6. IEEE 802.15.6 communication mode [27]: (a) Beacon mode with superframe boundaries, (b) Nonbeacon mode with superframe boundaries, (c) Nonbeacon mode without superframe boundaries.

1.8.4 IEEE 802.15.6 PHY Specifications

Three operational PHYs are supported by IEEE 802.15.6, two of which are obligatory and one of which is non-compulsory. The two obligatory PHYs are UWB and HBC PHYs, while the NB PHY is considered non-compulsory. In IEEE 802.15.6, PHY is accountable for (1) the activation and deactivation of the radio transceiver, (2) clear channel assessment, and (3) data reception and transmission [28].

1.9 IEEE 802.15.6 CSMA/CA

This thesis concentrates on a superframe (SF)-based MAC layer: the coordinator periodically broadcasts beacon frames, which characterizes the query of the situation, for synchronization and maintenance of the network. The period of time between two consecutive beacons is known as SF. The SF shall be composed of several different phases [27]. The EAP is used merely for the transmission of emergency data; in RAP and CAP, the nodes use CSMA/CA or Slotted ALOHA protocols and in the MAP the coordinator may ascribe the resources, in terms of time, to specific nodes. Only RAP1 is obligatory. This work examines the CSMA/CA which works as follows. At the point when a node has a data frame to be transmitted, it should set its backoff counter to a sample of an integer random variable uniformly distributed over the interval [1, W], where W is the contention window value initialized to W_{min}, which relies on upon the user priority (UP) allotted to that frame as illustrated in [[30], Table 20]. The node decreases the backoff counter by one toward the end of each CSMA/CA slot if the channel has been idle for pCCATime (clear channel assessment of duration time) = 315 μs at the beginning of the slot [27], [30]. The frame is transmitted when the backoff counter got to zero and there is sufficient time in the present access phase to complete the full transmission. If the channel is discovered busy as a result of other nodes transmission, the node locks its backoff counter until the channel is found idle. The *W* value is doubled at even number of consecutive failures, until it gets to W_{max} [27][30].

1.10 Model for inspecting the performance of the CSMA mechanism of IEEE 802.15.6.

The substantial model comprises of three inter-related sub-models: Markov chain sub-model [38], sub-model of backoff durations, and queuing sub-model. The most significant parameters are presented in Table 2.

Table 2. Significant parameter representation (k denotes user priority for a node) [38].

Parameter	Description	Parameter	Description
K	Index of UP	σ_k	Probability that neither a data frame nor its ACK is corrupted by noise
n_k	Umber of nodes of UP_k	λ_k	Data frame arrival probability during a CSMA slot
T_k	Medium access probability	gk	Probability that medium idle during backoff countdown
$L_{k,s}$	Successful data frame transmission time	$L_{k,c}$	Unsuccessful data frame transmission time
$L_{k,so}$	Mean successful data frame transmission time of other node	$L_{k,co}$	Mean unsuccessful date frame transmission time of other nodes
η_k	Probability of successful medium access	p_k	Probability that there is not enough time to complete a date frame transmission from the current CSMA slot to the end of the RAP1 period
$\pi^{I}_{k,o}$	Probability of an empty queue after serving a data frame	$p_{k,Idle}$	Probability of being in the idle state in a CSMA slot

Parameter	Description	Parameter	Description
$p_{so,k}$	Probability of a successful transmission by the other node	$p_{co,k}$	Probability of an unsuccessful transmission by the other node
$\phi_k(z)$	PGF for waiting time for a data frame	$\pi_k(z)$	PGF of steady state probability distribution of number of frames in the queue after completing data frame service
ω_k	Mean waiting time for a data frame	ς_k	Mean response time for a data frame
R	Maximum retransmission limit		

In each of the three sub-models mentioned above, we can think in such a way that a node of UP_k has a single queue of user priority k. (In all successive discussions, we assume that k = 0...7, unless if not indicated.)

The network, operating in 2.4 GHz ISM band, is presumed to be single hop including a hub as the coordinator and n_k nodes of UP_k and as a result we pay no attention to the hidden terminal problem [38]. We assume that there is only uplink traffic from the nodes to the hub. Let λ_k represent the data frame arrival probability during a CSMA slot for a node of UP_k. Then assume that during a slot at most one data frame arrives to the queue which is not an unrealistic assumption due to the small length of a CSMA slot. It is clear that the inter-arrival time I_k is geometrically distributed with the mean of $\frac{1}{\lambda_k}$ slots. The lengths of EAP1 and RAP1 in slots are represented with eap and rap, respectively [31]. Then assume that the size of the beacon is small; hereafter we pay no attention to it in the model.

The control frames and headers are transmitted at 91.4 kbps [31] despite the fact we assume the payload of the data frames is transmitted at 971.6 kbps. The size of the data frames for a node of $UP_k$is denoted by I_k (in slots) and $I_{k,b}$ (in bits), while ack and ack_b represent the size of an ACK frame in slots and in bits, in that order [31].

Then assume an error-prone channel having the bit error rate (BER) of ber, in which case $\sigma_k = (1 - ber)^{l_{k,b}+ack_b}$ represents the probability that the data frame and the conforming acknowledgement are transmitted devoid of getting corrupted by the noise.

Markov Chain Sub-model [38]

The mathematical description of the Markov Chain Sub-model is beyond the scope of this thesis. It is available in [38].

1.11 IEEE 802.15.6 CSMA/CA Mechanism

The flow chart presented in Figure 7 illustrates the IEEE 802.15.6 standard. The node starts its back-off counter (BC) to a random integer that is evenly distributed over the interval [1, CW], in which CW denote the contention window [29]. The value of CW is decided by the UP described in the standard; in spite of that, for easiness and without loss of generalization, they are not taken into consideration in this dissertation. The node decreases BC by one for each idle CSMA slot with length equal to L_{CSMA}. Remind that the node allows a CSMA slot to be idle, if it ascertains that the channel has been idle for less than clear channel assessment (T_{CCA}) after the onset of the CSMA slot. After which the T_{CCA} expires, the node decreases the BC. If there is not adequate remaining time for a transmission in the CAP, the counter locks until the next CAP [29]. Furthermore, if the node notices a busy channel owing to another frame transmission, the counter locks until the channel is idle. The BC unlocks when the channel has been idle for a short interframe space period (pSIFS) within the CAP and the time duration from the current time with a CSMA slot to the end of the CAP is long in an adequate amount for carrying out a frame transmission. As soon as the BC gets to zero, the node transmits the frame at the end of the CSMA slot. If the node does not obtain an acknowledgment (ACK) for this transmission, a failure occurred. The CW is doubled for an even number of failures (R) and the process is repeated. If the new CW surpasses a maximum value (CWmax), the node sets the CW to CWmax. However, it is vital to say that if the number of failures exceeds an upper limit of repeats, which is equal to Rmax, the transmission has failed and the frame is dropped [32].

Most of these studies are centered on theoretical models to derive analytical expressions of quality metrics (see for example [30]-[32] and references therein).

In Figure 7 “Y” stands for “Yes”, “N” for “No” and UP for user priority, respectively.

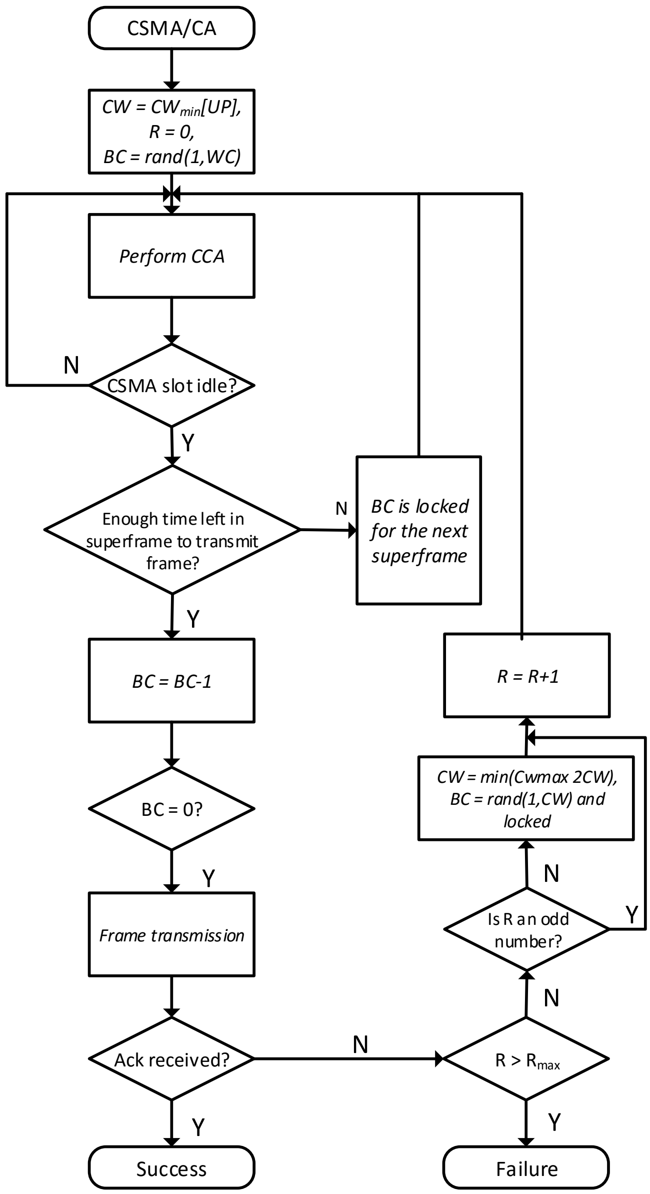


Figure 7. IEEE 802.15.6 CSMA/CA mechanism [31]-[33].

This chapter has given an overview of WSNs, BANs as well as a review of CSMA. The next chapter further explores multiple access techniques.

2 Introduction to Multiple Access Techniques

Channel access mechanisms delivered by the MAC layer are likewise stated as multiple access techniques. For this reason, it is possible for many stations associated to the same physical medium to share it. Different types of networks use multiple access techniques. And each technique is utilized by necessity. In this dissertation, I am relating the activities of different multiple access techniques with change in throughput, delay and offered load. I have plotted them considering three scenarios:

- Throughput as a function of delay;
- Offered load as a function of delay;
- Offered load as a function of throughput.

2.1 CSMA/CA

The extended version of CSMA is CSMA/CA [33]. Collision avoidance is utilized to improve the performance of CSMA by not permitting a node to send data if other nodes are transmitting. In a typical CSMA case, the nodes sense the medium, if they discover it free, and this then leads to a collision if they transmit the packet without observing that a different node is already sending the packet. CSMA/CA is recommended for among other things to improve the probability of collision CSMA/CA was suggested, which results in the enhancement of collision probability [33].

The CSMA/CA functionality is described with the flow chart shown in Figure 8. For each node it is first needed to sense the channel, and as soon as channel is free, the node sends a RTS (Request to Send) packet to the proposed destination; if the channel is busy, the node goes to back-off timer. The node waits for SIFS (Short Inter Frame Space) time after sending the RTS packet node. The node waits for SIFS time if CTS (Clear To Send) is successfully received, or else it goes to back-off time. The node looks for the medium to get free in the back-off time state [33]. Once SIFS time has elapsed, the node start transmitting data packets towards the destination node, then the node waits for SIFS and looks for successful reception of ACK (Acknowledgment) packet from the destination node. Then the node looks for available data packets if ACK packet is successfully received. The node returns to back-off timer state if ACK is not received which results in a collision. The node ends the communication once there are no data packets to be sent. But, if data packets are to be sent, the node once more looks for the medium to get free and these procedures start again for every data packet [33].

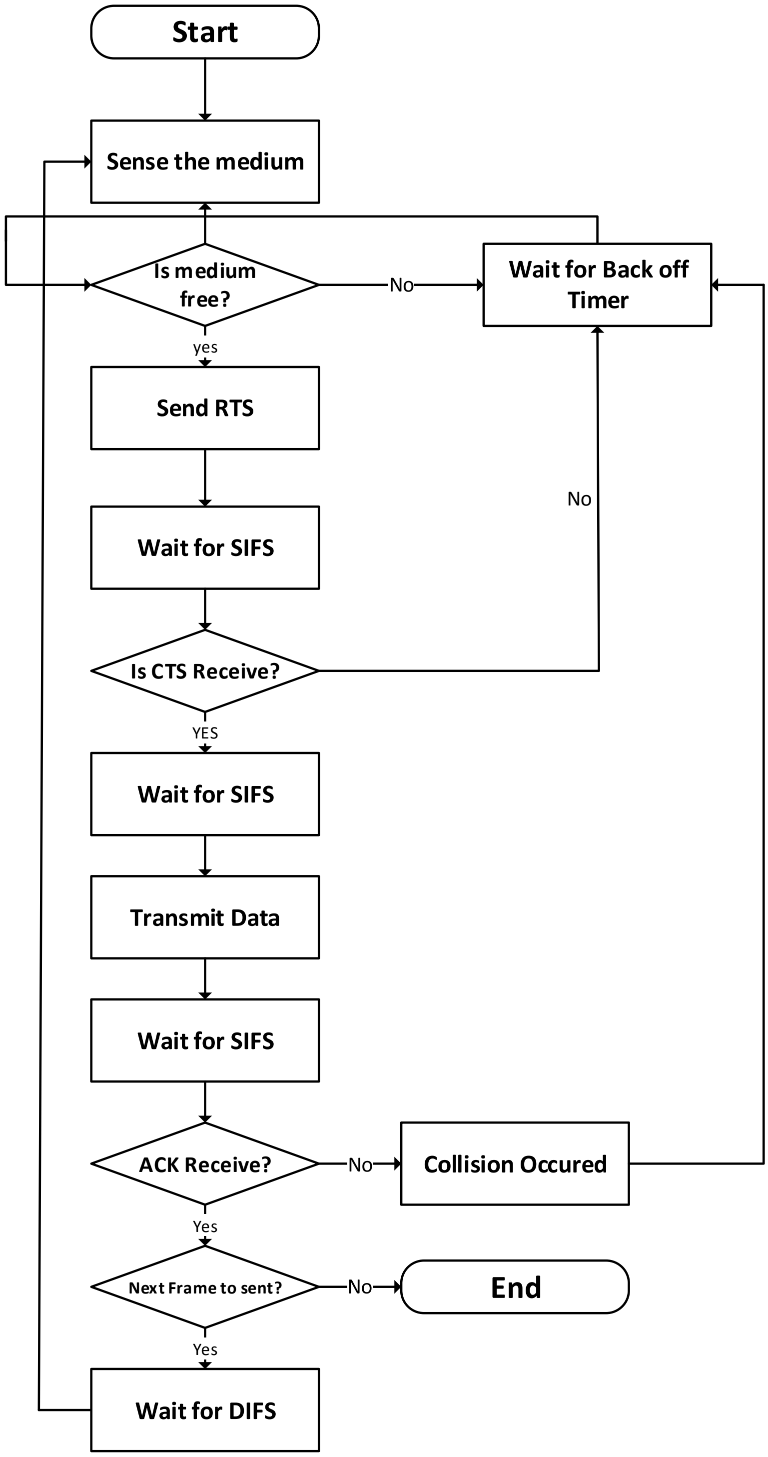


Figure 8. Flow chart of CSMA/CA. Based on [30], [33].

2.2 TDMA

The rules of dividing the time frame in dedicated time slots are the process performed by TDMA. One after the other, individually each node sends data in quick sequence in its own time slot. One of the important aspects used while applying TDMA is synchronization. It uses full channel width, allocating it into two alternating time slots. Owing to less collision and no idle listening, TDMA utilizes less energy than others and its protocols are more power efficient [34]-[35] compared to multiple access protocols because the nodes transmit only in assigned time slots and all the other time are in inactive state [36].

The flow chart for TDMA is shown in Figure 9. In TDMA, first each node is allocated a specific time slot needed for its transmission. Amid source node and destination nodes, synchronization is carried. The node looks for its specific time slot and transmits data packets in its appropriate time slot, or else waits for its relevant time slot. The communication ends if packets are not available for transmission. Or else, the node looks for availability of slot and this procedure repeat until communication ends [34]-[35].

2.2.1 FDMA

FDMA is a simple technique used in e.g. analog Advanced Mobile Phone Service (AMPS). Individually, each channel can be allotted to only one user at a time through FDMA. Individually, the nodes share medium simultaneously, all transmit at a single frequency. Both analog and digital signals are used by FDMA [34]-[36].

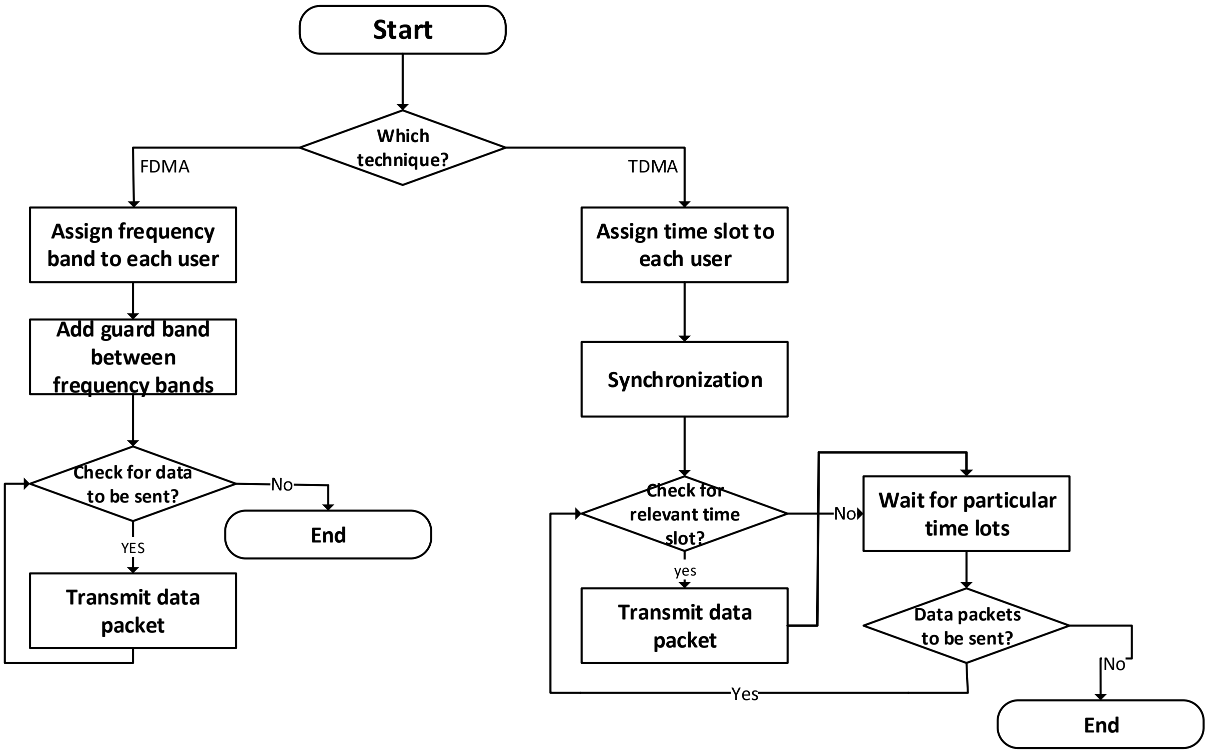


Figure 9. Flow chart of FDMA and TDMA [34].

2.3 Mathematical modeling of throughput for Multiple Access Techniques

The throughput of different multiple access techniques are considered in this section (based on [39]). And using one of the procedures, data is transferred from sender to receiver, and the throughput resulting from these procedures is considered. There are no packet losses as a result of collision due to less difference between sender and receiver; no packets are lost as a result of buffer overflow. A perfect channel is being assumed for the calculation of throughput. Through the following equations, throughput is calculated for all access techniques (1):

$$T = \frac{8.x}{\text{delay}(D)(x)} \quad (1)$$

Where D is the delay, T the throughput, and x the number of bits passing through the frame.

2.3.1 Throughput of TDMA

By using (1), throughput is calculated. Delay with a packet as it circulates from sender to destination is calculated as per (2) [39]:

$$D = T_{oh} + T_{ack} + T_g + T_{sync} + T_{ta} \quad (2)$$

The different time delays are given in (2) and can be calculated by (3-6):

$$T_{oh} = \frac{N_{oh}}{f_c} \quad (3)$$

$$T_{ack} = \frac{N_{ack}}{f_c} \quad (4)$$

$$T_{sync} = \frac{N_{syn}}{f_c} \quad (5)$$

$$T_{data} = \frac{N_{data}}{f_c} \quad (6)$$

where

T_{sync} is the synchronization time,

T_{data} is the time for data to reach end of frame,

T_{ta} = Turnaround Time,

T_{ack} = Acknowledgement time,

T_{oh} = OverHead time,

T_g = Guard time,

f_c = Communication Data Rate,

N_{oh} = Total overhead bits,

N_{ack} = ACK/NACK message bits,

N_{syn} = Total synchronized bits,

N_{data} = Total data bits.

2.3.2 Throughput of FDMA

The throughput of FDMA is close by to that of TDMA. The difference between throughputs of the two multiple access technique is very small. And by (1) the calculation for the throughput of FDMA and the delay which it experiences is calculated as per (7) [39]:

$$D = T_{oh} + T_{ack} + T_g + T_{ta} + T_{data} \quad (7)$$

In (7), the different time delays given can be calculated as per (8-10):

$$T_{oh} = \frac{N_{oh}}{f_c} \quad (8)$$

$$T_{ack} = \frac{N_{ack}}{f_c} \quad (9)$$

$$T_{data} = \frac{N_{data}}{f_c} \quad (10)$$

where

$T_{data}$is the time for data to reach end of frame,

T_{ta} = Turnaround Time,

T_{ack} = Acknowledgment time,

T_{oh} = OverHead time,

T_g = Guard time,

f_c = Communication Data Rate,

N_{oh} = Total overhead bits,

N_{ack} = ACK/NACK message bits,

N_{data} = Total data bits.

2.3.3 Throughput of CSMA/CA

By the formula given in (1), the CSMA/CA throughput is calculated. By adding the delays of all elements of frame while it gets to the receiver, as per (11) [39], the total delay D is calculated:

$$D = T_{bo} + T_{data} + T_{ta} + T_{ack} + T_{ifs} + T_{rts} + T_{cts} \tag{11}$$

where

T_{bo} is the Back Off Period,

T_{rts} = Resquest To Send,

T_{cts} = Clear To Send,

T_{data} = Transmission Time of Data,

T_{ta} = Turnaround Time,

T_{ack} = Acknowledgment Transmission Time,

T_{ifs} = Inter Frame Space.

Now we calculate the delay times given in (11) as:

$$T_{bo} = bo_{slots} + T_{boslots} \tag{12}$$

$$T_{ta} = T_{data} + T_{ack} \tag{13}$$

where bo_{slots} is the Back off slots number and $T_{boslots}$ the off slots time. Further,

$$\mathrm{T_{ack}} = \frac{\mathrm{N_{ack}}}{\mathrm{f_c}} \tag{14}$$

$$\mathrm{T_{ifs}} = \mathrm{T_{data}} - \mathrm{T_{ack}} \tag{15}$$

where

f_c is the Communication Data Rate, N_{ack} the ACK/NACK message bits, and Turnaround times $T_{turnaround}$ and T_{ack} are equal to zero if there is no acknowledgement.

3 Simulated Performance Evaluation

Scenario

In this section we assess the performance of the CSMA/CA mechanism when it is being run under different number of nodes bearing in mind the IEEE 802.15.6 standard [40] parameters and specifications. The goal behind this work is to model a physical layer (PHY). This model depends on the method of Krishnamachari and Zuniga [41], [42] and the MATLAB model “PhyModel” implements the calculations at the PHY level and decides the probability of good frame reception towards channel (signal-to-noise ratio) and radio (modulation and coding) parameters. The comparison includes delay, reliability, throughput and UDP against offered load variation. MATLAB simulation tool is used in order to generate the results.

3.1 Matlab Model Inputs and Outputs

This model needs seven inputs and these inputs concern features of a node and parameters inspired and taken from [43], [44]. They are mentioned in the subsequent subsection.

3.1.1 Inputs

Like in [40], different values for the per-station offered load, λ, measured in frame/s where tested in MATLAB. The vector $lvec$ stores the offered load values. Table 3 shows the available parameters.

Table 3: Available parameters for simulating CSMA/CA

Attribute	**Description**
λ	Per-station offered load
N_stations	Number of stations
K	Station system size in frames

Attribute	Description
W0	Minimum retry backoff window maximum counter value:
data_rate	Data rate in bits/s
macMaxFrameRetries	Maximum number of frame transmission retries: (represents the maximum number of retries allowed after a transmission failure)
macMaxCSMABackoffs	Maximum number of backoff stages: (represents the maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure)
macMinBE	Minimum value of the backoff exponent in the CSMA-CA algorithm
macMaxBE	Maximum value of the backoff exponent in the CSMA-CA algorithm
L_application	Size of MAC frame payload data in bits
L_overhead	Size of overhead added in PHY layer in bits
L_ACK	Acknowledgement (ACK) frame size at PHY layer in bits
T_prop	Mean propagation delay in seconds
aUnitBackoffPeriod	Basic backoff time period used by the CSMA-CA algorithm in seconds
L0	Idle state length without generating packets in seconds
A	Coefficient to translate the frame time length to the frame slot length in bits/slot
t_IFS	Inter-Frame Space in seconds
macACKWaitDuration	Maximum time to wait for an acknowledgement frame to arrive following a transmitted data frame in seconds
aTurnaroundTime	RX-to-TX or TX-to-RX maximum turnaround time in seconds
sensing_time	Time used to detect if the channel is busy or not in seconds
sigma_s	Shadowing standard deviation in dB

Attribute	Description
p0_tolerance	Tolerance for convergence of p0

There is as well detailed inputs relation to [45] and physical layer parameters for the PhyModel function (PHY layer) as shown in Table 4.

Table 4: Inputs relation to [45] and physical layer parameters

Attribute	Description
NOISE_FIGURE	Noise figure in dB
BW	Bandwidth in Hz
PATH_LOSS_EXPONENT	Path Loss Exponent
SHADOWING_STANDARD_DEVIATION	Shadowing standard deviation in dB
D0	Standard distance to measure the effect of path loss in meters
Prdbm	Transmission power in dBm
NOISE	Average white noise in dB
Lambda	Wavelength in meters
DATA_RATE	Data rate in bits
PREAMBLE_LENGTH	Preamble length in bits
FRAME_LENGTH	Frame length in bits
Distmin	Minimum node's range in meters
Distmax	Maximum node's range in meters

3.1.2 Outputs

The outputs of the MATLAB model are more or less the same as in [40]. They recount to the following vectors:

- Mean frame service time at the MAC layer: ET

- Standard deviation of the MAC layer service time: Std_dev
- Blocking probability: P_blocking
- Probability to find a node idle: P_idle
- Probability of transmission attempt fail: P_failure
- Average number of frames in a station's system: L_value
- Channel access failure probability (equation (19) in [38]): Pcf
- Packet discarded due to retry limits probability (equation (20) in [38]): Pcr
- Alpha probability (probability of finding the channel busy during the first carrier sensing): Alpha
- Beta probability (probability of finding the channel busy during the second carrier sensing): Beta
- Probability for successful frame sending: Reliability
- Average frame delay, including waiting time on queue: D_value
- Average per-station throughput in bits/s: S_avg
- Instantaneous per-station throughput in bits/s: S_{inst}

3.2 Simulation Analysis with Results and Performance Metrics

Our analysis takes into account the CSMA/CA overall performance when it is being run under different metrics. In this section, we achieve the expressions for the important performance metrics, namely throughput and reliability; it also includes average delay or wait time of the node, and user dissatisfaction probability versus the offered load; they are represented in Figures 10, 11, 12 and 13, respectively.

By following the General Markov chain model as described in [38], probabilities are calculated, and the input parameter values set during these analyses is viewed for most relevant outputs provided by the MATLAB model are shown in Table 5 and 6. It was decided on to start from a per-node offered load equal to 0.5 frames/s and to increase this parameter by 0.5 up until attaining a load of 50 frames/s.

Table 5: Parameter values used for simulating the MAC layer

Parameters	**Value**
$N\_stations$	10

Parameters	Value
K	51 frames
$data\_rate$	19.2 kbits/s
$W0$	8
$macMaxFrameRetries$	3
$macMaxCSMABackoffs$	4
$macMinBE$	5
$macMaxBE$	3
$L\_application$	800 bits
$L\_overhead$	48 bits
L_ACK	88 bits
T_prop	222e-9 seconds
$aUnitBackoffPeriod$	320e-6 seconds
$L0$	0
A	80 bits/slots
t_IFS	640e-6 seconds
$macACKWaitDuration$	1920e-6 seconds
$aTurnaroundTime$	192e-6 seconds
$sensing\_time$	128e-6 seconds
$sigma\_s$	4
$p0\_tolerance$	e-10

Table 6: Parameter values used for simulating the PHY layer

Parameter	Value
$NOISE\_FIGURE$	23 dB
BW	30 kHz
$PATH\_LOSS\_EXPONENT$	4

Parameter	Value
$SHADOWING\_STANDARD\_DEVIATION$	4
$D0$	1 meter
$Prdbm$	5 dB
$NOISE$	15 dB
$lambda$	12.5 e-2 meters
$DATA\_RATE$	19.2 kbits/s
$PREAMBLE\_LENGTH$	40 bits
$FRAME\_LENGTH$	808 bits
$distmin$	1 meter
$distmax$	20 meter

3.2.1 Throughput

The throughput (S) of a node is defined as the number of correctly received bits divided through the total slots length (in seconds) which the node takes to transmit those bits correctly.

$$S = \frac{Number\ of\ correctly\ received\ bits}{Total\ consumed\ time}$$

Throughput against applied load is calculated by basically multiplying the probability of successful transmitted packets by applying a load of 10 nodes. The generated MATLAB simulation results shown in Figure 10 show that throughput increases up to 480 bits/application/node/s for an offered load of ca. 1250 bits/application/node. It then decreases with the increase in offered load. It can also be noted that, in this example, for an offered load above ca. 4500 bits/application/node, the throughput is even lower than for an offered load of ca. 500 bits/application/node. The overall performance in terms of throughput is as expected since we have seen previously (see Section 1.4.1.) that scaling is an issue, i.e. above a certain offered load; the system is not able to cope with the demand.

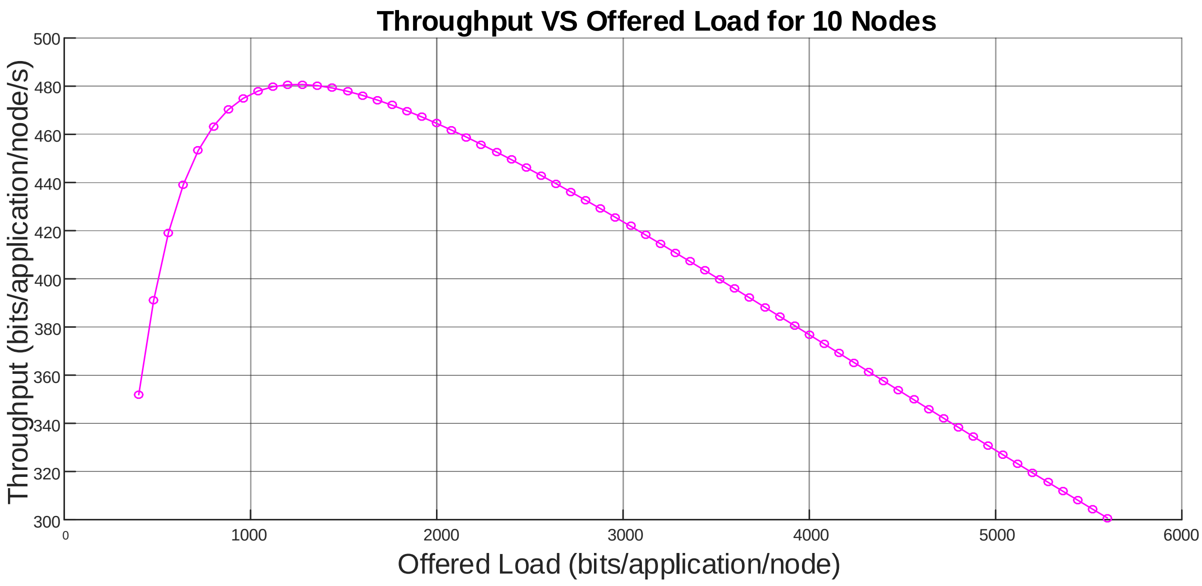


Figure 10. Simulated average per-node throughput as a function of per-node offered load for a system with 10 nodes.

3.2.2 Reliability

We explain reliability of a node as the probability of successful delivery of a transmitted packet (i.e., the number of packets at which it reached its destination successfully). However, reliability should also account for the corresponding probability with which a transmitted packet is dropped due to finite retry limits. The frame payload for each packet is thought to be the same. It can possibly be illustrated that, unlike most wireless communication protocols (as in [3]), in IEEE 802.15.6, a packet is not dropped due to channel access failure. Therefore, the reliability (R) is calculated as per (16) [40].

$$R = 1 - (Pcf + Pcr) \quad (16)$$

The generated MATLAB simulation results for reliability are shown in Fig. 11. They illustrate that reliability increases up to 0.9 for an offered load of ca. 400 bits/application/node. It then keeps on decreasing as the offered load increases. For example, it can be noticed that reliability passes below 0.5 for an offered load larger than ca. 1000 bits/application/node and below 0.3 for an offered load larger than ca. 1500 bits/application/node. The overall performance in terms of reliability is as expected, in line with the theory discussed earlier.

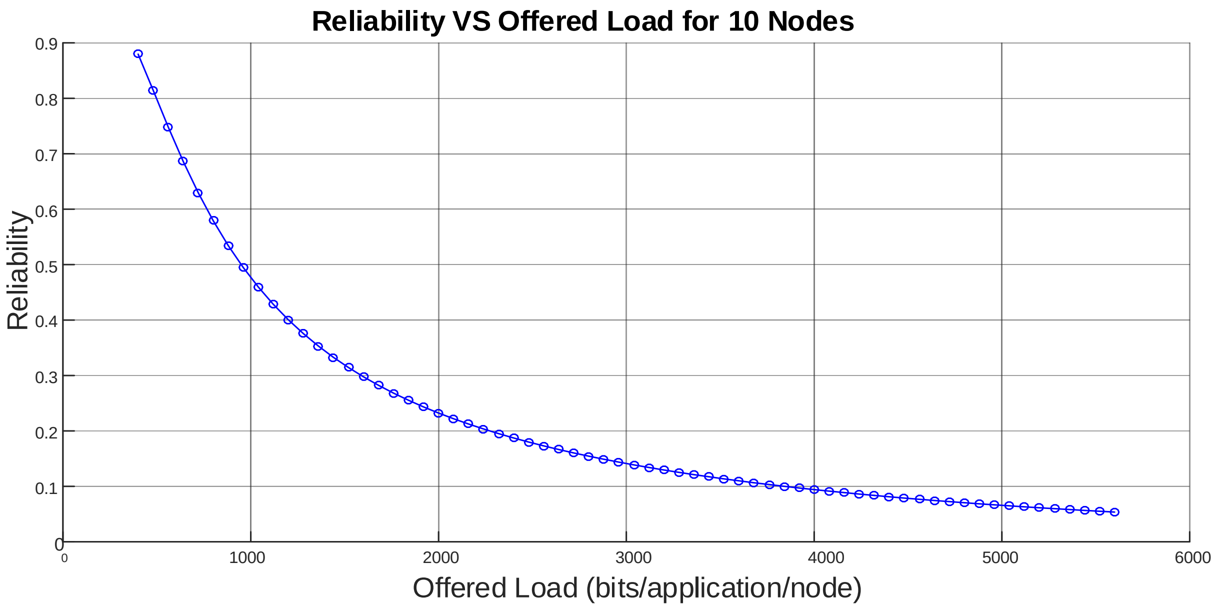


Figure 11. Per-node reliability as a function of per-node offered load for a system with 10 nodes.

3.2.3 Average Delay

Delay of a received packet is described as the interval in time from the time-instant, when for the first time, a packet moves to the head of the MAC queue and is ready to be transmitted, till the I-ACK frame for the transmitted data-packet is received [39].

The average delay consists of the total time elapsed while a node decrements its backoff counter value (until it gets to zero) in the respective backoff stages and the wait duration for the I-ACK frame. The average delay (D) required to transmit data with Acknowledgement can be expressed as per (17) [39],

$$TD = Tbackoff\ +\ Tdata\ +\ 2Tprop\ +\ Tta\ +\ Tack\ +\ Tifs \qquad (17)$$

where

$Tbackoff\ =\ node'swaitingtimeduringBackoff,$

$Tdata\ =\ Timerequiredtotransmitframe,$

$Tprop\ =\ propagationdelay,$

$Tta\ =\ TurnaroundTime,$

$Tack\ =\ Acknowledgementtime,$

$Tifs = Time\ for\ interframespace.$

The delay required for transmitting data without acknowledgement is given in (18) [39].

$$D = Tdata + Tprop + Tifs \quad (18)$$

The corresponding generated MATLAB simulation results in Figure 12 show that the average delay is about 0.08 second for an offered load of ca. 400 bits/application/node. As the offered load increases, the delay time increases as well, exceeding 0.1 second for an offered load of ca. 2000 bits/application/node and 0.2 second for an offered load of ca. 5600 bits/application/node. The overall performance in terms of delay is as expected, in line with the theory discussed earlier.

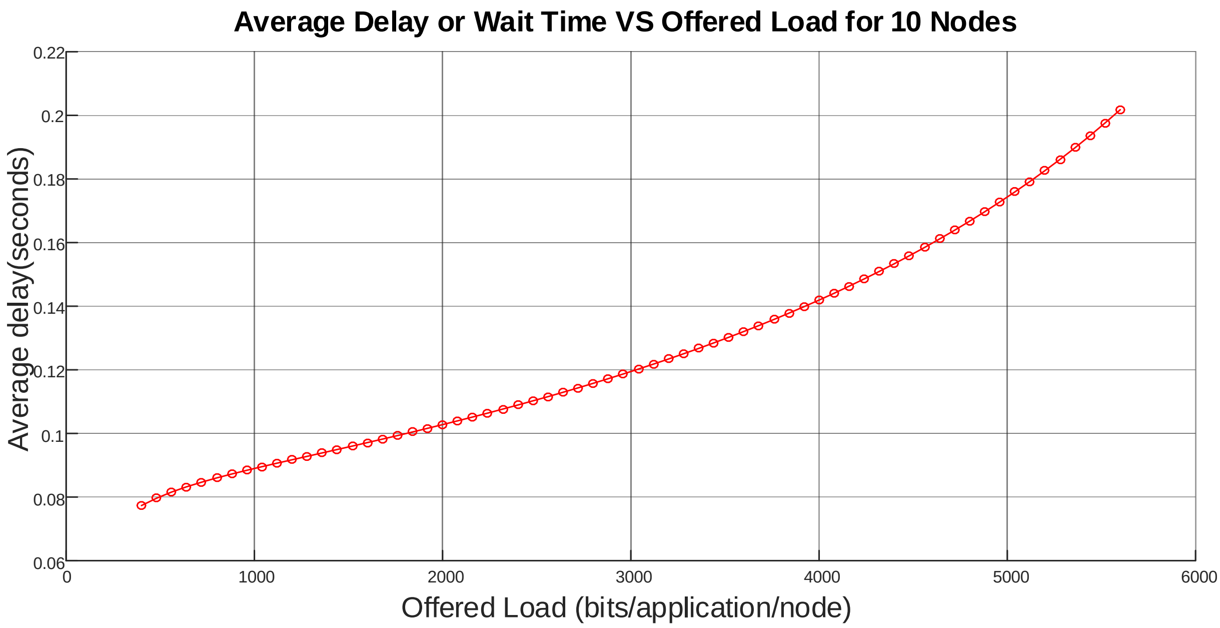


Figure 12. Average Delay per-node throughput as a function of per-node offered load for a system with 10 nodes.

3.2.4 User Dissatisfaction Probability

User dissatisfaction probability is described as the failure when node(s) could (not) find the channel idle for two sequential times within its maximum permitted backoff stages ($maxcsmabackoff$). It can be calculated as in (19) [41]-[42].

$$UDP = xm + 1(1 - yn + 1) / (1 - y) \quad (19)$$

where

UDP = User Dissatisfaction Probability,

$m = macMaxcsmabackoff$,

$x = \alpha + (1 - \alpha)\beta$,

$y = Pfail(1 - xm + 1)$.

Equation (19) shows that UDP generally relies upon the values of α, β and $macMaxcsmabackoff$.

The generated MATLAB simulation results in Figure 13 show that UDP is 0.28 for an offered load of ca. 400 bits/application/node. As the offered load increases, the UDP also increases. It reaches 0.5 for an offered load of ca. 1400 bits/application/node and almost 0.9 for an offered load of ca. 5600 bits/application/node. As for the previous metrics, the overall performance in terms of UDP is as expected.

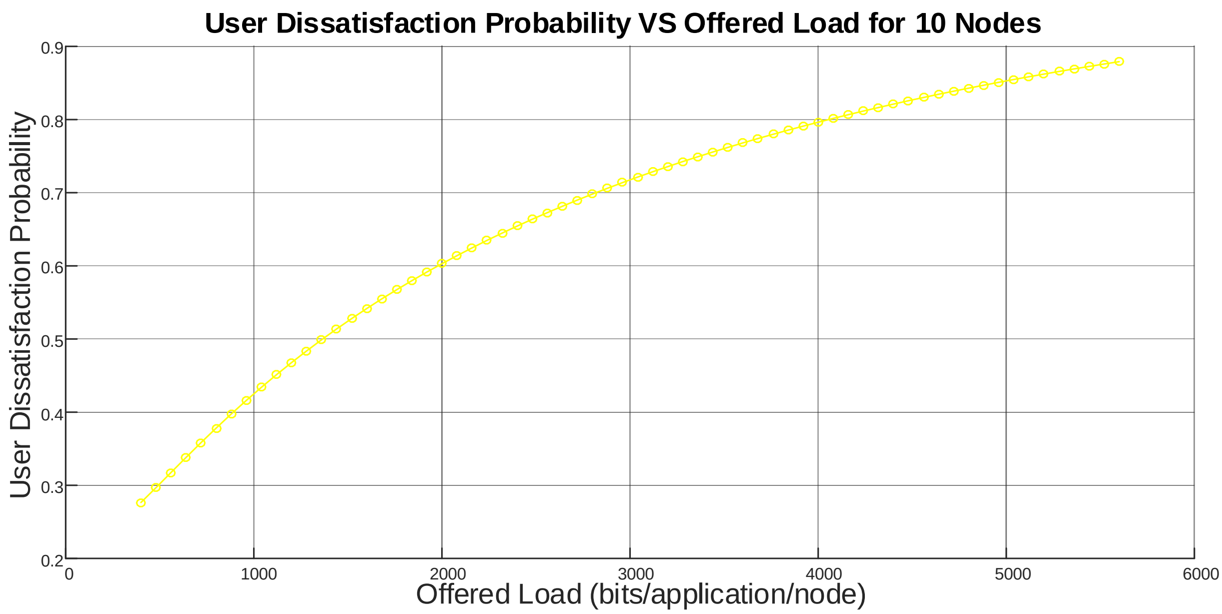
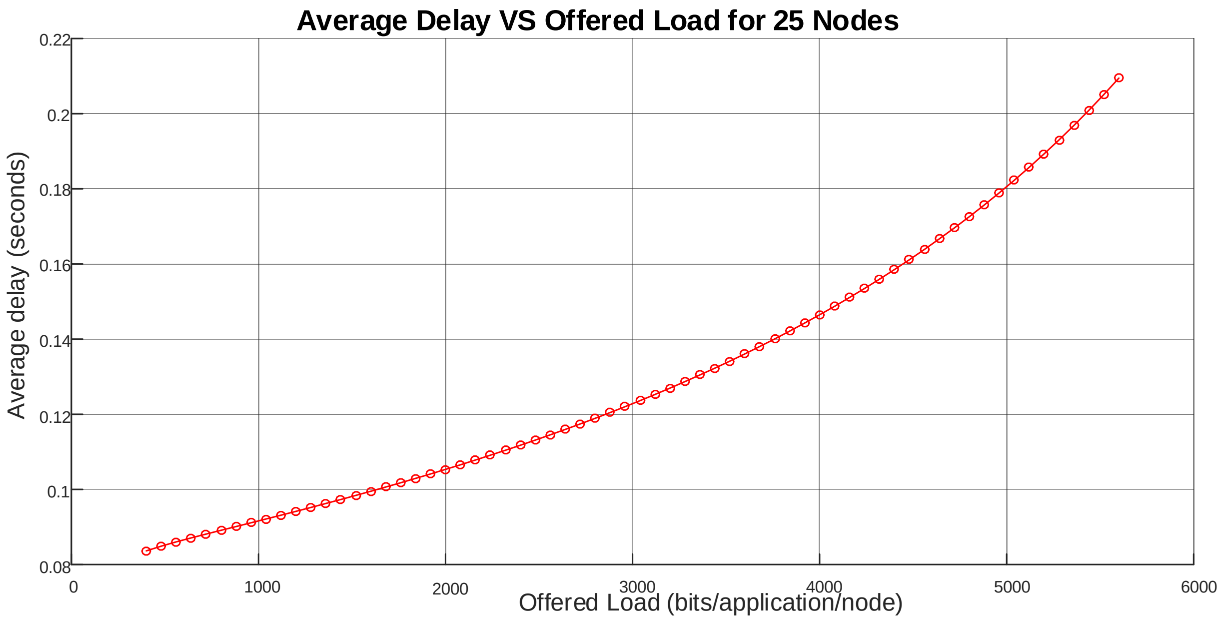


Figure 13. User Dissatisfaction Probability per-node throughput as a function of per-node offered load for a system with 10 nodes.

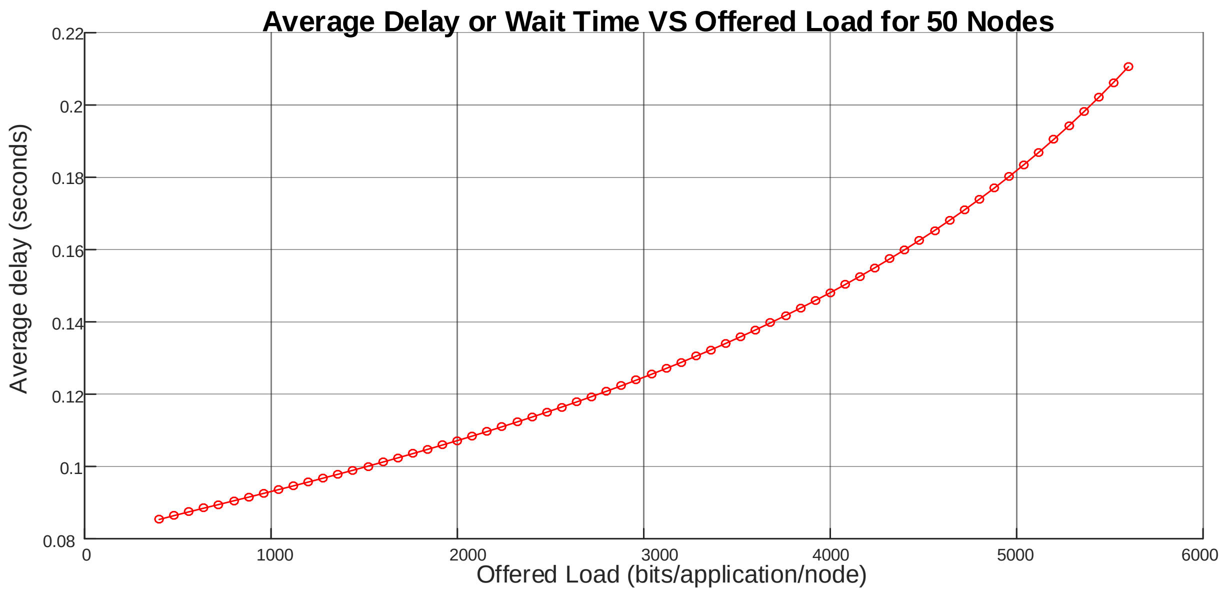
3.3 Comparison with different number of nodes

The previous results have been obtained for a relatively small (but realistic) number of nodes, i.e. 10. In order to further evaluate the scalability of such a system, the following graphs show the comparison results of the output for average delay, throughput, reliability and UDP for 25, 50, and 100 nodes, respectively.

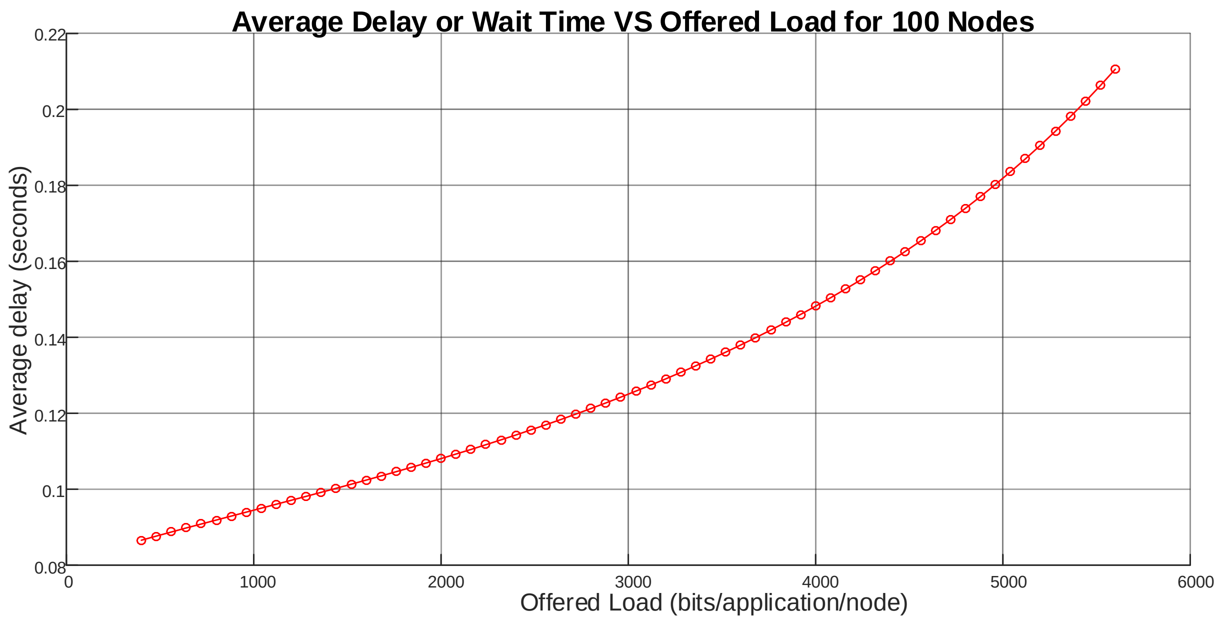
As can be seen in the generated MATLAB simulation results in Figure 14 (a), (b), and (c), the average delay for 25, 50 and 100 nodes is ca. 0.082 seconds for an offered load of ca. 400 bits/application/node for all case.



(a)



(b)

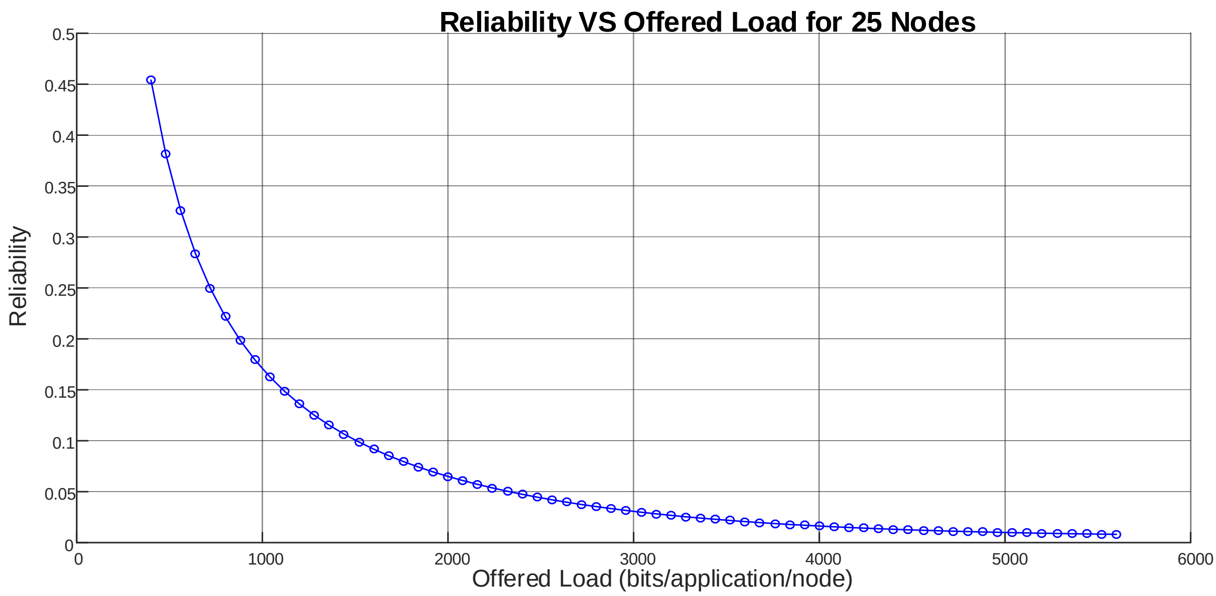


(c)

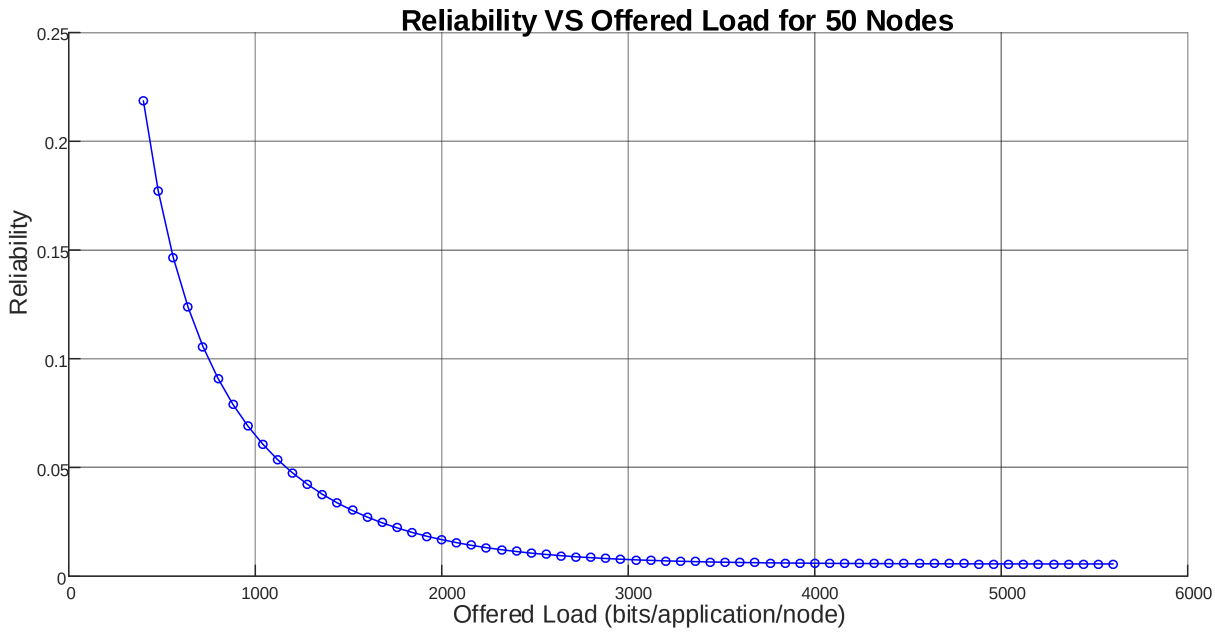
Figure 14. Average Delay per-node throughput as a function of per-node offered load for a system with (a) 25 nodes, (b) 50 nodes and (c) 100 nodes.

Furthermore, the number of nodes does not impact the shape and values of the curve proportionally as can be seen in the graphs (i.e., average delay as a function of the load conditions does not change very much even as the number of nodes is increased). All in all, the results are similar as when the number of nodes is10, as seen for the average delay mentioned in Section 3.2.3.

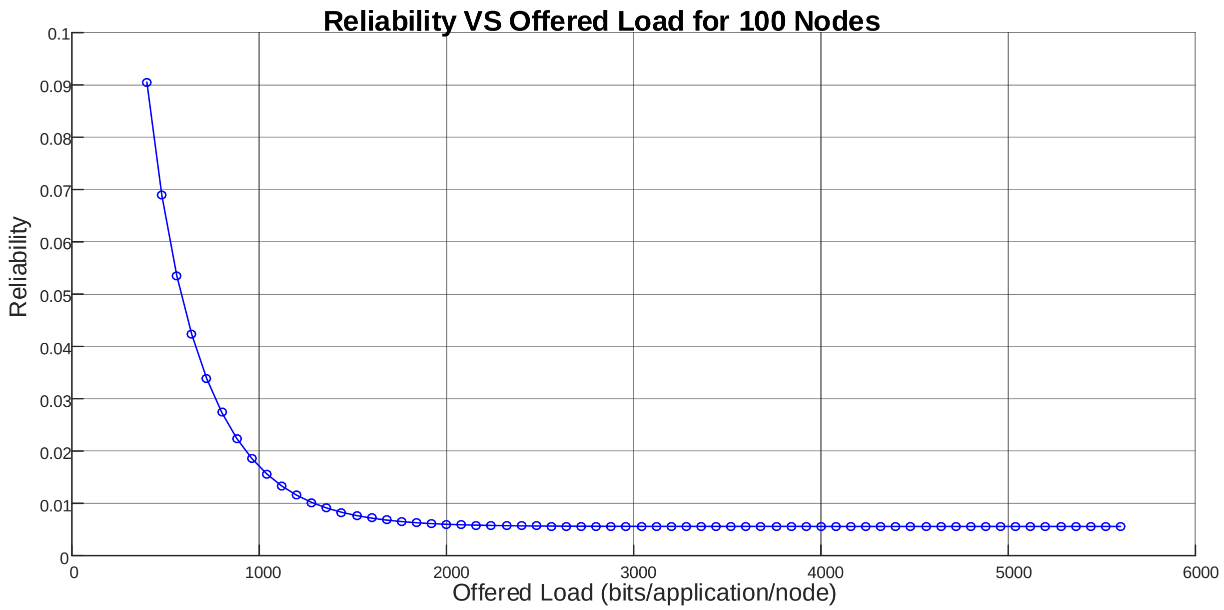
On the other hand, the generated MATLAB simulation results in Figure 15 (a), (b), and (c), show that the reliability for 25, 50 and 100 nodes is significantly impacted.



(a)



(b)

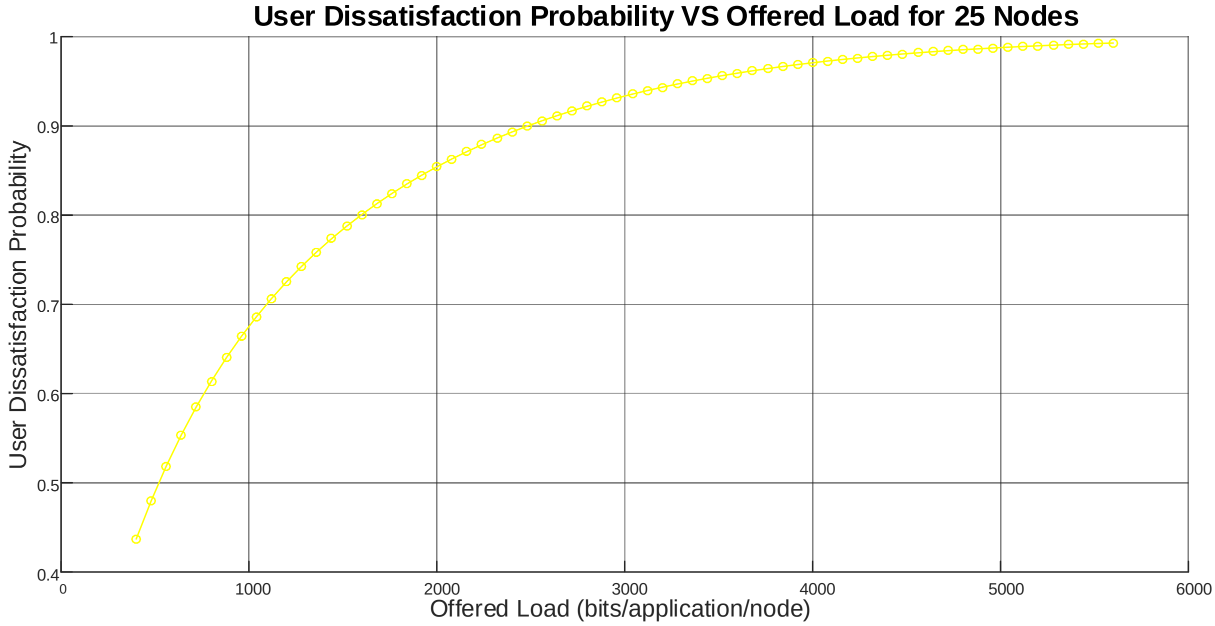


(c)

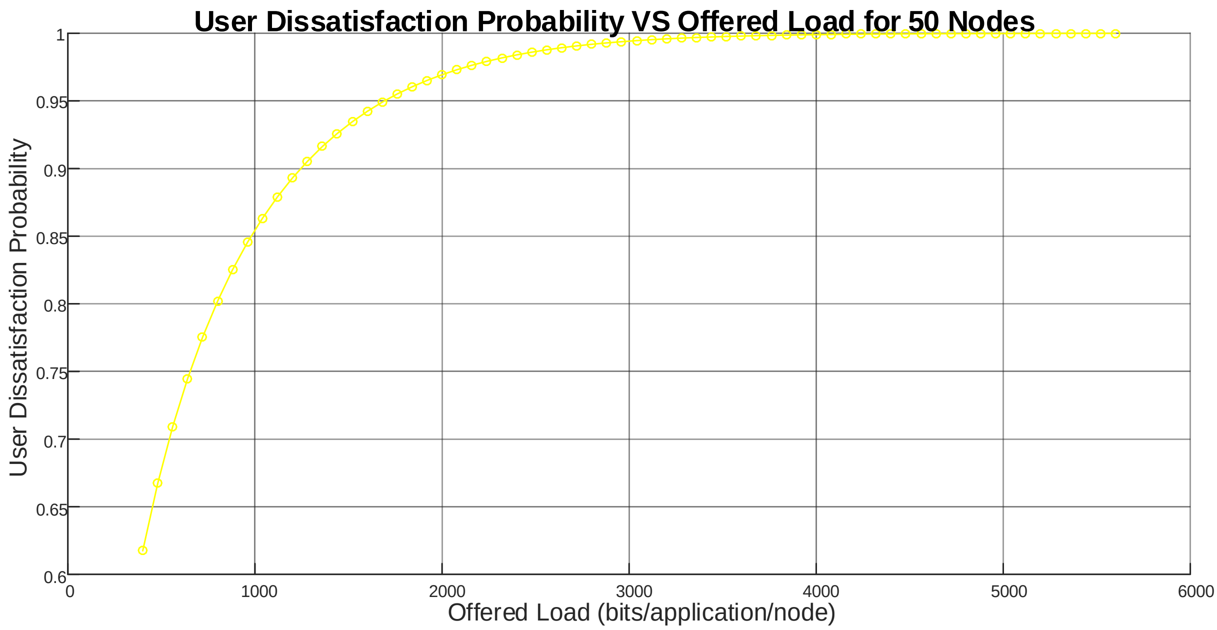
Figure 15. Per-node reliability as a function of per-node offered load for a system with (a) 25 nodes, (b) 50 nodes and (c) 100 nodes.

Whereas the reliability curves share the same trend in all cases (including for 10 nodes as shown in Section 3.2.2), the actual reliability values range from ca. 0.9 to 0.05 for 10 nodes, from ca. 0.45 to ca. 0.01 for 25 nodes, from ca. 0.22 to 0.01 for 50 nodes, and from ca. 0.09 to ca. 0.005 for 100 nodes. Those results clearly show that reliability depends on the number of nodes. For the given scenario, they also show that using more than 10 nodes might yield unacceptable performance in terms of reliability.

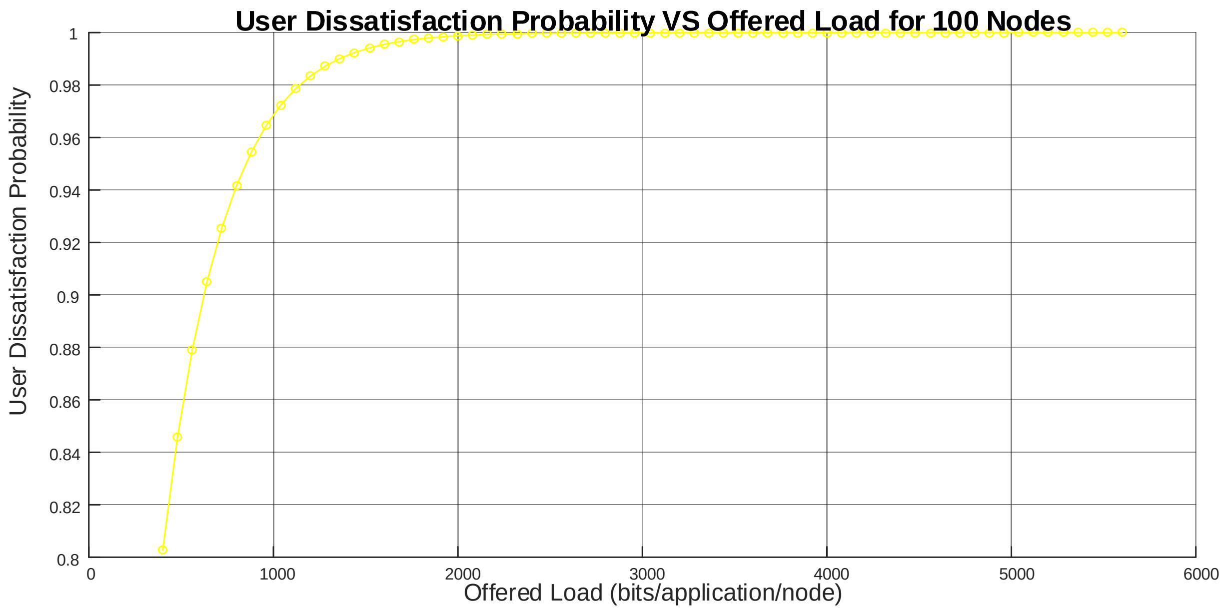
Similarly, the generated MATLAB simulation results shown in Figure 16 (a), (b), and (c) show that the UDP for 25, 50 and 100 nodes have different values.


User Dissatisfaction Probability VS Offered Load for 25 Nodes
User Dissatisfaction Probability
Offered Load (bits/application/node)
0
1000
2000
3000
4000
5000
6000
0.4
0.5
0.6
0.7
0.8
0.9
1

(a)


User Dissatisfaction Probability VS Offered Load for 50 Nodes
User Dissatisfaction Probability
Offered Load (bits/application/node)
0
1000
2000
3000
4000
5000
6000
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

(b)

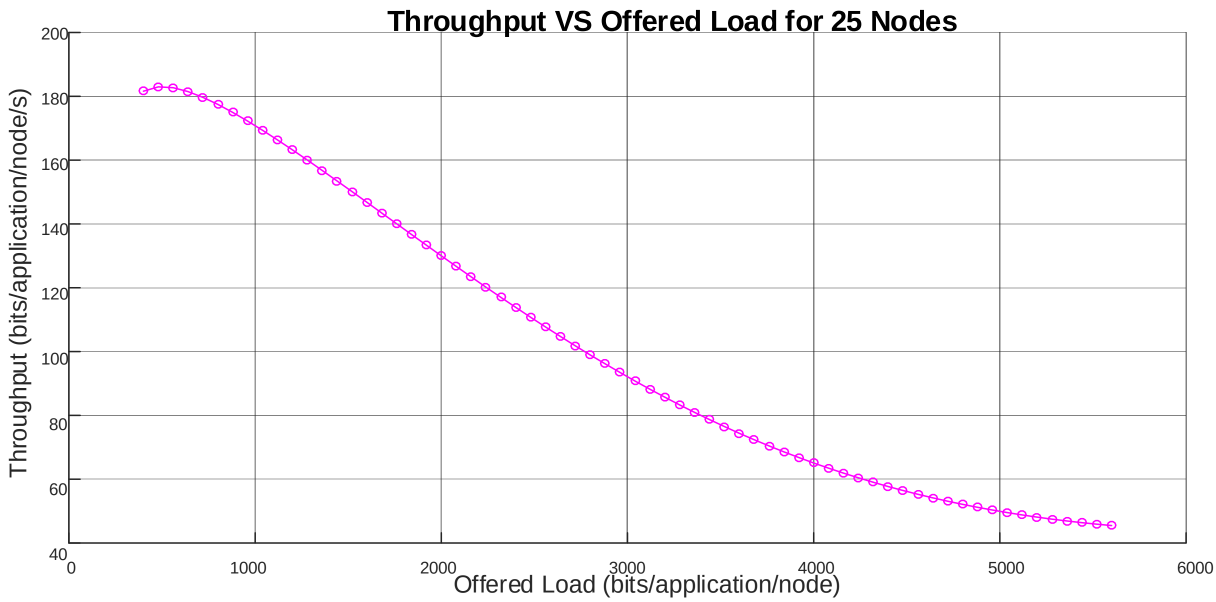


(c)

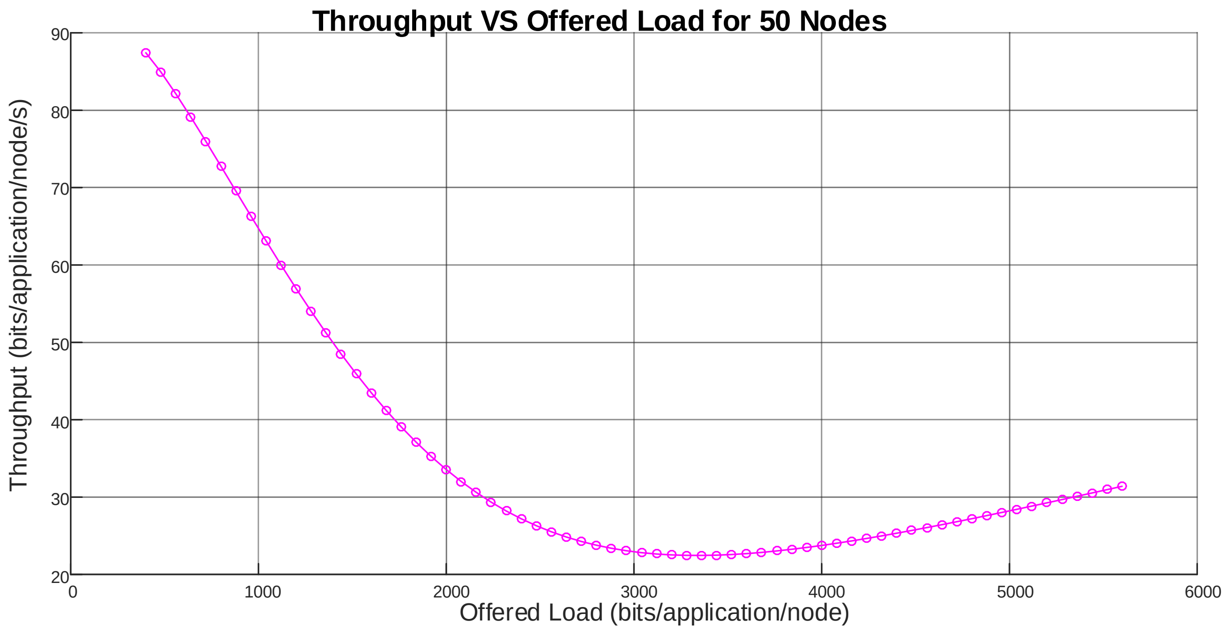
Figure 16. User Dissatisfaction Probability per-node throughput as a function of per-node offered load for a system with (a) 25 nodes, (b) 50 nodes and (c) 100 nodes.

With 10 nodes, UDP started relatively low at ca. 0.28 and slowly increased before reaching ca. 0.9. On the other hand, for 25, 50, and 100 nodes the minimum UDP values are ca. 0.44, ca. 0.61, and ca. 0.8, respectively. Furthermore, the curves are sharper and the maximum UDP values (0.9 and 1) are reached more rapidly as the number of nodes increases. The results show that the performance in terms of UDP might still be acceptable for 25 nodes, but less likely for 50 and 100 nodes.

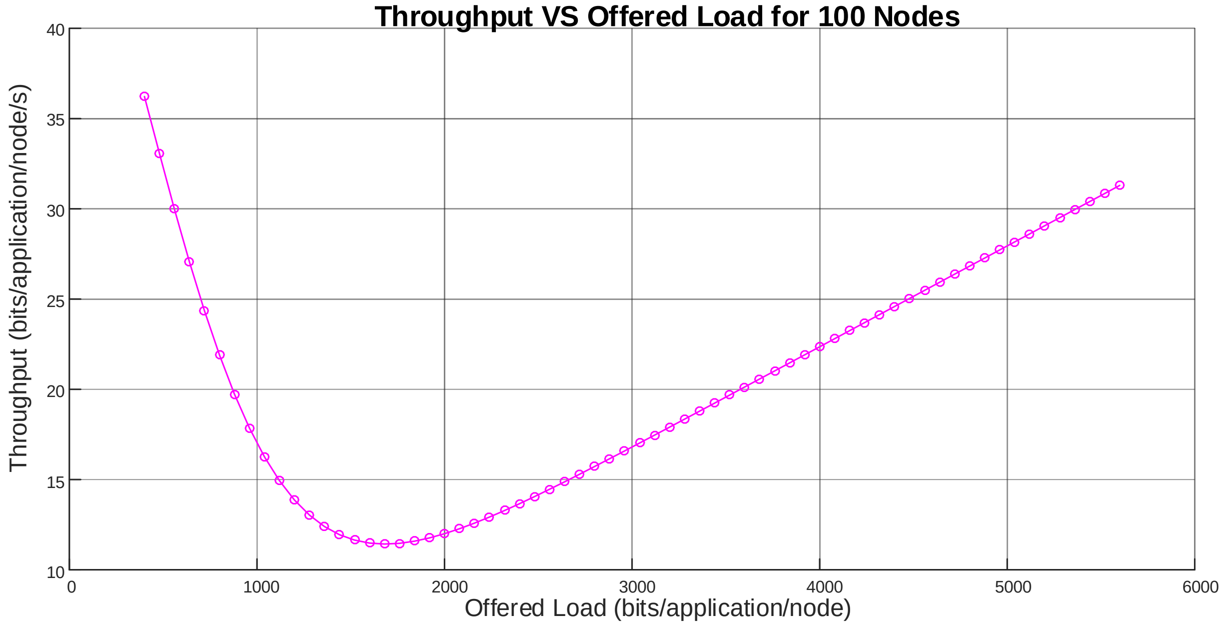
Finally, the generated MATLAB simulation results in Figure 17 (a), (b), and (c), show that throughput is significantly impacted by the number of nodes.


Throughput VS Offered Load for 25 Nodes
Throughput (bits/application/node/s)
Offered Load (bits/application/node)
200
180
160
140
120
100
80
60
40
0
1000
2000
3000
4000
5000
6000

(a)


Throughput VS Offered Load for 50 Nodes
Throughput (bits/application/node/s)
Offered Load (bits/application/node)
90
80
70
60
50
40
30
20
0
1000
2000
3000
4000
5000
6000

(b)



(c)

Figure 17. Average per-node throughput as a function of per-node offered load for a system with (a) 25 nodes, (b) 50 nodes and (c) 100 nodes.

Not only the shapes of the curves look quite different (also as compared to the case with 10 nodes), but also the ranges of values are quite different. The generated MATLAB simulation results in Figure 17 (a) show that for 25 nodes throughput increases a little bit at the beginning and then as the offered load increases, throughput decreases as well. Figure 17 (b) shows that for 50 nodes, the throughput first decreases down to 20 bits/application/node/s for an offered load of ca. 3200 bits/application/node. It then slightly increases again with the increase of the offered load. However, in Figure 17 (c), it can be noted that for 100 nodes, the throughput rapidly decreases as the offered load increases, reaching a minimum value of ca. 12 bits/application/node/s for an offered load of ca. 1600 bits/application/node. It then increases again, but for an offered load of ca. 5600 bits/application/node the throughput is lower than for an offered load of ca. 450 bits/application/node.

All in all, the results for 10 and 25 nodes show acceptable performance. However, considering the lower throughput values for 50 and 100 nodes, as well as the corresponding relatively low performance in terms of reliability and user dissatisfaction probability, the results also indicate that such a system does not scale well above 25 nodes.

4 Conclusion

4.1 Summary

In this thesis, we have studied different Multiple Access Techniques of MAC protocols that are used in Wireless Body Area Networks. We have compared techniques such as TDMA, FDMA, and CSMA/CA, showing their inner working and corresponding algorithms. Furthermore, the numerical equations for the calculation of throughput for all these techniques have been shown in mathematical modeling. Also shown is the performance metrics for the better understanding of these techniques such as reliability, throughput, delay, UDP and offered load. MATLAB simulations have been conducted to compare performance metrics such as throughput versus offered load, delay versus offered load, and reliability versus offered load and UDP versus offered load for 10, 25, 50, and 100 nodes.

At different performances stages starting from 12.5 frames/s (10000 bits/s), the network saturation is observed, and can be described by different causes, such as the low data rate that induces longer channel occupation (higher α and β probabilities), the low number of maximum backoff stages ($macMaxCSMABackoffs = 4$), and the low size of largest contention windows (32). However, when the per-node offered loads are somewhere between 1 and 12.5 frames/s (800 bits/s and 10000 bits/s), it cause the performances to change to a lower state, influencing a quick weakening of the ratio between average throughput as against offered load. Then, when the traffics are tied to a per-node offered load lower than 1 frame/s (800 bits/s), by the simulation results we can tell that the performances remain tolerable.

The results have shown that the average delay is not much impacted by the number of nodes. However, reliability, UDP, and throughput are indeed impacted by the number of nodes. The simulation results indicate that such a system does not scale well above 25 nodes. On the other hand, this is not necessarily a problem since in practical WBAN application, the number of nodes placed on a body would probably remain relatively small.

The experiments performed in this thesis illustrate how a MATLAB model can be used to examine an IEEE 802.15.6 MAC layer, which provides an appropriate framework to support the development of WBANs. However, due to the limited scope of a typical MSc thesis, not all issues have been explored; some of them are mentioned in what follows.

4.2 Future work

Since the IEEE 802.15.6 standard supports short-range, low power wireless communication with great quality of service and high data rate up to 10 Mbps in the region of living tissues, it is deemed as one of the enabling technology for WBANs. Thus, it would be beneficial to further explore and simulate it to help designers understand and exploit such a standard. For future work, we suggest observing the performance measures of the IEEE802.15.6 standard when modifying the default parameters as well as identifying the best combination(s) of parameters for different offered loads. It would also be desirable to analyze other performance metrics such as Alpha/Beta probability, failure probability, utility (U) and, importantly, power and energy consumption on different frequency bands.

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Appendix 1 – MATLAB main file [46]

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Copyright (c) 2012 Telecom SudParis.
%
% Permission is hereby granted, free of charge, to any person obtaining
% a copy of this software and associated documentation files (the
% "Software"), to deal in the Software without restriction, including
% without limitation the rights to use, copy, modify, merge, publish,
% distribute, sublicense, and/or sell copies of the Software, and to
% permit persons to whom the Software is furnished to do so, subject to
% the following conditions:
%
% The above copyright notice and this permission notice shall be included
% in all copies or substantial portions of the Software.
%
% THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND,
% EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF
% MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT.
% IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY
% CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT,
% TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE
% SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
% Get the time when we start computations:
start_time = clock;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
% Define global parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
% Number of stations:
N_stations = 10;
% System size (buffer + service, so buffer holds K-1 frames):
K = 51;
% Set the MAC contention scheme:
access_schemes = {'basic'};
MAC_scheme = access_schemes{1};
%Physical layer data rate in bits/s, based on the IEEE 802.15.4 mode
data_rate = 19.2*10^3;
%The minimum value of the backoff exponent (BE) in the CSMA-CA algorithm
macMinBE=3;
%The maximum value of the backoff exponent (BE) in the CSMA-CA algorithm
```

```
macMaxBE=5;
%The maximum number of backoffs the CSMA-CA algorithm will attempt
before
%declaring a channel access failure
macMaxCSMABackoffs=4;
%The maximum number of retries allowed after a transmission failure
macMaxFrameRetries=3;
% Initial retry backoff window size:
W0 = 8;
% Maximum number of frame transmission retries:
alpha = macMaxFrameRetries;
% Maximum number of backoffs, maximum backoff window size is Wmax = 2^m
*
% W0:
m = macMaxBE-macMinBE;
% Compute the vector of backoff window sizes.  If the number of
% transmission retries is bigger than the maximum backoff window size,
the
% window expands by a factor of 2 with each backoff until the limit m is
% reached and remains fixed at Wmax thereafter.
W(1) = W0;
if alpha > m,
    if m > 0,
        W(2:m+1) = 2.^(1:1:m) * W(1);
        W(m+1:alpha+1) = W(m+1) * ones(1, alpha - m + 1);
    elseif m == 0,
        W(2:alpha+1) = W(1) * ones(1,alpha);
    end
else
    W(2:alpha+1) = 2.^(1:1:alpha) * W(1);
end

% Size of MAC frame payload (Data Field), in bits:
L_application = 100*8;
% Size of overhead added in PHY layer (Preamble + Start of Packet
Delimiter
% + PHY Header), in bits:
L_overhead = 6*8;
% Size of frame payload in bits (application + overhead) MAX should be
127 bytes
% as defined in the standard
L_payload = L_application + L_overhead;
% ACK frame size in bits at PHY layer
L_ACK = 11*8;
% Mean propagation delay in seconds:
T_prop = 222e-9;
```

```
% Vector of lambda values where each entry is the per-station frame
% arrival rate in frames/s:
lvec = 0.5:0.1:7;
% Set the basic backoff time period used by the CSMA-CA algorithm, in
% seconds
aUnitBackoffPeriod = 16*20e-6;
% Idle state length without generating packets
L0 = 0;
% Coefficient used to translate the time length of a frame to slot
length
% (bits/slot)
A = 60;

% IFS Definition in function of payload size
if L_payload > 18*8
    t_IFS=40*16e-6;
else
    t_IFS=12*16e-6;
end
% The maximum time to wait for an acknowledgment frame to
% arrive following a transmitted data frame
macACKWaitDuration = 120*16e-6;
% RX-to-TX or TX-to-RX maximum turnaround time
aTurnaroudTime = 12*16e-6;
% The time used to detect if the channel is busy or not
sensing_time = 8*16e-6;

% C_t is the length of a collision slot or a slot in which the frame is
% lost due to bit errors, in seconds
C_t = (L_payload/data_rate) + T_prop + macACKWaitDuration;
% S_t is the length of a successful transmission cycle, in seconds.
S_t = (L_payload/data_rate) + aTurnaroudTime + aUnitBackoffPeriod +
(L_ACK/data_rate) + 2*T_prop + t_IFS;

% Allocate memory for output arrays:
% Mean service time:
ET = zeros(size(lvec));
% Standard deviation of the service time:
Std_dev = zeros(size(lvec));
% Blocking probability:
P_blocking = zeros(size(lvec));
% Probability station is idle:
P_idle = zeros(size(lvec));
% Frame transmission failure probability:
P_failure = zeros(size(lvec));
% User Dissatisfaction probability:
UDP = zeros(size(lvec));
```

```
% Frame transmissions failure probability:
Pcr = zeros(size(lvec));
% Average number in system:
L_value = zeros(size(lvec));
% Reliability metric (Probability that application-generated packet is
% successfully sent):
Reliability = zeros(size(lvec));
% Average frame delay or wait time (using Little's Theorem):
D_value = zeros(size(lvec));
% Average throughput:
S_avg = zeros(size(lvec));
% Instantaneous throughput:
S_inst = zeros(size(lvec));
% User Dissatisfaction probability from (19) in Park
UDP = zeros(size(lvec));
% Packet discarded due to retry limits probability from (20) in Park
Pcr = zeros(size(lvec));
% Alpha and beta probabilities from (17) and (18) in Park
Alpha = zeros(size(lvec));
Beta = zeros(size(lvec));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
% Compute P_e, the Frame Error Rate (FER):
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%

% Nakagami fading parameter (m=1 is Rayleigh fading, m=inf is no
fading):
% Nakagami_m = inf;
% Shadowing standard deviation, in dB:
sigma_s = 4;
% The FER is the probability that the link is up, based on the channel
% conditions. PhyModel is a function that returns the probability that a
% packet is successfully received towards channel conditions. The
function
% relies on the model proposed by Zuniga & Krishnamachari:
P_e = 1-PhyModel(sigma_s, L_payload, data_rate);

% Tolerances for convergence of p0len and tau:
p0_tolerance = 1e-10;

% Initialize counter to point to the first element of the vector lvec:
counter = 1;

for lambda = lvec,
```

```
     % Get the time when we start computations for this value of lambda:
    loop_start = clock;

    % Initialize the values for p0 and p so that the while look will
    % execute on the first pass:
    p0 = -1;
    p = zeros(1,K+1);

    while abs(p0 - p(1)) > p0_tolerance,

        % Update p0 with the value that we got on the previous
iteration:
        p0 = p(1);

        % Solve the four non-linear equations (16), (17) for alpha1 and
        % alpha2 and (18) in Park and inspired from Pollin [6]. The
        % equations are written in their long form to highlight the four
        % probabilities to determine : tau (probability that a node
        % attempts a first carrier sensing as z(1)), alpha1 (probability
of
        % finding channel busy during CCA1 due to data transmission as
        % z(2)), alpha2 (probability if finding channel busy during CCA1
        % due to ACK transmission as z(3)) and beta (probability
        % probability of finding channel busy during CCA2 as z(4))


        f=@(z)([
                % Equation (16) in Park
                z(1)-(((1-(z(2)+z(3)+(1-z(2)-z(3))*...
                z(4))^(macMaxCSMABackoffs+1))/...
                (1-(z(2)+z(3)+(1-z(2)-z(3))*z(4))))*...
                ((1-(1 - (1 - P_e) * (1 - (1 - (1-(1-
p0)*z(1))^(N_stations-1))))*((z(2)+z(3)+(1-z(2)-
z(3))*z(4))^(macMaxCSMABackoffs+1))^...
                (macMaxFrameRetries+1))/...
                (1-(1 - (1 - P_e) * (1 - (1 - (1-(1-
p0)*z(1))^(N_stations-1))))*(1-(z(2)+z(3)+(1-z(2)-
z(3))*z(4))^(macMaxCSMABackoffs+1))))*...
                ( (W0/2)*(1+2*(z(2)+z(3)+...
                (1-z(2)-z(3))*z(4)))*...
                (1+(1 - (1 - P_e) * (1 - (1 - (1-(1-
p0)*z(1))^(N_stations-1))))*(1-(z(2)+z(3)+...
                (1-z(2)-z(3))*z(4))^(macMaxCSMABackoffs+1)))+S_t*(1-
(z(2)+z(3)+...
                (1-z(2)-z(3))*z(4))^2)*...
                (1+(1 - (1 - P_e) * (1 - (1 - (1-(1-
p0)*z(1))^(N_stations-1))))*(1-(z(2)+z(3)+(1-z(2)-
z(3))*z(4))^(macMaxCSMABackoffs+1)))+...
```

```
                ((L0*p0)/(1-p0))*...
                (((1 - (1 - P_e) * (1 - (1 - (1-(1-p0)*z(1))^(N_stations-1))))*(1-(z(2)+z(3)+(1-z(2)-z(3))*z(4))^2))^2*...
                (((1 - (1 - P_e) * (1 - (1 - (1-(1-p0)*z(1))^(N_stations-1))))*(1-(z(2)+z(3)+(1-z(2)-z(3))*z(4))^2))^(macMaxFrameRetries-1)+1)+1) )^(-1)),

                % Equation (17) for alpha1 in Park
                z(2)-(L_payload/A)*((1-(1-(1-p0)*z(1))^(N_stations-1))*(1-z(2)-z(3))*(1-z(4))),

                % Equation (17) for alpha2 in Park
                z(3)-(L_ACK/A)*(N_stations*(1-p0)*z(1)*((1-(1-p0)*z(1))^(N_stations-1))*(1-(1-(1-p0)*z(1))^(N_stations-1))...
                *(1-z(2)-z(3))*(1-z(4))*(1/(1-(1-(1-p0)*z(1))^N_stations))),

                % Equation (18) in Park
                z(4)-(( 1-((1-(1-p0)*z(1))^(N_stations-1))+N_stations*(1-p0)*z(1)*(1-(1-p0)*z(1))^(N_stations-1) )...
                / ( 2-(1-(1-p0)*z(1))^(N_stations)+N_stations*(1-p0)*z(1)*(1-(1-p0)*z(1))^(N_stations-1) ))
                ]);

        % Initial solution for the system
        param0=[0.3,0.8,0.05,0.5];

        % Options of the solving method 'fsolve'
options=optimset('MaxFunEvals',100000,'MaxIter',10000,'Display','off');

        % Results after solving the system
        out=fsolve(f,param0,options);


        % Assignment of found results
        tau = out(1);
        alpha1_CCA1 = out(2);
        alpha2_CCA1 = out(3);
        alpha_CCA1 = alpha1_CCA1 + alpha2_CCA1;
        beta_CCA2 = out(4);

        % Computation of the probability of a collision.
        % This is the probability that at least one other station
        % transmits during the desired time slot:
        P_col = 1 - (1-(1-p0)*tau)^(N_stations-1);

        % Computation of the equivalent probability of a failed
```

```
        % transmission attempt.  This is the probability that a
        % sent frame is received correctly and it does not collide
        % with any other frames:
        P_fail = 1 - (1 - P_e) * (1 - P_col);

        % Computation of x and y parameters like in Park (section III,
        % page 3)
        x = alpha_CCA1+(1-alpha_CCA1)*beta_CCA2;
        y = P_fail*(1-x^(macMaxCSMABackoffs+1));


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % With tau in hand, get throughput and other statistics.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Computing the average backoff period (approximation) based on
        % (35) in Park
        E_T = 0;
        for i = 0:macMaxCSMABackoffs
        E_T = E_T + 2*sensing_time + ( ((max(alpha_CCA1,(1-
alpha_CCA1)*beta_CCA2)).^(i)) ./ ...
            (sum(max(alpha_CCA1,(1-
alpha_CCA1)*beta_CCA2).^(0:macMaxCSMABackoffs) ) ) .* ...
            ( sum( (((W0*2.^(0:i))-
1)/2)*aUnitBackoffPeriod+2*sensing_time.*(0:i) ) ));
        end
        % Computing the average delay for a successfully received packet
        % (approximation) based on (34) in Park
        ET(counter) = sum( (1-P_fail.*(1-
x^(macMaxCSMABackoffs+1))).*P_fail.^(0:macMaxFrameRetries)...
            .*(1-x^(macMaxCSMABackoffs+1)).^(0:macMaxFrameRetries)...
                    *(1/(1-(P_fail*(1-
x^(macMaxCSMABackoffs+1)))^(macMaxFrameRetries+1))) ...
                    .*
(S_t+(0:macMaxFrameRetries)*C_t+((0:macMaxFrameRetries)+1).*E_T)  );

        Std_dev(counter) = sqrt( sum( (1-P_fail.*(1-
x^(macMaxCSMABackoffs+1))).*P_fail.^(0:macMaxFrameRetries)...
            .*(1-x^(macMaxCSMABackoffs+1)).^(0:macMaxFrameRetries)...
                    *(1/(1-(P_fail*(1-
x^(macMaxCSMABackoffs+1)))^(macMaxFrameRetries+1))) ...
                    .*
(S_t+(0:macMaxFrameRetries)*C_t+((0:macMaxFrameRetries)+1).*E_T).^2) -
ET(counter)^2);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Compute M/M/1/K queue model state probabilities

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % The utilization is the ratio of the arrival and service rates,
        % and the service rate is the reciprocal of the mean service
time.
        rho = lambda * ET(counter);

        % p_0 is the reciprocal of the sum of powers of rho, and p_i is
        % given by p_i = rho^i * p_0:
        p(1) = 1/sum(rho.^(0:1:K));
        p(2:K+1) = rho.^(1:1:K) * p(1);

    end % End of p0-updating while loop


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Compute metrics associated with the current lambda value in the
    % vector lvec:

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 % Blocking probability
    P_blocking(counter) = p(K+1);
    % Probability that the station is idle (this is p_0, the probability
    % that the queue is in state 0):
    P_idle(counter) = p(1);
    % Frame transmission failure probability (due to collisions and
channel
    % errors):
    P_failure(counter) = P_fail;
    % Average number of frames in the system at each station:
    L_value(counter) = (0:K) * p';
    % User Dissatisfaction probability from (19) in Park
    UDP(counter) = (1/(1-y))*x^(macMaxCSMABackoffs+1)*(1-y^(alpha+1));
    % Packet discarded due to retry limits probability from (20) in Park
    Pcr(counter) = y^(alpha+1);
    % Alpha and beta probabilities
    Alpha(counter) = alpha1_CCA1+alpha2_CCA1;
    Beta(counter) = beta_CCA2;
    % Reliability (probability that frame is not blocked or lost):
    Reliability(counter) = (1-P_blocking(counter)) * (1 - UDP(counter))
* (1 - Pcr(counter));
    % Average frame delay or wait time (using Little's Theorem), in
seconds:
```

```
    D_value(counter) = L_value(counter) / (lambda * (1-
P_blocking(counter)));
    % Throughput (in bits/s):
    S_avg(counter) = lambda * Reliability(counter) * L_application;
    % Instantaneous throughput (in bits/s):
    S_inst(counter) = L_payload / ET(counter);

    X_c(counter)=x;
    Y_c(counter)=y;

    % Generate the status text block and display it in the Command
    % Window:
    out_s = [sprintf('lambda = %f\np0 is now %f\n',lambda,p0), ...
        sprintf('Got P_fail, P_e, P_col and tau; they are %f, %f, %f and
%f\n',P_fail,P_e, P_col, tau), ...
        sprintf('Got alpha and beta; they are %f and %f\n',alpha_CCA1,
beta_CCA2), ...
        sprintf('Getting state probabilities.\n'), ...
        sprintf('p_B = %f, p_f = %f, R =
%f\n',P_blocking(counter),P_failure(counter),Reliability(counter))];
    disp(out_s);

    % Increment the lvec counter:
    counter = counter + 1;

    fprintf('Time for lambda = %f is %f seconds\n\n',...
        lambda,etime(clock,loop_start))
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Compute total elapsed time and break it out into hours, minutes, and
% seconds.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

% First get the current time:
end_time = clock;
% The difference in the start and end times is returned in units of sec
by
% etime():
elapsed_time = etime(end_time,start_time);
% There are 3600 seconds in an hour:
elapsed_hours = floor(elapsed_time/3600);
% Divide the remaining elapsed time by 60 and round down to get minutes:
elapsed_minutes = floor((elapsed_time - 3600*elapsed_hours)/60);
% The remainder is measured in seconds:
```

```
elapsed_seconds = elapsed_time - 3600*elapsed_hours -
60*elapsed_minutes;
fprintf('Total execution time is %d hours, %d minutes, %3.1f
seconds\n',...
    elapsed_hours,elapsed_minutes,elapsed_seconds)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Plots of metrics evolution associated to lambda increment
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

cnt = 1:counter-1;
figure,
hold on,
grid on,
plot(lvec*L_application,D_value(cnt),'-or');
title( ['Average Delay or Wait Time VS Offered Load for
',num2str(N_stations),' Nodes']);
xlabel('Offered Load (bits/application/node)');
ylabel('Average delay(seconds)');
figure,
hold on,
grid on,
plot(lvec*L_application,Reliability(cnt),'-ob');
title( ['Reliability VS Offered Load for ',num2str(N_stations),'
Nodes']);
xlabel('Offered Load (bits/application/node)');
ylabel('Reliability');
figure,
hold on,
grid on,
plot(lvec*L_application,P_failure(cnt),'-oy');
title( ['User Dissatisfaction Probability VS Offered Load for
',num2str(N_stations),' Nodes']);
xlabel('Offered Load (bits/application/node)');
ylabel('User Dissatisfaction Probability');
figure,
hold on,
grid on,
plot(lvec*L_application,Alpha(cnt),'-*');
hold on,
plot(lvec*L_application,Beta(cnt),'-o');
title( ['Alpha & Beta Probabilities VS Offered Load for
',num2str(N_stations),' Nodes']);
legend('Alpha','Beta');
xlabel('Offered Load (bits/application/node)');
ylabel('Alpha/Beta');
```

```
figure,
hold on,
grid on,
plot(lvec*L_application,S_avg(cnt),'-om');
title( ['Throughput VS Offered Load for ',num2str(N_stations),'
Nodes']);
xlabel('Offered Load (bits/application/node)');
ylabel('Throughput (bits/application/node/s)');
figure,
hold on,
grid on,
plot(lvec*L_application,S_inst(cnt),'-og');
title( ['Instantaneous Throughput VS Offered Load for
',num2str(N_stations),' Nodes']);
xlabel('Offered Load (bits/application/node)');
ylabel('Instantaneous Throughput (bits/application/node/s)');
figure,
hold on,
grid on,
plot(lvec*L_application,UDP(cnt),'-o');
hold on,
plot(lvec*L_application,Pcr(cnt),'-*');
title( ['UDP/Pcr VS Offered Load for ',num2str(N_stations),' Nodes']);
legend('UDP','Pcr');
xlabel('Offered Load (bits/application/node)');
ylabel('UDP/Pcr');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% End of M-file
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```