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Test and Development of Digital Subscriber Line Simulator

Master's thesis

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Digitaalse Abonendiliini simulaatori test ja arendus

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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

Aim for this thesis work is to develop an alternative solution on how to simulate various distances of a twisted pair transmission line for Digital Subscriber Line. The main purpose of this device is to match the attenuation based on the length of cable. The device developed in this thesis is measured and these measurements are analysed. A comparison between the newly developed device is made between the previously used commercial EXFO device and a physical cable with the corresponding length. As a result of this thesis an improved solution of a Digital Subscriber Line simulator is provided which is capable of manual and automated testing while having a better accuracy as its predecessor.

This thesis is written in English and is 40 pages long, including 7 chapters, 35 figures and 7 tables.

Annotatsioon

Digitaalse Abonendiliini Simulaatori test ja arendus

Käesoleva lõputöö eesmärgiks on välja töötada alternatiivne lahendus, kuidas simuleerida keerdpaarülekandeliini erinevaid kaugusi digitaalse abonendiliini jaoks. Selle seadme põhieesmärk on sobitada sumbumine kaabli pikkuse alusel. Käesolevas lõputöös väljatöötatud seadet mõõdetakse ja antud mõõtmisi analüüsitakse. Värskelt välja töötatud seadme võrdlus tehakse varem kasutatud EXFO toote ja vastava pikkusega füüsilise kaabli vahel. Lõputöö tulemusena valmib digitaalse abonendiliini simulaatori täiustatud lahendus, mis on võimeline manuaalseks ja automatiseeritud testimiseks, omades eelkäijaga võrreldes paremat täpsust.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 39 leheküljel, 7 peatükki, 35 joonist, 7 tabelit.

List of abbreviations and terms

ADSL   Asymmetric Digital Subscriber Line

AM   Amplitude Modulation

AWG   American Wire Gauge

CPE   Customer-Premise Equipment

CO   Central Office

DSLAM   Digital Subscriber Line Access Multiplexer

DSL   Digital Subscriber Line

DUT   Device Under Test

IO   Input/Output

LDO   Low Dropout

MCU   Microcontroller Unit

PCB   Printed Circuit Board

PTOS   Plain Old Telephone Service

RTOS   Real-Time Operating System

SNR   Signal-to-Noise Ratio

TCP   Transmission Control Protocol

UDP   User Datagram Protocol

VDSL   Very-High-Bit-Rate Digital Subscriber Line

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1 Introduction

This thesis work has been conducted based of a project from Teleplan Estonia OÜ. This project focuses on finding a solution for a hardware simulator of different Digital Subscriber Line distances required from our clients. A Digital Subscriber Line (DSL) is a group of technologies which is used to transmit high-bandwidth data over twisted pair telephone cables. Even though the technology has existed for a couple of decades, it is still used in the industry. The length of these cables can reach up to 5000 meters and with these long lengths of cable a drop in the speed of transmitted data inevitably decreases as the length of cable increases. To test the equipment which uses the DSL technology, on how these changes in the data rate affect different devices, a testing method or a device is needed to be developed.

This study investigates the possible solutions on how to simulate different wire lengths as currently the only available option is to connect the actual length of wires between the DSL devices depicted in Figure 1. To clarify, if an engineer needs to test how certain equipment functions when the cable length of the DSL is 1 kilometre, one would need to connect the actual length of the cable and measure it. This study aims to replace these long lengths of cable rolls with a small handheld device. Currently there are no available products capable to fulfil all the requirements needed. The requirements for the testing device are:

- Physical size of device (PCB) as small as possible, no more than 10x10 cm

- Simulate wire lengths of 300m, 600m, and 2000m

- Attenuation difference compared to the real cable less than 3 dB

- Able to simulate all these lengths in DSL and ADSL frequencies. For VDSL frequencies only simulation of 300m and 600m is required.

- Able to select cable length manually and automatically. Automated testing is controlled via Ethernet and is required for the larger testing system in which it will be deployed ultimately.

This thesis includes the analysis of existing commercial device and provides an alternative solution which better suits the requirements based on theoretical aspects of transmission line characteristics and simulations conducted in LTspice. Measurements of the device are made and compared with the existing commercial device and a physical cable with the corresponding length.

Figure 1 300m cable roll

2 Overview of Digital Subscriber Line

A Digital Subscriber Line (DSL) is a group of technologies which is used to transmit high-bandwidth data over twisted pair telephone cables. DSL encodes a stream of digital data to maximize the use of the available bandwidth and continuously monitors the transmission to detect and correct errors. Features such as echo cancellation and equalization are required for error identification and correction during the transmission. By using digital modem (modulation/demodulation) methods, bits of data are sent through the traditional telephone wire, making it commercially attractive since it offers high bandwidth on, already installed in most households, telephone wires [1].

There are many variants of Digital Subscriber Line (DSL), which are usually referred to as xDSL. Common types of DSL are symmetric digital subscriber line (SDSL, with matching upload and download speeds); asymmetric digital subscriber line (ADSL), featuring faster download speeds than upload speeds; and digital subscriber line with extremely high rates (VDSL, featuring much faster asymmetric speeds). ADSL is an essential variation and the most extensively deployed version of DSL technology, capable of delivering data at speeds of up to 8.1 Mbps to a subscriber for ADSL1 technology and higher for other technologies such as ADSL2+ and VDSL. The data rate and frequency ranges are illustrated in Figure 2. This technology can deliver both traditional telephone service and high-speed digital transmissions on the same line as the telephone without interfering with the telephone signal. Because the telephone infrastructure is already in place, there is no need to rewire offices, high rises, or campuses. The performance of an ADSL service in sending data, on the other hand, is greatly dependent on transmission line attenuation factors. Figure 3 depicts DSL technologies speed compared to the distance of cable. When the attenuation or transmission loss throughout the copper cable and every connection spanning from the exchange to the customer premises is negligible, the line is called good. This is especially true for higher frequency spectrum (up to 2.2 Mbps) [2].

Technology	Freq range	Max Rates	Max # of carriers and Bin spacing
ADSL	25kHz – 1.1MHz	800kbps up 8Mbps down	256 with 4.3125kHz bins
ADSL2+	25kHz – 2.2MHz	1Mbps up 24Mbps down	512 with 4.3125kHz bins Amend. 1 = 29 Mbps down
VDSL(1)	25kHz – 12MHz	15Mbps up 55Mbps down	2782 with 4.3125kHz bins
VDSL2	25khz – 30MHz	100Mbps up 100Mbps down	4096 with 4.3125kHz bins 3478 with 8.625kHz bins
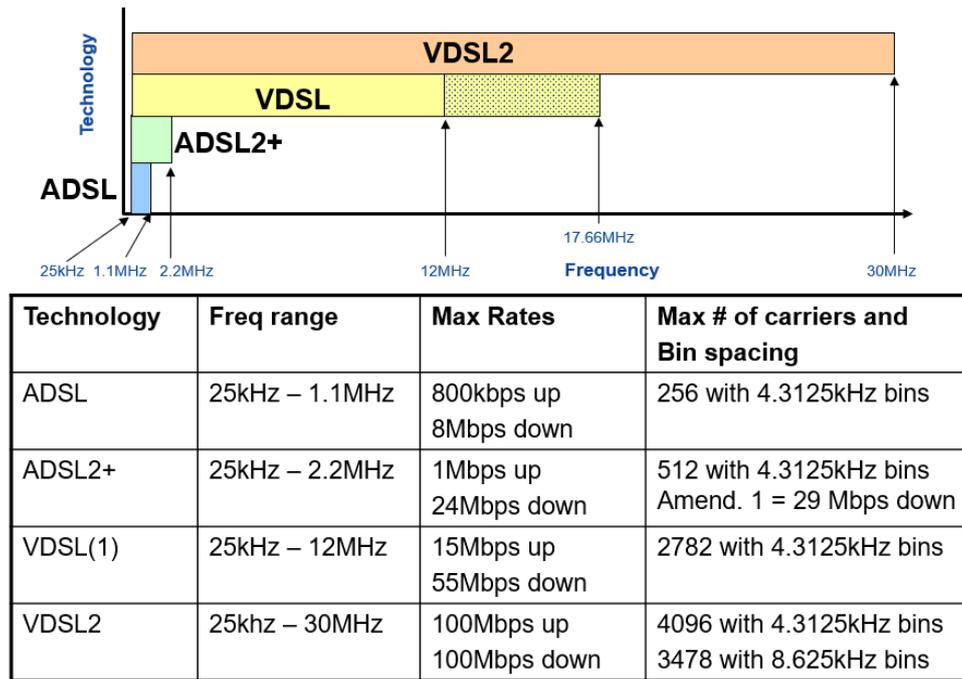
Figure 2 Comparison of DSL technologies [3]

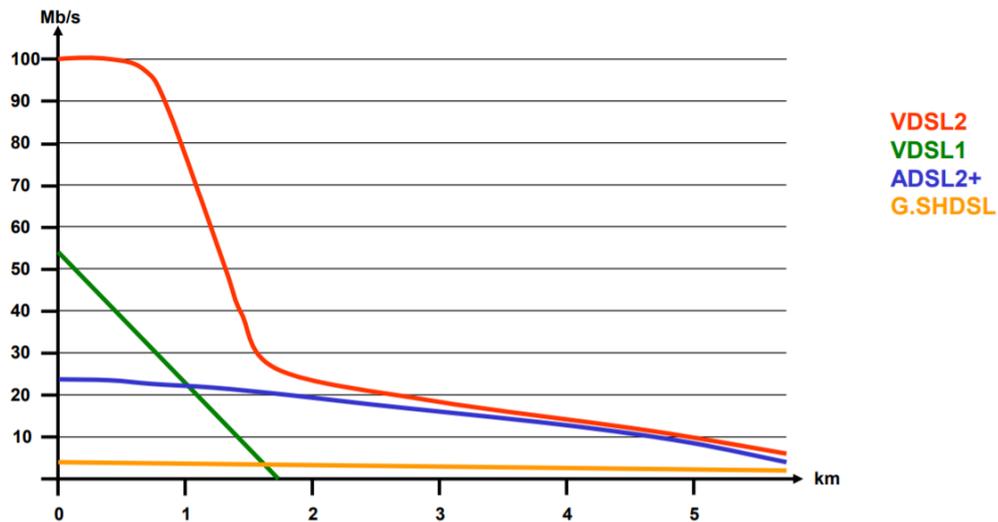Figure 3 DSL technologies speed vs distance [4]

2.1 ADSL

ADSL is the most widespread form of DSL technology. Most households and businesses that use DSL technology use ADSL. The characteristics of ADSL are as follows: [1]

- ADSL is used to transmit digital information over existing telephone lines [1].

- Unlike dial-up connection, ADSL provides a permanent connection to the Internet [1].

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- ADSL is capable of transmitting voice and data information over the same line [1].

- ADSL is asymmetric. This means that ADSL is designed to provide more bandwidth in one direction than the other [1].

- ADSL allows downstream speeds of about 8 Mbps and upstream speeds of up to 640 Kbps [1].

The typical ADSL setup consists of various subsystems and is shown in Figure 4:

- Digital Subscriber Line Access Multiplier (DSLAM) - Is the interface to the Internet and controls the routing of traffic. It provides multiple DSL connections to access the Internet bandwidth provided to subscribers over copper lines [4].

- Voice Switch - It is connected to the Public Switched Telephone Network (PSTN) and provides analog voice connections [4].

- Splitter - The twisted pair wires terminate at the DP box, which is located on the subscriber's premises and is first connected to the splitter. The splitter is basically a low-pass filter that filters out the low-frequency Plain Old Telephone Service Line (POTS) voice signals in the range of 300 Hz to 3400 Hz. It forwards high-frequency ADSL signals to the ADSL modem [4].

- ADSL modem - The final connection to the user's computer is made via Ethernet cables connected to the Ethernet port of the ADSL modem. The physical layer portion of the ADSL modem converts the signal into a format that the computer understands [4].

- Filter - passive filter that isolates POTS devices from ADSL frequencies [4].
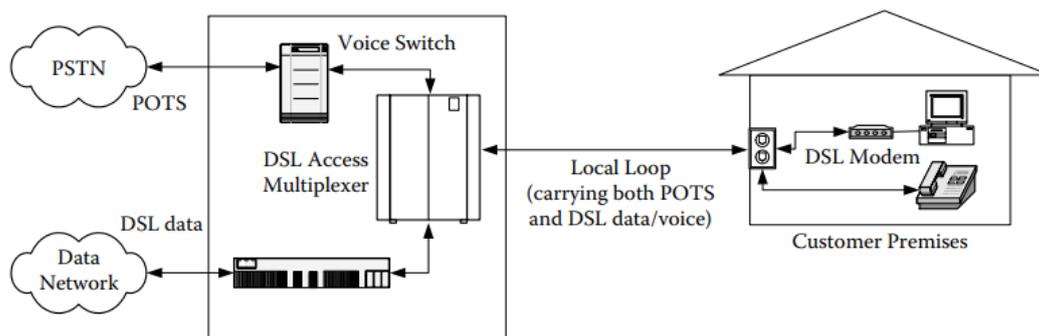
Figure 4 Generic DSL setup [5, p. 133]

2.2 DSL limitations

DSL is a technology that is sensitive to distance. The signal quality and connection speeds suffer accordingly over the growing distances between the subscriber and their local Central Office (CO). The maximum distance of 5460m between the DSL Customer-premises equipment (CPE) and the DSLAM is the absolute limit for the ADSL service, although many ADSL provides recommend even lower distances to ensure the quality of the service. It should be noted that these distance restrictions only apply to ADSL data transfer, not voice telephone calls. [6].

To amplify voice signals, telephone companies utilize load coils as miniature amplifiers. These load coils can interfere the data transmission of the DSL, meaning that if there are load coils in the loop between the customer and its central office, it is likely that the customer is unable to receive the DSL service in its current area [6].

Table 1 Transfer rate and maximum distance of different DSL technologies [6]

DSL technology	Data rate (downstream/upstream)	Maximum distance (m)
ADSL	8 Mbps/1 Mbps	5000
VDSL	55 Mbps/13 Mbps	1300
IDSL	144 kbps/144 kbps	550
SDSL	768 kbps/768 kbps	6700
G. SHDSL	2.3 Mbps/2.3 Mbps	8500

Based on Table 1 it can be observed that different DSL technologies are offered in a wide range of transfer rates. Theoretically the maximum throughput potential of any first-generation ADSL technology is 8.448 Mbps. However, this would require very short cable lengths between the subscriber and the central office [6].

Second-generation ADSL (ADSL2) was released to provide 12 Mbps downstream for distances of 2500m or less. Furthermore, ADSL2+ was designed to give speeds of up to 24 Mbps over shorter distances of below 1500m [6].

Throughput capacity and the distance between the subscriber and central office are inversely proportional in nature. With increase in distance of cable lengths the maximum upstream and downstream speeds decrease. Furthermore, reduced functionality or quality can be contributed by the following conditions [6].

- AM radio interference - AM radio frequencies can degrade the output by interfering with the quality of the DSL signal. This interference is especially problematic when employing low-quality cabling for in-house wiring [6].

- Bridge taps – Bridge taps are the extensions between the CPE and the CO. These are extra wires with unterminated cable ends that are linked to the local loop. These unterminated cables can cause reflections, noise, and reduced signal strength which leads to reduced signal throughput [6].

- Crosstalk - Crosstalk interference between unshielded twisted pair cables in a bundle can result in electromagnetic interference between the twisted pair cables. This occurs when the frequency is overlapping between channels [6].

- Fiber optic cable - ADSL signals are not capable of passing through the analog to digital to analog conversion that occurs when a part at any given point of the telephone circuitry passes through the fiber optic cable [6].

- Impedance mismatch – Impedance mismatch causes reflections which results the decrease of the Signal to Noise Ratio (SNR). Changes in wire gauge, splices, and corrosion can all contribute to the mismatch. [6].

- Load coils – To increase the distance of voice operations in the local loop load coils are used. Load coils are used to compensate for the parallel capacitance of the transmission line. Load coils function as inductions which act as a low-pass filter, blocking higher frequency signals. These filters can significantly distort or interfere with the DSL frequencies and need to be removed from the line for the DSL to function. Load coils are mostly used in transmission lines where the distance is larger than the maximum allowed DSL distance [6].

- Signal attenuation - The loss of signal power due to distance is known as attenuation. The distance between the subscriber and the CO affects attenuation. [6].

- Wire gauge – Difference in wire diameter can cause impedance mismatches which affect throughput of the transmission line. Furthermore, to improve the throughput and signal strength, thicker wires can be used in the local loop [6].

3 Twisted Pair Telephone Transmission Line

A twisted pair cable is essentially two wires that are twisted around, sensed differentially, and electrically driven to reduce the impact of external influences, for example, crosstalk from other twisted pair wires inside the bundle or other external interferences. When the wires are driven in a differential mode, any outside interference is eliminated because they are physically close and symmetrical to one another. The present telephone industry's cabling infrastructure is made up of several distinct types and quality of twisted pair cable. These cables are often clumped together in a cable sheath, with each bundle containing 25 to 100 twisted pairs of cables. To decrease electromagnetic interference (EMI) from outside sources the exterior shield of the cable bundle is grounded at the system's termination blocks. To further limit twisting, the rate of twisting varies between pairs within each bundle (typically between 12 and 40 twists per meter). In addition to the insulation material, the diameter of the copper wire distinguishes twisted pair cables. [7, p. 243].

Copper wire is often measured in American Wire Gauge (AWG). Twisted pair cables are commonly made with wire diameters of 19, 22, 24, and 26 AWG. From 11 to 40, Figure 5 displays the metric and English equivalents of AWG [8, p. 40].

AWG	mil	mm	AWG	mil	mm	AWG	mil	mm
11	90.741	2.3048	21	28.462	0.7229	31	8.9276	0.2268
12	80.807	2.0525	22	25.346	0.6438	32	7.9503	0.2019
13	71.961	1.8278	23	22.572	0.5733	33	7.0799	0.1798
14	64.083	1.6277	24	20.101	0.5106	34	6.3048	0.1601
15	57.067	1.4495	25	17.900	0.4547	35	5.6146	0.1426
16	50.820	1.2908	26	15.940	0.4049	36	5.0000	0.1270
17	45.257	1.1495	27	14.195	0.3606	37	4.4526	0.1131
18	40.302	1.0237	28	12.641	0.3211	38	3.9652	0.1007
19	35.890	0.9116	29	11.257	0.2859	39	3.5311	0.0897
20	31.961	0.8118	30	10.025	0.2546	40	3.1445	0.0799

Figure 5 AWG physical dimensions [8, p. 41]

In office cabling, twisted- pair cables are traditionally used to connect computers to 10BaseT or 100BaseTX Ethernet. Category 3 (CAT 3) or Category 5 (CAT 5) twisted-pair cable is commonly used in office environments but old in-buildings SYT1 and SYT2

cables are still in use. CAT A Category 5 cable has better transmission characteristics than a CAT 3 cable. A Category 4 twisted pair cable with transmission characteristics midway between the two is also available [8, p. 41]. Category 3 UTP cables have a frequency range of up to 16 MHz. Category 4 for specifications up to 20 MHz and Category 5 for specifications up to 100 MHz were created because of further advancements. Category 6 and 7 cables of the next generation are also available on the open market. Those categories' parameters are 200 MHz and 600 MHz, respectively. Category 6 cable can be shielded, and Category 7 cable is shielded [9, p. 111]. Attenuation at a frequency of 10 MHz is used to determine the transmission characteristics of these twisted pair cables. For Category 3, 4, or 5 cables, the attenuation at this frequency should be less than 98, 72, or 65 decibels per kilometre (dB/km), respectively. Within a plastic shield, these cables typically have 4 or 25 twisted pairs. Category 3 cables consist of 24-pin copper wires, while Category 4 and 5 cables can be made with 22- or 24-pin wires. The transmission quality of a twisted pair cable is determined not only by the size of the copper wires inside [8, p. 41].

Because the transmission characteristics of twisted pair cables vary with wire size and other manufacturing processes, the performance of a twisted-pair cable can be adequately described only by its basic electrical parameters of resistance, inductance, capacitance, and conductance per unit length. Such a definition is more of a reference model for industry than a production standard. Computer simulation studies that have led to the definition of sophisticated broadband communications systems such as DSL and Ethernet have shown that twisted pair cable models defined by their primary electrical properties are quite advantageous. Temperature, measurement methods, and manufacturers may cause the electrical properties of a particular twisted pair cable to vary somewhat from those of the reference model. However, if the changes are kept to a minimum, the overall transmission performance of the reference model can be maintained [8, p. 42].

3.1 Primary Parameters of Twisted Pair Cables

The primary line coefficients, the series resistance $R(f)$, the series inductance $L(f)$, the shunt capacitance $C(f)$, and the shunt conductance $G(f)$, or their combination, the longitudinal impedance $Z_P(f)$ and the shunt admittance $Y_P(f)$, or the secondary line coefficients, the propagation constant (f) and the characteristic line impedance Z_0, can be

used to describe the transmission characteristics of a twisted pair transmission. The primary and secondary line coefficients can be translated using telegraph equations; however, the attenuation t is the most essential transmission line frequency characteristic nowadays [10, p. 2]. Series resistance inductance, shunt conductance G, and shunt capacitance C can accurately determine the transmission characteristics of a twisted pair cable. It is worth noting that these key parameters are also frequency dependent. The values of these key parameters are given in units of length. Consequently, the values must be scaled appropriately for either the metric or English measurement system. Figure 6 shows the basic parameters of an equivalent circuit of a twisted pair cable with a unit length dx. The equivalent circuit of a twisted pair cable should consist of many of these unit length circuits connected in a cascade [8, p. 42].
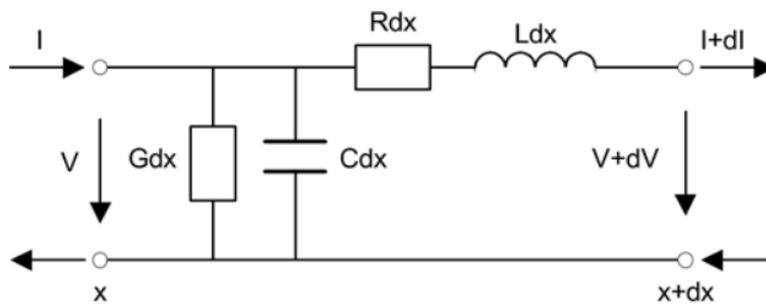

Figure 6 Basic parameters of an equivalent circuit of a twisted pair cable [8, p. 42]

Consider a model of a transmission line with discrete resistors, capacitors, and inductors. A transmission line of length x can be divided into an unlimited number of increments of length Δx (dx), resulting in the series and shunt R_s, L_s, and C_s shown in Figure 6. G (=1/Rshunt) may have been labelled as a resistor, but it is typically easier to deal with reciprocal resistance values for shunt resistors analytically. As demonstrated in Figure 7 a segment of line approximated by three segments of length x, a true twisted pair telephone line has resistance, capacitance, and inductance spread evenly across both wire components of the pair [11].

Figure 7 A balanced line model in three increments [11]

These parameterized models can be used to establish the primary electrical parameters of twisted pair with high accuracy compared to real data for frequencies ranging from 0 to 50 MHz. Telephone lines are often made of 26 AWG and 24 AWG wire, with drop wire and flat pair used to connect the telephone lines to the subscriber premises. Category 5 twisted pairs are typically used for Ethernet cabling. Residential telephone cabling typically uses Quad-22, which consists of four twisted 22 AWG pairs, and FW -26, a 26 AWG flat wire [8, p. 45].

Characteristics impedance must be as consistent as possible. Signal distortion and loss occur when the conductor quality and cable geometry are not consistent. The speed at which an electrical signal travels down a transmission line is known as propagation speed. Velocity factor is the proportion of propagation speed within the cable to propagation speed in free space [12]. Characteristic impedance and propagation constants are two secondary factors for twisted pair cables. According to the Equation (1), the characteristic impedance of a twisted pair cable is connected to primary parameters [8, p. 45].

$$\gamma(f) = \sqrt{\frac{R(f) + j2\pi f L(f)}{G(f) + j2\pi f C(f)}} \tag{1}$$

A twisted pair cable's propagation constant is also related to primary parameters and can be expressed in the following Equation (2): [8, p. 45].

$$\gamma(f) = \sqrt{[G(f) + j2\pi f C(f)][R(f) + j2\pi f L(f)]} \tag{2}$$

A twisted pair cable's characteristic impedance and propagation constants are frequency dependent as well. Even though the propagation constant is a function of frequency, we

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nevertheless refer to it as a "propagation constant" because of its origins in an ideal transmission line [8, p. 45].

Attenuation is caused by three main factors: loss of conductors ohmic resistance, skin effect (driven by the high frequency film effect) and dielectric loss [12]. The transfer function or insertion loss of a simple twisted pair cable terminated with its characteristic impedance is related to the propagation constant according to the following Equation (3) [8, p. 46]:

$$H(d, f) = e^{-d\gamma(f)} \tag{3}$$

where d is the twisted pair cable's length. The measurement of a twisted pair cable's transfer function or insertion loss is relatively simple, and the result is frequently represented in terms of the output-to-input power ratio. The transfer function of a twisted pair cable is described using a scaled version of the logarithm of the output-to-input power ratio. The following Equation (4) defines the logarithmic form of the transfer function [8, p. 46]:

$$H_L(d, f) = 20log_{10}[H_L(d, f)] = 20log_{10}e^{-d\alpha(f)} = \frac{20}{ln10}[-d\alpha(f)]$$
$$= -8{,}68d\alpha(f) \tag{4}$$

Where $\alpha(f)$ is the real part of propagation constant $\gamma(f)$. $\alpha(f)$ can be approximately represented in the following Equation (5) [8, p. 46]:

$$\alpha(f) = a\sqrt{f} + bf \tag{5}$$

Parameters of a and b for insertion loss are listed in **Table 2** for different pair cables and in house wirings. These parameters should be used in conjunction with distance d in terms of meters and frequency f in terms of Hertz [8, p. 46].

Table 2 Parameters for $\gamma(f)$ [8, p. 46]

Type	a	b
Cat.3	$8{,}17 \times 10^{-7}$	$8{,}07 \times 10^{-11}$
Cat.4	$7{,}37 \times 10^{-7}$	$9{,}12 \times 10^{-11}$
Cat.5	$7{,}26 \times 10^{-7}$	$4{,}56 \times 10^{-11}$
Quad-22	$6{,}77 \times 10^{-7}$	$4{,}97 \times 10^{-11}$
FW-26	9.17×10^{-7}	$4{,}87 \times 10^{-11}$

For a distance of 100m, Figure 6 depicts the insertion losses caused by these predicted propagation constant model parameters [8, p. 47].
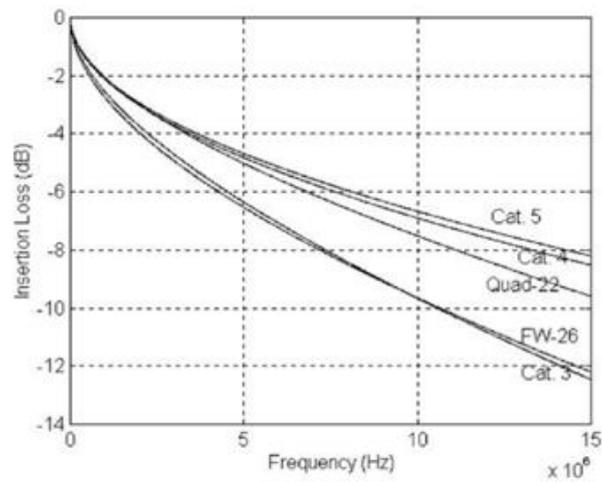
Figure 8 Insertion loss according to propagation parameter estimations [8, p. 47]

4 Electronics Design

4.1 Commercial device

Figure 9 EXFO DSL Attenuator

The company in which master's thesis was conducted in previously used a DSL Attenuator by EXFO for measurements, however as the production of the device has now been discontinued and the results of measurements were heavily questioned by the engineers (actual attenuation didn't match to real cable), it was necessary to look for another solution. Furthermore, this device is only suitable for manual testing however automated testing is required for our specifications. According to the specification sheet of this device, it should be able to simulate the attenuation of ADSL/2/2+ in distances of 900, 2400, 3000, 4000, 5500, and 6700 meters [13]. To verify that the previously mentioned product EXFO DSL Attenuator is not suitable to fulfil the requirements for this thesis the device was analysed by replicating the schematic and the PCB design while designing theses to suit our specification. The developed device was then measured in the DSL system and the results of these measurements are documented further of this thesis. Figure 10 and Figure 11 depict the schematic and the PCB layout of the device in Altium Designer software. Based on Figure 10 it can be observed that the design only switches between capacitors with different values to simulate various distances of a transmission line. It takes no consideration of how increased distance also results increased resistance and inductance of a twisted pair transmission line.
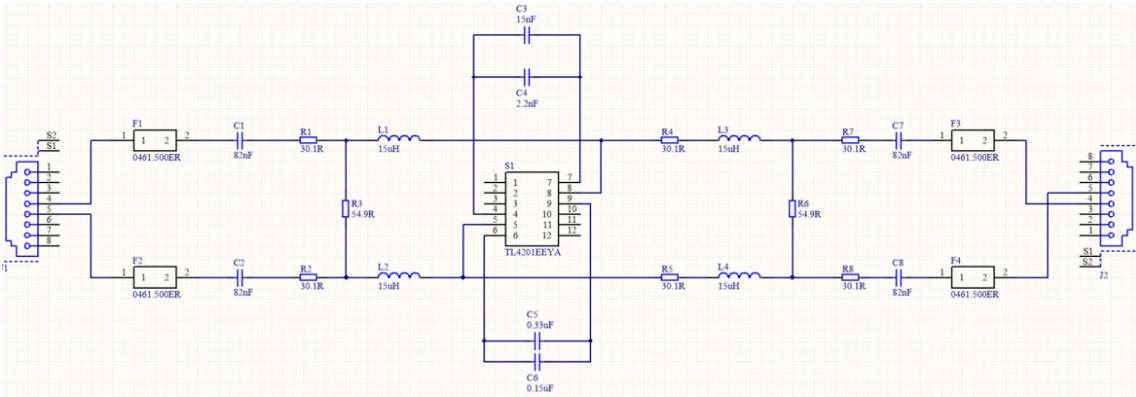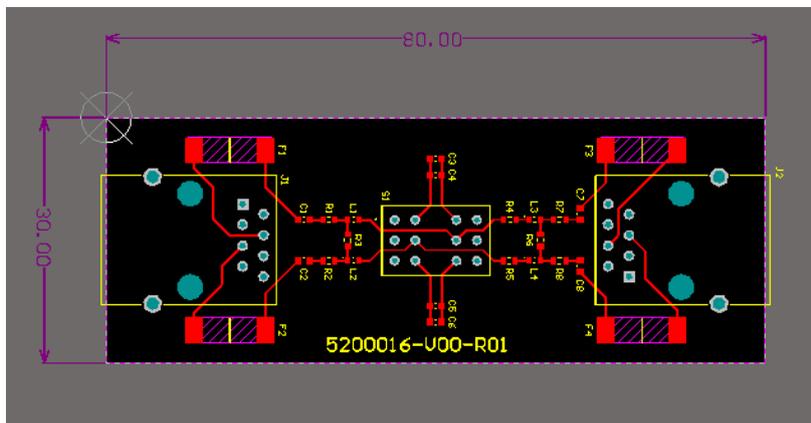
Figure 10 EXFO attenuator schematic

Figure 11 EXFO attenuator PCB layout

Measurement setup for the EXFO simulator is depicted in Figure 12. For the EXFO simulator attenuation from frequencies of 150 kHz to 1 MHz for distances of 900m, 3000m and 4000m was measured. The results of these measurements along with the calculated theoretical values for the same distances are depicted in Figure 13.
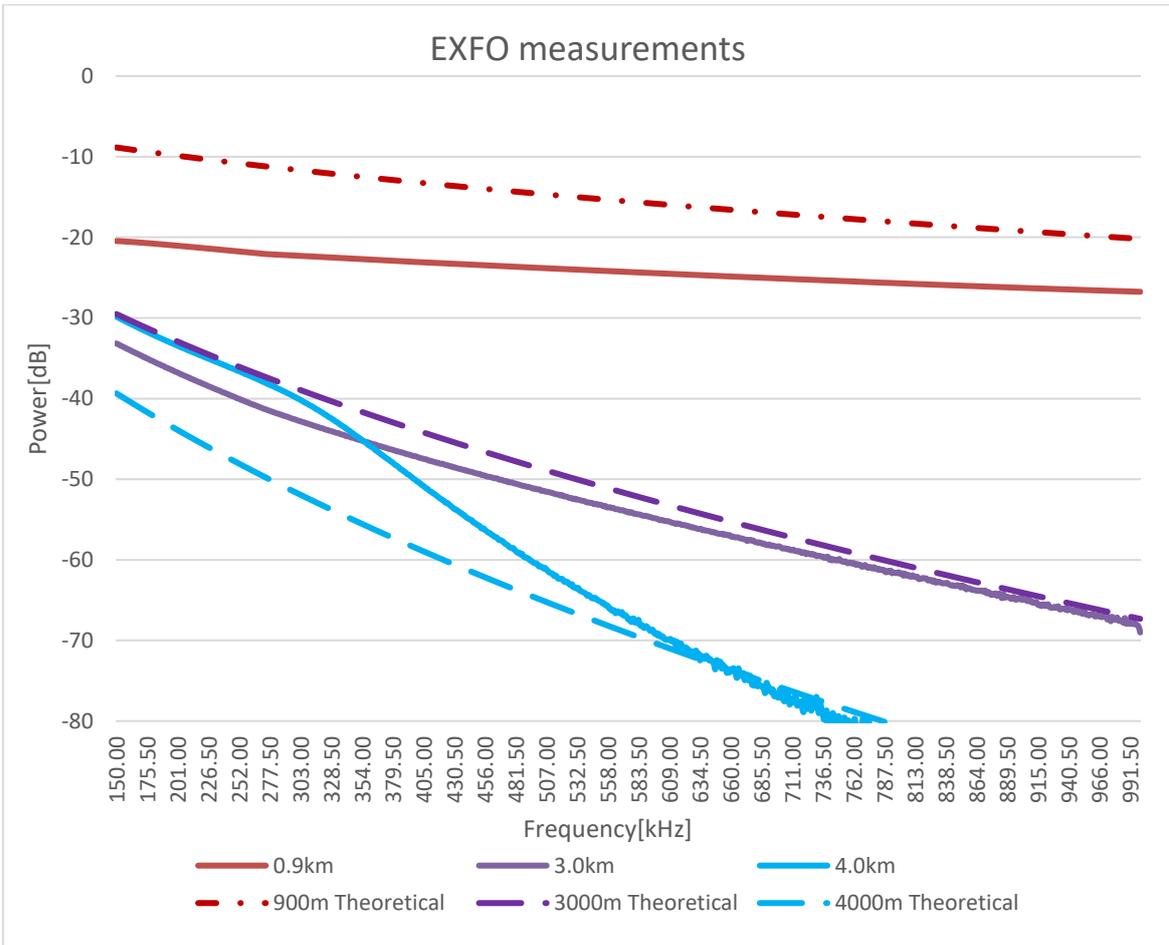

Figure 12 Measurement setup for EXFO device

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Figure 13 EXFO simulator measurements

Comparing the measurements of the EXFO simulator attenuation with calculated theoretical attenuation from Figure 13 it can be observed that there is a large mismatch between these values. The theoretical attenuation characteristics are explained later in this thesis. Table 3 describes the difference between the EXFO simulator and the theoretical attenuation in the frequency ranges of 150 kHz to 1 MHz. The reason for only measuring up to 1 MHz for this device is that during measurements it was observed that measurement above the 1 MHz frequency range shows difference from theoretical attenuation of -60 dB or more which would suggest that this device is not capable of simulating ADSL2+ or VDSL frequency ranges.

Table 3 Comparison of measured and theoretical attenuation of EXFO simulator

Frequency [MHz]	900m difference from theoretical attenuation [dB]	3000m difference from theoretical attenuation [dB]	4000m difference from theoretical attenuation [dB]
0,15	-11,6	-3,65	9,50
0,2	-11,16	-3,86	10,48
0,3	-10,63	3,83	11,78
0,4	-9,87	-3,29	8,34
0,5	-9,20	-2,61	4,03
0,6	-8,60	-2,17	1,33
0,7	-8,60	-1,51	-0,23
0,8	-7,55	-1,20	-2,98
0,9	-7,06	-0,89	-5,07
1,0	-6,56	-1,69	2,48

4.2 Design and simulation of a twisted pair transmission line model

To calculate the insertion loss of a twisted pair cable Equation (6) was used:

$$InsertionLoss_{cable100m} \leq k1\sqrt{f} + k2f + \frac{k3}{\sqrt{f}}\frac{dB}{100m} \tag{6}$$

Where constants for horizontal cable insertion loss k1 = 1,967, k2 = 0,023, k3 = 0,050

These constants and the formula are specified in the TIA-EIA-568-B.2 standard [14, p. 9]. Using equation 6 theoretical graphs of attenuation for specified distances were generated in Figure 14.
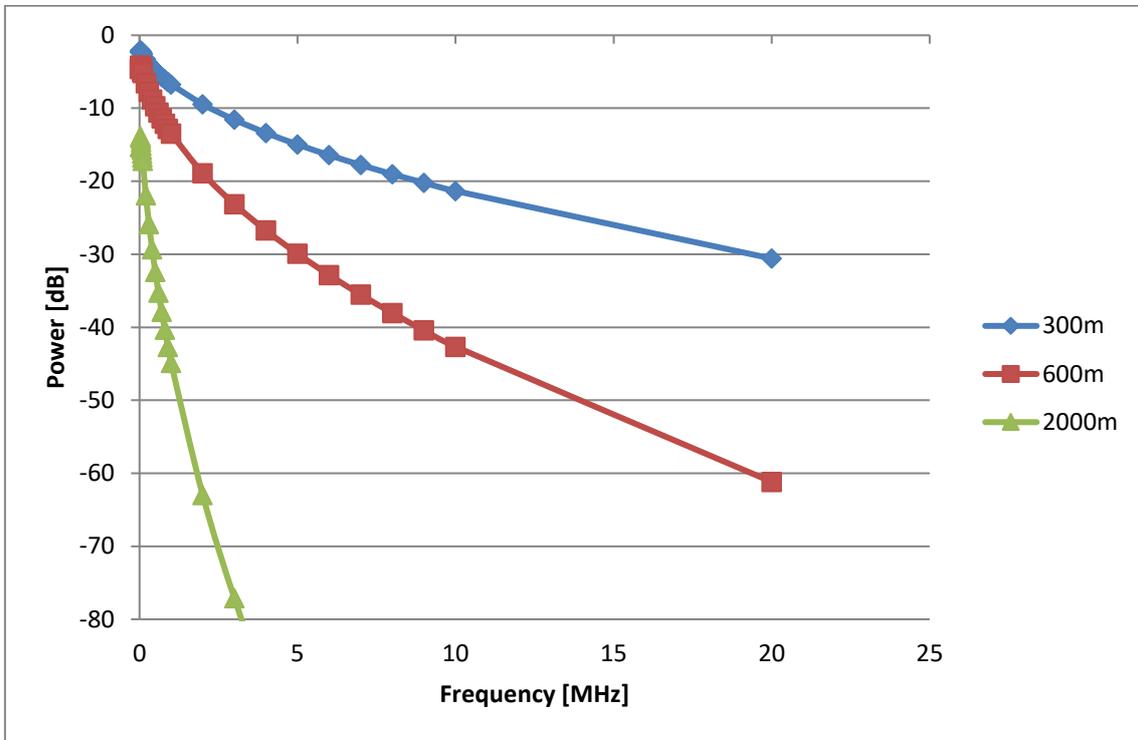

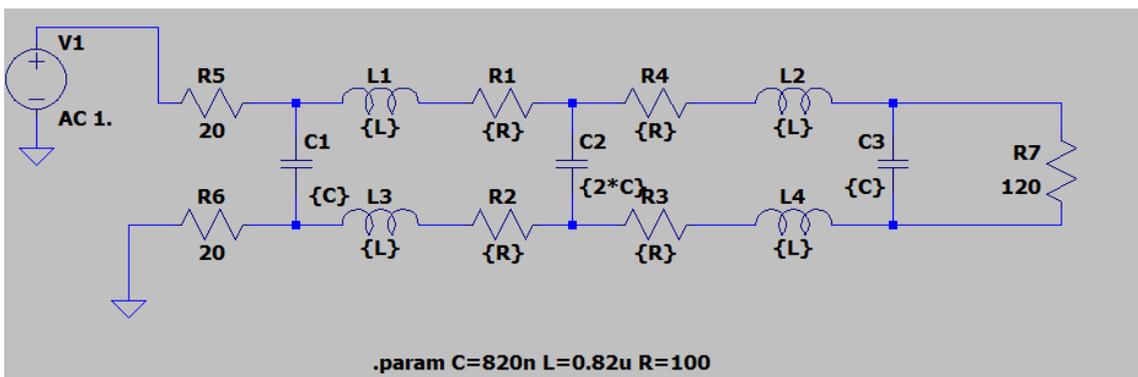Figure 14 Theoretical attenuation for 300m, 600m and 2000m for twisted cable pair

Figure 15 LTspice simulation schematic

A simulation schematic in LTspice software is depicted in Figure 15. The schematic consists of 2 increments of RLC lumped elements of a twisted pair cable model. Based on the graphs depicted Figure 14 the values of capacitors and inductors were chosen based on the simulations to match the simulation results with the graphs for each distance. The

only known variable is the resistance of the cable, which for 24 AWG is 0,08942 ohm per meter [15]. The following values for resistance, capacitance and inductance finally chosen for the simulation schematic are described in Table 4:

Table 4 Resistance, capacitance, and inductance values of individual passive components for each distance

Distance [m]	Resistor value [Ω]	Capacitor value [nF]	Inductor value [nH]
300	15	0,47	51
600	30	1,2	150
2000	100	4,7	820

It should be noted that the LTspice simulation cannot fully replicate the characteristics of a real physical cable especially since the simulation uses only 2 increments of RLC lumped elements of the twisted pair cable model. The more there are increments of these lumped elements, the more this schematic replicates the characteristics of a twisted pair cable, however the increased cost and the PCB area needed to add these increments were the deciding factor of choosing the number of increments for the device. Furthermore, it was not possible to match the phase characteristics however this is not important as we are dealing with narrowband channels.

During the simulation it was observed that using 2 increments was enough to replicate the attenuation characteristics of twisted pair transmission line up to 11 MHz of frequency for 300m and 600m and 2 MHz for 2000m. The attenuation characteristics for 300m and 600m were also within the specified offset of 3dB even in the higher frequencies (up to 50MHz), however the attenuation for the 2000m it was not possible to replicate the attenuation characteristics for 2 increments of RLC lumped elements to the theoretical attenuation characteristics within the required 3dB error range. Even though this is within the specified requirements of frequency range, it should be noted that when simulating longer distances the number of increments should be increased. Figure 16 depicts the results of attenuation characteristics for all 3 distances with the chosen passive component from Table 4 and is based on the LTspice simulation compared to the theoretical attenuation characteristics from Figure 14.
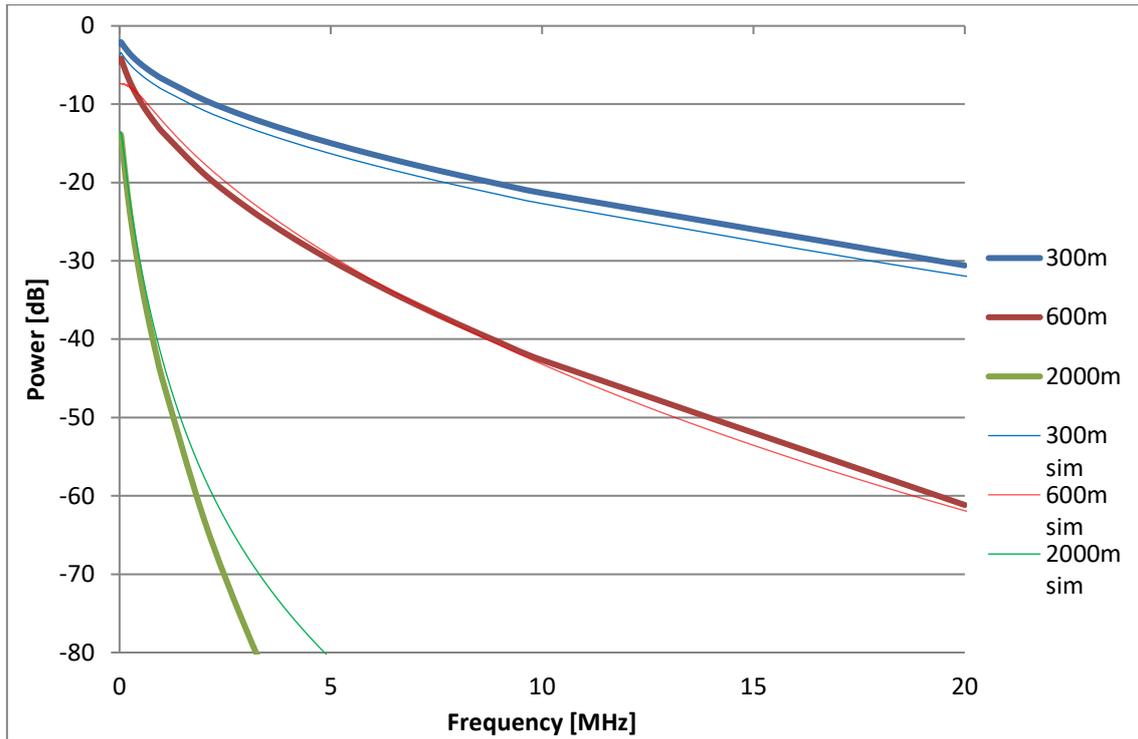
Figure 16 LTspice simulation results for 300m, 600m and 200m

4.3 Design

All the necessary schematics and designs for the printed circuit board (PCB) were created using Altium Design software. The electrical schematics are divided by function into 3 different subsections:

1. Digital subscriber line simulator schematics – Based on the twisted pair cable model and the simulations in LTspice 4 different distances were designed, the values of the passive components are provided in Table 4. Figure 17 depicts the schematic for passthrough of the DSL simulation, meaning that the distance is basically 0 meters. Figure 18, Figure 19, and Figure 20 depict the distances of 300, 600, and 2000 meters as these were the specified distances required for this master's thesis. A combination of 6 RF signal relays is used to switch between these distances.
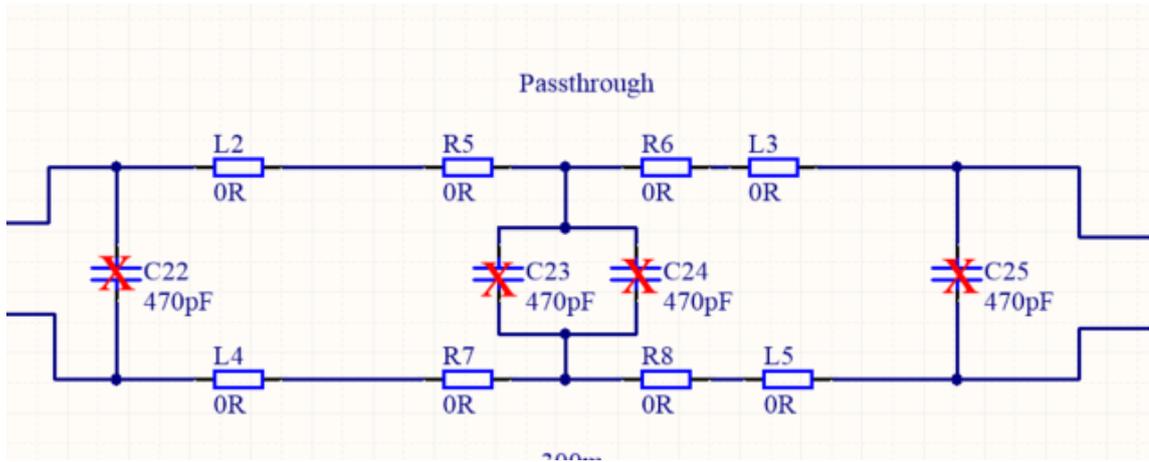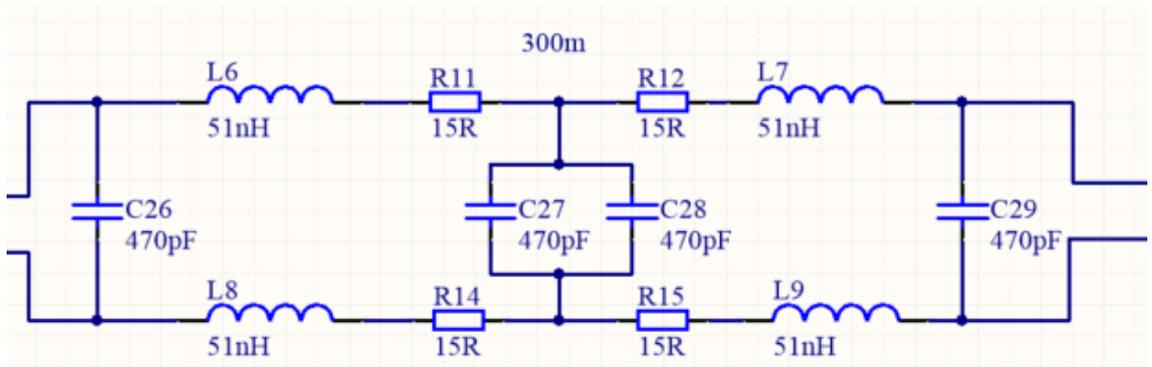
31

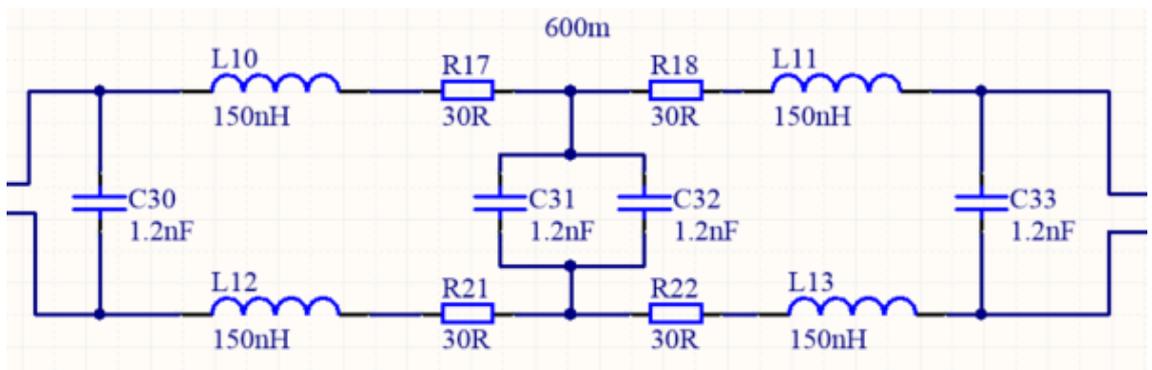Figure 17 DSL passthrough schematic

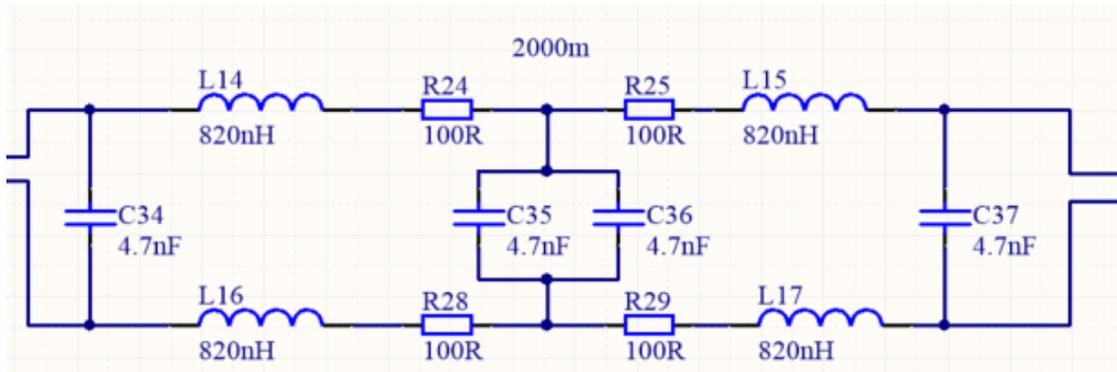Figure 18 DSL 300m schematic

Figure 19 DSL 600m schematic

Figure 20 DSL 2000m schematic

2. Microcontroller schematics – Consists of:

- All the necessary IO connections for controlling each relay of the digital subscriber line to switch between the necessary distances of the simulator. Furthermore, a push-down button and 5 LED-s are provided to switch between these distances and to indicate which distance is currently being used.

- Power delivery of the microcontroller depicted in Figure 21. The value of these capacitors is based on TM4C129K4CPDT datasheet specifications [16].
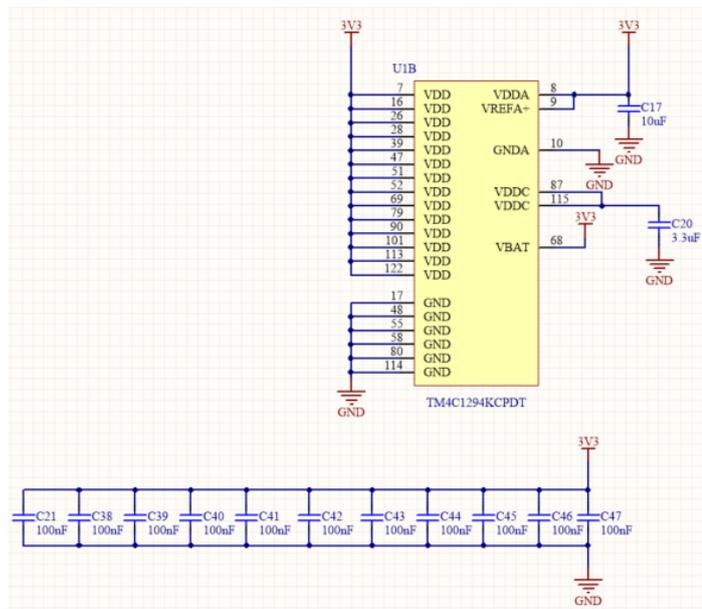

Figure 21 Power connections and decoupling of the microcontroller schematic

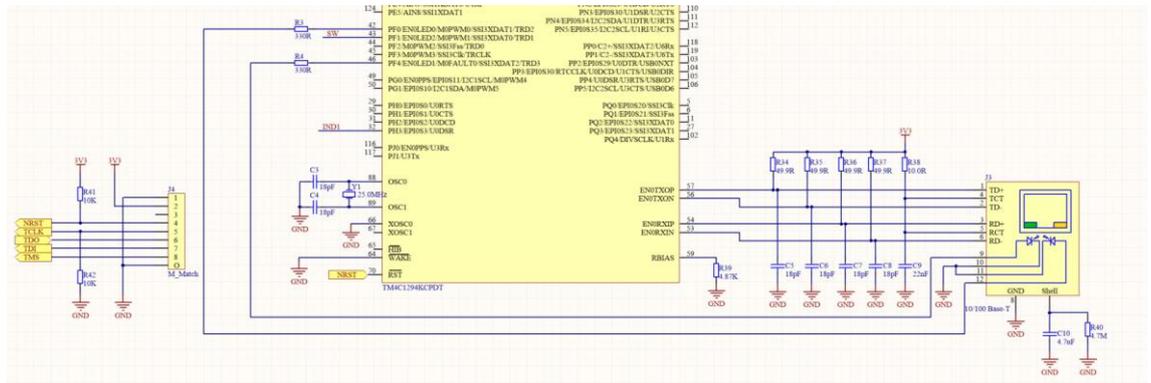- All the necessary connections for the ethernet connector and JTAG debugging are depicted in Figure 22.

Figure 22 MCU connections schematic

3. Power schematics – providing the necessary voltage and current for the components on the board. Source voltage is 12 V which is converted into 5 V using a DC/DC synchronous step-down converter and is depicted in Figure 23. The 3.3 V is converted from the 5 V using a low dropout (LDO) converter and is depicted in Figure 24. A green LED is used to indicate that the power is provided correctly.
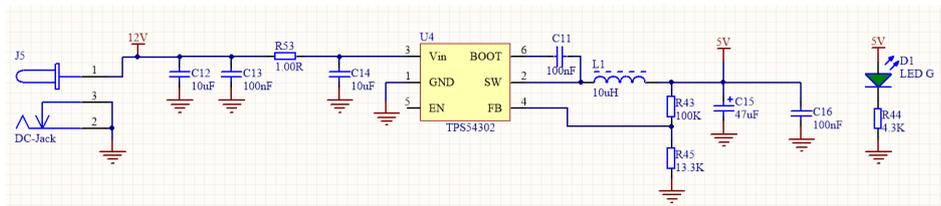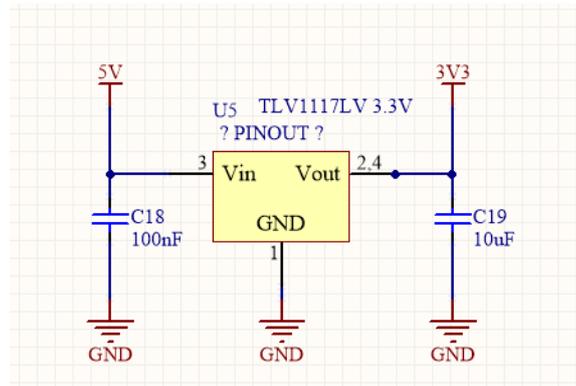

Figure 23 12V to 5V schematic

Figure 24 5V to 3.3V schematic

The design of the printed circuit board consists of 4 layers. The top and bottom layers of the board are used for signal connections and component placements. The 2 middle layers are used for providing ground and 3.3 V across the board. The dimensions of the board are 80mm x 55mm. Figure 25 depicts the PCB in 2D view and Figure 26 depicts the 3D view of the PCB.
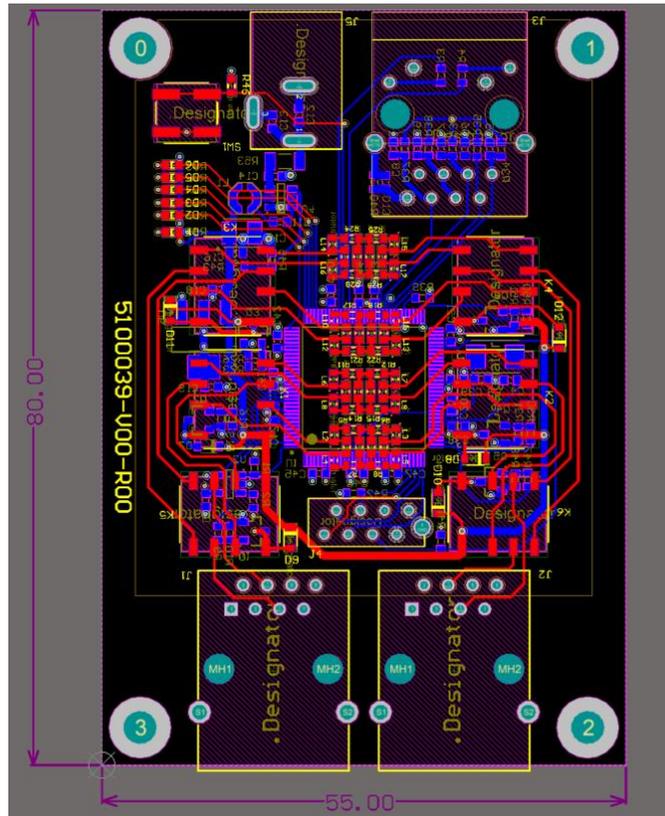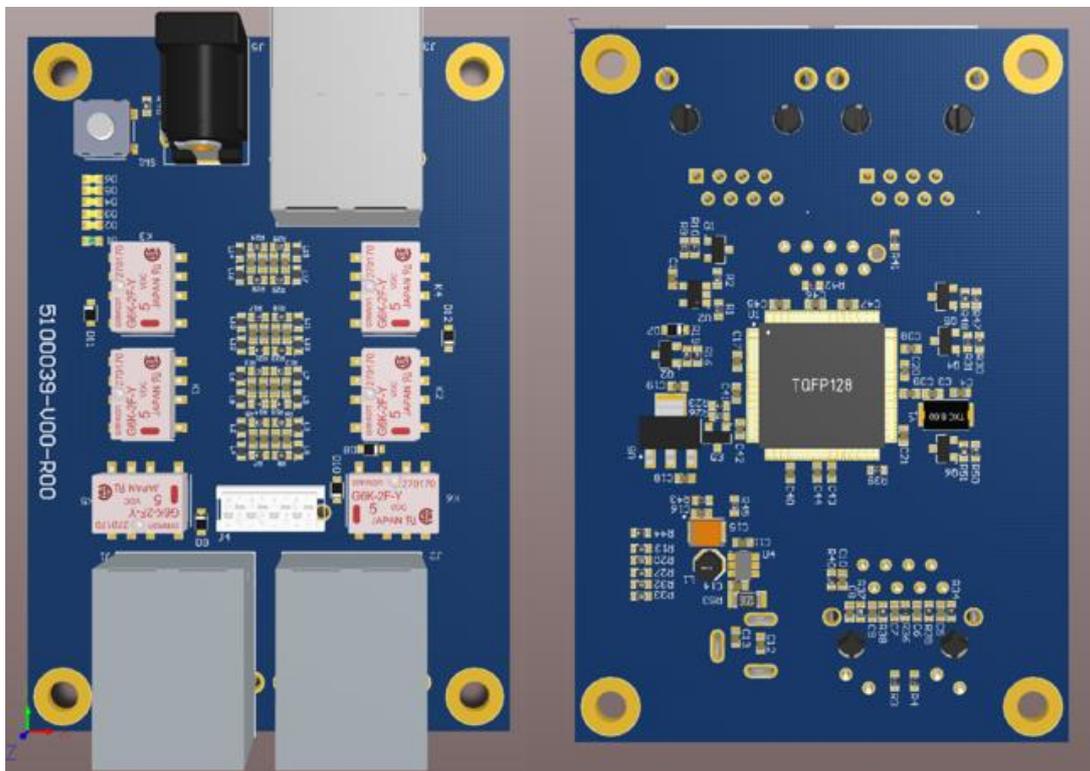
Figure 25 PCB layout of the DSL simulator

Figure 26 Top and bottom 3D view of the PCB

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5 Software

The most important requirement for the device software was the fact that the user must be capable of changing the distances of DSL simulator remotely i.e., via the ethernet. Therefore, it was necessary to research and decide which transport layer protocol to use.

5.1 Transport layer protocols

The transport layer prepares the data for transmission over the network and manages the logical connection. The transport layer can provide the following: [17, p. 56]

- **Data flow service and flow control**. The top layer can use the data stream simply and do not have to deal with packet sizes [17, p. 56].

- **Establish a connection-oriented connection**. The top layer can use the established connection [17, p. 56].

- **Port**. A port is required on a machine to communicate with a specific process or service (connections differentiation) [17, p. 56].

- **Dealing with blockages**. Potential congestion is also addressed in the transport layer resolution [17, p. 56].

- **Reliable connection**. If any packets are lost (if or example checksum is incorrect), the data will be resent [17, p. 56].

- **Consideration of order**. On the network, packets may reach their destination in a different order than they were sent out or some package may be lost [17, p. 56].

The data unit of the transport layer is a packet. Unlike the network layer protocol, the transport layer protocol used must be supported only by the connection end hosts. Today, the most used transport layer protocols are TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). In addition to TCP and UDP, there are other transport layer protocols they are still very new [17, p. 56].

5.1.1 TCP and UDP overview and comparison

The original specification for TCP (Transmission Control Protocol) was published by the IETF, based on ARPAnet. The TCP protocol provides the top layer with all the functions of the transport layer. TCP connections are designed to create a virtual and reliable full-duplex connection when transmitting data between two hosts. The data unit of the TCP protocol is a packet. The field structure of the TCP packet consists of: Source port, target port, queue number, confirmation number, header length, reserved bits for the future, code bits, window size, checksum, urgent pointer, choices, and data [17, pp. 56-57].

UDP (User Datagram Protocol) is one of the important transport layer protocols in the Internet protocol domain. UDP is a simple, low-ballast protocol that operates offline and does not guarantee that the information sent will reach its destination. Compared to TCP, UDP is faster because no connections are formed, and the packet header is smaller. Also, there are no sequence numbers in UDP, which makes it impossible to assemble the packets in the correct order in the transport layer. However, the correct order of packets is not important for our case as only one frame is used. If necessary, things must be implemented separately in the upper layers. The UDP packet consists of the following fields: Source port, destination port, length, checksum, and data [17, p. 63].

The ports have the same function for UDP as for TCP. The UDP packet can also be fragmented, but this is often not the case. Unlike TCP, UDP can use multicast and broadcast addresses as destination addresses [16]. Table 5 gives a very general overview of the differences between UDP and TCP [18].

Table 5 TCP vs UDP [18]

Characteristics	TCP	UDP
Functionality	Data travels from one computer to another through the internet. Connection based	UDP is also a message transport or transfer protocol. This is not a connection-based system, meaning a program may transmit a bunch of packets to another, and the relationship would be over.
Usage	In non-time critical applications	UDP is utilized in gaming and other applications that require quick data transport. The statelessness of UDP is also advantageous for servers that respond to small queries from many clients.
Transfer speed	TCP has a slower rate than UDP	UDP is faster since packets are not error-checked
Reliability	There is a 100% assurance that the data transferred is unaltered and arrives in the same order as it was sent.	There's no guarantee that the messages or packets delivered will reach their intended destination.
Error checking	TCP checks for errors.	UDP checks for errors, but there are no recovery alternatives.

Between choosing between the UDP and TCP protocol a choice was made to use UDP protocol mainly because it is a faster protocol in terms of transfer speed and is more familiar to the author of this thesis.

5.2 UDP implementation

The software portion for the DSL simulator was written in C language using Eclipse IDE. The company in which this thesis was conducted in has a programming project template integrated FreeRTOS and necessary libraries for the same MCU used in this project. Therefore, the only necessary work regarding the software part of this thesis was to implement UDP protocol to the device. Figure 27 depicts UDP initialization and Figure 28 depicts UDP message handling.

```
void DSL_INIT(void)
{
      IOConfig();
      sendDoneSemaphore = xSemaphoreCreateBinary();
      DSL_CommandQueue = xQueueCreate(16, sizeof(DSL_internalCommand_t));
      struct udp_pcb *UDPPCB = udp_new();
      if(!UDPPCB)
      {
            return;
      }
      UDPPCB->local_port = 1779;
      udp_bind(UDPPCB, IP_ADDR_ANY, 1779);
      udp_recv(UDPPCB, (udp_recv_fn) UDPReceive, NULL);
   xTaskCreate(vDSLTask, "DSL", DSL_TASK_STACK_SIZE, NULL, DSL_TASK_PRIORITY, NULL);
}
```

Figure 27 DSL initialization

```
static void vDSLTask(void *pvParameters)
{
      DSL_internalCommand_t inCmd;
      char response[12];
  for(;;)
  {
        xQueueReceive(DSL_CommandQueue, &inCmd, portMAX_DELAY);
              switch(inCmd.cmd)
              {
                  case SELECT_NONE:
                          Select_None();
                          strcpy(response, "SHORTED");
                          sendReply(inCmd.pcb, &inCmd.addr,
inCmd.port,(void*)&response , sizeof(response));
                          break;

                  case SELECT_PASSTHROUGH:
                          Select_Passthrough();
                          strcpy(response, "PASSTHROUGH");
                          sendReply(inCmd.pcb, &inCmd.addr,
inCmd.port,(void*)&response, sizeof(response));
                          break;
              {
{
```

Figure 28 DSL response case example

The *vDSLTASK()* function use an endless for loop for a switch case. Each case responds
to a specific command which can be sent via UDP. When a specific command has
reached the MCU the corresponding relays to control which transmission line simulator
distances are required to be used, are turned on. When this is done a response of the
received case is sent back as a string. The response is required to ensure to the user that
the device received the message and switched to the corresponding mode.

6 Measurements and Results

The testing setup is depicted in Figure 29 Testing setup The setup consists of connecting a network analyzer, which is depicted in Figure 30 Network Analyzer, with two 50 ohm BNC cables to two 50 ohm unbalanced to 100 ohm balanced transformers to match the cable impedance with that of the network analyzer. Two RJ45 are soldered to the baluns and are connected to the input and output of the DUT accordingly. The measurement setup is based on [19] and [20]. For these measurements North Hills 0300BB wideband transformer was used as it was one of the recommended baluns to use in measuring the insertion loss of the twisted pair cable from Intel's 1000BASE-T/100BASE-TX/10BASE-T Physical Layer Compliance Tests Manual [19]. The equipment was calibrated using a calibration kit (ZV-Z21) and the Short-Open-Load-Through (SOLT) calibration technique before tests.
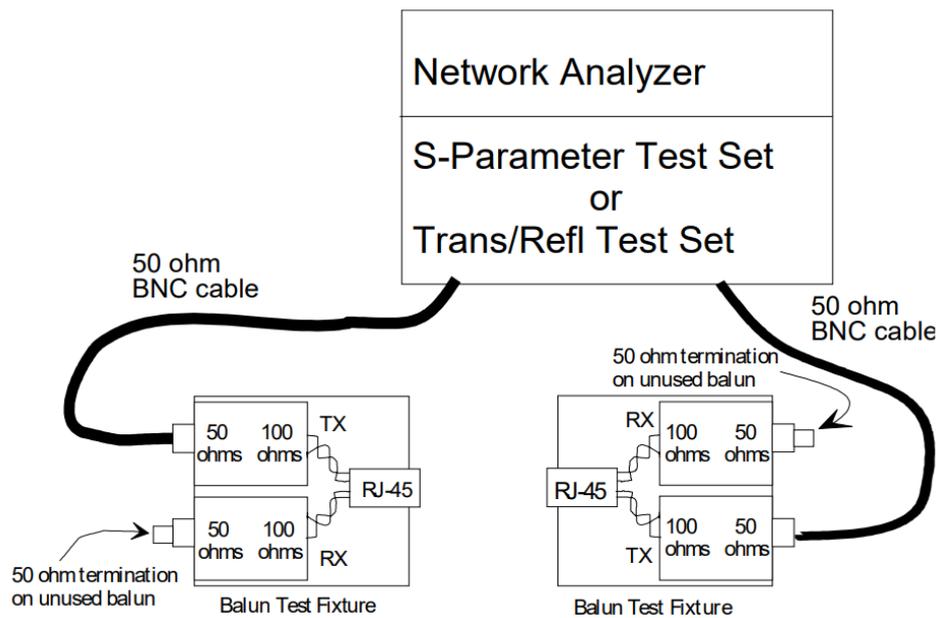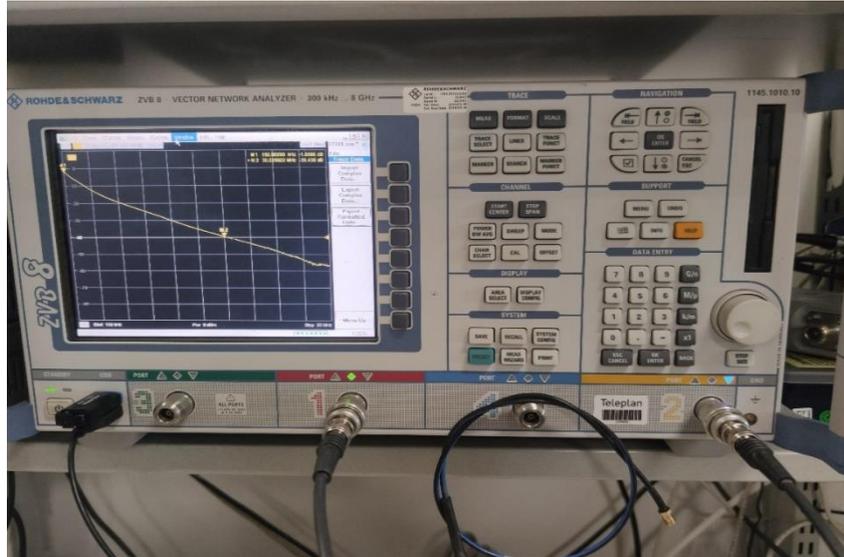

Figure 29 Testing setup [17]

Figure 30 Network Analyzer

6.1 Electrical measurements

6.1.1 DSL simulator measurements

Measurement setup for the DSL simulator is depicted in Figure 31. For the DSL simulator attenuation from frequencies of 150 kHz to 50 MHz for every distance was measured. The results of these measurements along with the calculated theoretical values for the same distances are depicted in Figure 32.

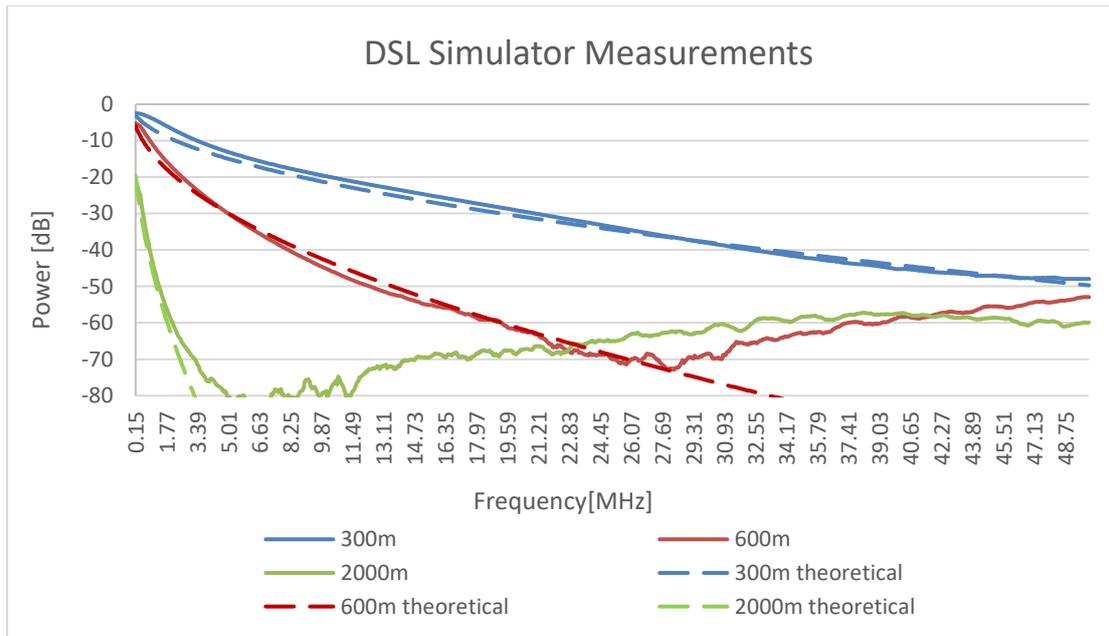Figure 31 Measurement setup for DSL simulator

Figure 32 Digital Subscriber Line simulator measurements

Comparing the measurements of the DSL simulator attenuation with calculated theoretical attenuation from Table 6 it can be observed that they do not fully correspond with each other which is also expected as the simulator uses only 2 increments of RLC lumped elements whereas for the real cable these elements can be divided into infinite number of increments. Table 6 describes the offset between the DSL simulator and the theoretical attenuation in the frequency ranges of 150 kHz to 11 MHz as these are the frequency ranges of ADSL, ADSL2+ and VDSL. For the 300m and 600m distances the offset is below 3dB for each frequency, which is within the specified requirements however for the 2000m the gap is much larger. As can be seen from the graphs in Figure 32 the 2000m attenuation continues to fall around 3 MHz frequency whereas the simulator measurements stop falling, this is due to parasitic capacitance. This was also confirmed from the model simulations made in LTspice software. There was no possibility to match the curve of the 2000m attenuation with its theoretical equivalent, as the model of only 2 increments of lumped elements was not enough to modify the curve of the attenuation to match it in higher frequencies. From 3 MHz and above the attenuation differs too much to provide us any reasonable result and the curves of the attenuation bear no resemblance. However, the requirements for the 2000m simulation only specified the capability to simulate the frequencies of DSL and ADSL, furthermore Table 1 specifies the maximum distance for VDSL as 1300m therefore the 2000m range is above the maximum distance. The conclusion for this issue is that to replicate a twisted pair cable of longer distances,

more increments should be used. Additionally, it was observed that from -70 dB attenuation does not continue decreasing as predicted from the simulations, it is caused by crosstalk and therefore the measurements from these ranges cannot be validated. The solution for this issue would be to change the design of the PCB to reduce the crosstalk for the signal traces or the usage of EMI shielding.

Table 6 Comparison of measured and theoretical attenuation of DSL simulator

Frequency [MHz]	300m offset from theoretical attenuation [dB]	600m offset from theoretical attenuation [dB]	2000m offset from theoretical attenuation [dB]
0,15	0,49	0,74	-0,96
0,52	2,15	2,94	3,53
1,02	2,89	2,73	2,37
2,02	2,82	1,88	2,98
3,02	2,39	1,18	-
4,02	2,05	0,54	-
5,02	1,84	-0,08	-
6,02	1,72	-0,64	-
7,02	1,67	-1,16	-
8,02	1,66	-1,59	-
9,02	1,67	-1,88	-
10,2	1,69	-2,19	-
11,2	1,73	-2,39	-

Even though the difference of simulated distance and a larger frequency range, the gap between the theoretical attenuation from the measured attenuation is much smaller compared to the EXFO simulator device in Figure 13. Comparing these results to the EXFO simulator it can be observed that the DSL simulator performs with better accuracy compared to the EXFO devices in terms of attenuation.

6.1.2   Cable measurements

To verify the accuracy of the theoretical attenuation formula a physical 300m length cable was also measured using the same measuring setup as for the DSL simulator. Figure 33 depicts the cable, simulator, and theoretical attenuation of 300m cable. As can be seen from the graphs in Figure 33, all attenuations are similar in terms of value and the shape of the attenuation curve. Table 7 describes the offset between the range of 150 kHz to 11,2 MHz. The simulator attenuation differs in some margins from the physical cable attenuation at the lower frequencies whereas the theoretical attenuation is more similar. However, as the frequency increases the difference between the theoretical and cable attenuation increases and the simulator attenuation matches with the cable more than the theoretical. Approximately from frequencies of 18 MHz and above, the difference for both the simulator and theorical attenuation from the cable attenuation increases marginally. This is acceptable as these higher frequencies are not required in the scope of this thesis.
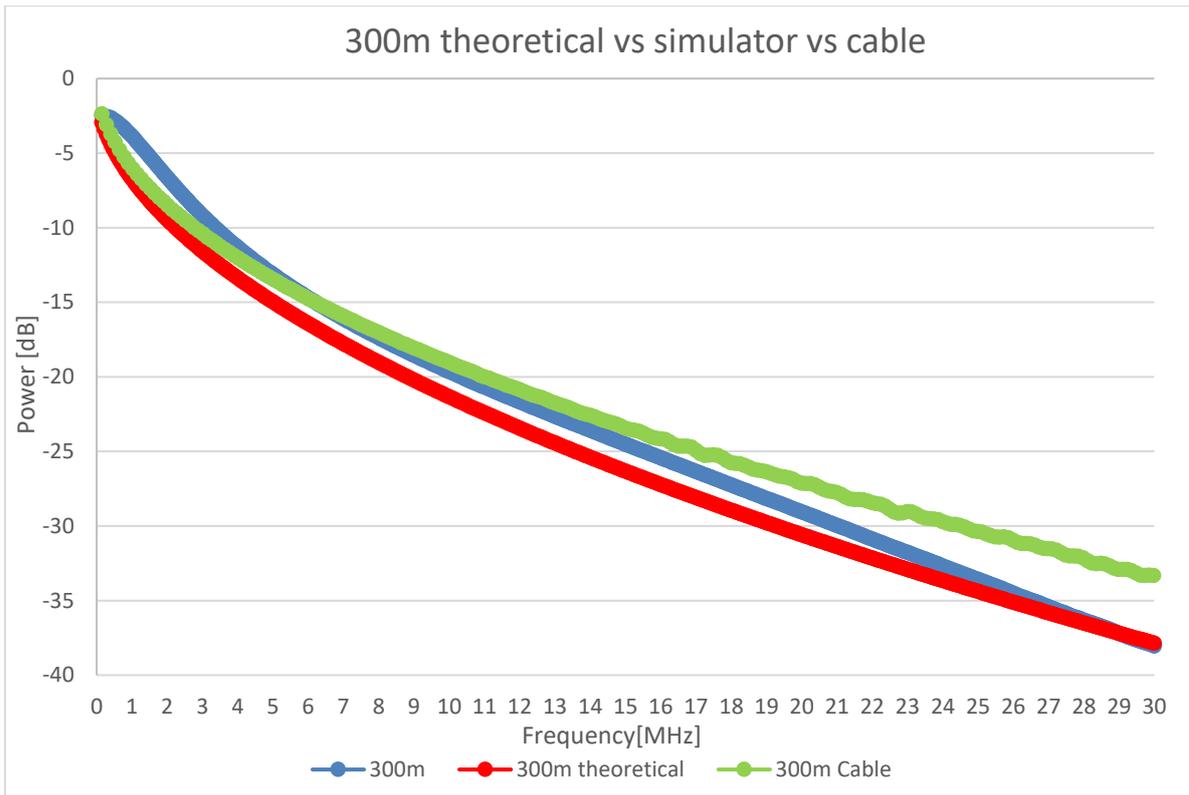
Figure 33 300m attenuation of theoretical, simulator and physical cable

Table 7 300m attenuation difference between theoretical and simulator values vs cable

Frequency [MHz]	DSL simulator and cable difference [dB]	Theoretical and cable difference[dB]
0,15	-0,08	-0,58
0,52	0,91	-1,24
1,02	2,14	-0,75
2,02	1,84	-0,99
3,02	1,21	-1,18
4,02	0,71	-1,35
5,02	0,34	-1,50
6,02	0,06	-1,66
7,02	-0,17	-1,84
8,02	-0,33	-1,99
9,02	-0,47	-2,13
10,2	-0,59	-2,29
11,2	-0,68	-2,41

6.2 Software testing

A simple testing script was generated to test whether the device will respond to command in the UDP transport layer. The program code was written in C++ and in the QT Creator environment. This script is depicted in appendix. It should be noted that this written

program code is only used for testing the device and will not be used in the device which it will be deployed. Figure 34 depicts the user menu in the windows command prompt and Figure 35 depicts the response from the DSL simulator when the corresponding command number is entered into the prompt.

Figure 34 Command prompt menu for DSL simulator software testing

Figure 35 DSL simulator with the response

7 Summary

Current thesis was presented to develop a Digital Subscriber Line simulator device. This thesis was conducted in Teleplan Estonia OÜ and investigates the possible solutions on how to simulate the characteristics of different lengths of twisted pair cable. The previous device used for such purpose only had the capability of manual testing moreover the measurements from this device were questioned by the engineers and the need for automated testing was necessary.

This thesis provides an alternative to the aforementioned device. Firstly, an overview regarding different DSL technologies and their parameters is investigated. Secondly, the theoretical model and its primary characteristics of a twisted pair transmission line are investigated. Based on these investigations a simulation model in LTspice is introduced and the design of the PCB is made and software for the capability of automated testing is implemented.

A testing setup to measure the attenuation for both devices and for a 300m physical cable is made. Measurements of the device are made, and the results are depicted in graphs and tables. These are compared with the previous device and a physical cable with the corresponding length.

As a result of this thesis an alternative solution has been developed. The new device has a better accuracy on simulating the attenuation of a twisted pair transmission line compared to its predecessor. All the requirements mentioned at the beginning of this thesis are fulfilled.

Further work could involve investigating on how many increments of RLC lumped elements are required for simulating longer distances. Furthermore, the effects of crosstalk and on how reducing crosstalk regarding the PCB design should be taken into consideration.

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