A First Step Toward Green Wireline Broadband

A tool for systematic measurement of Digital Subscriber Line parameters
as input to dynamic power optimization algorithms

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Communication Technology

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A tool for systematic measurement of Digital Subscriber Line parameters as input to dynamic power optimization algorithms

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Abstract

This project aims to lower the power consumption of broadband networks by developing software algorithms that continuously and automatically configures their equipment to achieve this goal. The primary motivation is that this decreases both the environmental impact of the networks and the operators' expenditures.

To appreciate the difficulties in performing this task, broadband networks in general must first be understood. Thereafter Digital Subscriber Line (DSL) networks and their equipment are investigated, relevant configuration parameters of these described, methods of analyzing these parameters developed, and lastly algorithms that may lead to power savings are proposed.

Progress is mainly made within the investigation of the configuration parameters of the equipment and whether they can be used to lower its power consumption. A tool is developed that significantly simplifies both the process of finding relationships between parameters and power consumption, and implementing algorithms that control the device. The methods that are proposed could in theory be applied to reach the goals of the project.

The requirements for reaching the aforementioned goals are met with no less knowledge and experience than those acquired in studying for a Master of Science. These include a keen skill for problem solving, quick apprehension, rationality, and both general and specialized scientific knowledge.

Sammanfattning

Projektet ämnar att minska effektförbrukningen i bredbandsnätverk genom att utveckla mjukvarualgoritmer som kontinuerligt och automatiskt konfigurerar deras utrustning för detta ändamål. Den främsta motiveringen är att detta minskar både nätverkets miljöpåverkan samt operatörernas utgifter.

För att uppskatta svårigheterna i att utföra denna uppgift, måste först bredbandsnätverk förstås i allmänhet. Sedan undersöks DSL-nätverk och dess utrustning, relevanta konfigurationsparametrar av dessa beskrivs, metoder för att analysera dessa parametrar utvecklas, och till sist föreslås algoritmer som kan leda till minskad effektförbrukning.

Framsteg görs framförallt inom utredningen av utrustningens parametrar och hur de kan användas för att minska dess effektförbrukning. Ett verktyg utvecklas som avsevärt förenklar både processen att hitta samband mellan parametrar och effektförbrukning, samt att implementera algoritmer som kontrollerar utrustningen. Metoderna som föreslås kan i teorin appliceras för att nå projektets mål.

Kraven för att nå de tidigare nämnda målen möts med ingen mindre kunskap och erfarenhet än dem erhållna i studierna till Civilingenjör. Dessa innefattar en stark förmåga för problemlösning, snabb uppfattningsförmåga, rationalitet, samt både allmän och specialiserad vetenskaplig kunskap.

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Chapter 1.

Introduction

This project aims to lower the power consumption of DSL networks by developing software algorithms that continuously and automatically configures equipment to achieve this goal. The environmental impact of the networks will decrease. The expenditures for the operator will be lowered due to minimizing the need for manual interventions and minimizing their expense for energy. These motivations are given in relation and with consideration to the possible resulting loss of performance.

1.1. Motivations

The evolution of technology is changing the Earth by greater use of resources than ever before. Enormous quantities of energy stored as fossil fuels are being released at a higher rate than it ever has. Land is covered by fields of crop, cities, homes, industry, and highways. Global temperatures have been shown to be increasing [1]. The diversity of species is decreasing. Meanwhile, nature itself is counteracting some of these effects. Thoughts of preservation such as environmentalists acting to preserve forests and animal life and researchers inventing methods that decreases negative impact of technology, are enabling mankind to counteract some of the negative effects of the growing population and its rising standard of living.

Information exchange plays a large role in the world we live today. The Internet brings everyone and everything closer to each other and makes it easier to regard the world as a single entity. Broadband is the driving force behind this change, but as the subscriber count is passing half a billion [2], consideration must be given to the power requirements of this global network. The total energy consumption of broadband equipment in Europe is estimated to reach 50 TWh per year in the year 2015. There exists a goal to halve this figure to 25 TWh set by the Renewable Energy Unit, Institute for the Energy, Joint Research Centre, of the Directorate-General of the European Commission [3]. Ericsson among other telecom equipment manufacturers is in pursuit of this goal, which has lead to the proposal of this thesis work, as well as many other projects.

1.2. Problem description

This project aims to lower power consumption in fixed broadband access (FBBA) networks by developing software algorithms that performs self-optimization of relevant network equipment. Much as humans are increasingly attempting to reduce their own environmental impact, the broadband network should by itself strive to be in balance and to exploit all opportunities to be power efficient, all the time. In pursuit of this goal, emerging concepts for self-optimization of wireless networks, applied to fixed broadband access networks, shall be used in addition to the introduction of novel approaches.

The analysis shall include a realistic approach for trading power consumption against other performance indicators such as bit rate and stability. The algorithms to be developed shall be characterized in terms of power reduction abilities, convergence time, complexity, interface requirements, and other implementation aspects. The main target technology that this project will focus on is Very high speed Digital Subscriber Line 2 (VDSL2), capable of data rates up to 200 Mbit/s.

1.3. Thesis organization

Chapter 1, which you are now reading, introduces the thesis project and its motivations.

Chapter 2 first introduces broadband networks and the concept of Self-Organizing Networks (SON), and continues with describing the details of DSL technology. It reviews previous studies of how to measure the power consumption of broadband network equipment, and describes the existing methods for reducing its power consumption.

Chapter 3 describes how a graphical analysis and configuration tool was created for the purpose of allowing the proposed self-optimization algorithms to be developed.

Chapter 4 contains an investigation of what possibilities exist for lowering the power consumption of a DSL network, and also proposes methods of utilizing these in an autonomous system.

Chapter 5 gives the conclusions of the project and proposes future work that can be made into this area.

1.4. The reader

Efforts have been put into making this thesis readable by everyone. The reader is only assumed to have a rational mind that can follow the reasonings made, and the patience to come through to the final conclusions.

Chapter 2.

Background

Broadband technology, which is accessible in most parts of the world, is becoming a basic necessity for both personal and professional life. The technology that is being investigated in this work is DSL, specifically VDSL2. DSL broadband technology has been utilized to provision internet access for the largest portion of the installed subscriber base. In previous years this was also the fastest growing portion of the subscriber base [4]. By the end of June 2010 there was a total of 497 million broadband subscribers globally, of which 320 million (64%) were using DSL [2].

To understand the opportunities of lowering the power consumption in DSL networks, an overview of the technology and its historical evolution is given in Section 2.1. The concept of SON that will be utilized is introduced in Section 2.2. In preparation of the following chapters, a more technical introduction to DSL technology is given in Section 2.3. Power saving schemes for use in DSL transceivers have been standardized by International Telecommunications Standardization organization (ITU-T) and are described in Section 2.5.1.

Ericsson and other telecom companies together with the European commission has the goal of reducing the power consumption of the broadband networks in Europe by 50% until the year 2015 [3]. Some studies of how this can be achieved have been found and shows that there indeed are opportunities to allow this to happen [5, 6, 7, 8].

There are many studies investigating how the concept SON can be applied to wireless networks. Ericsson has done research into how some parts of SON can be used in improving wireline broadband networks like DSL networks [9, 10].

2.1. Broadband networks

In addition to DSL, the dominant broadband technologies are Cable and Fiber To The x, where x is generally Home or Curb. Currently, wireless access constitutes less than 2.6% of the total market [2], but is increasing globally [11]. The total energy consumption of the broadband equipment in Europe is estimated to reach 50 TWh per year in the year 2015 [3]. A large amount of this power today is consumed by the DSL equipment - consisting of devices at both the subscriber and the operator premises.

2.1.1. Topology

Figure 2.1 illustrates the general topology an Internet Service Provider (ISP) network providing e.g. web access and Internet Protocol television (IPTV) through e.g. DSL or a Passive Optical Network (PON). The part of the network that this work focuses on is the IP DSLAM (Internet Protocol Digital Subscriber Line Access Multiplexer), the CPE (Customer Premises Equipment) and the copper cables between them.

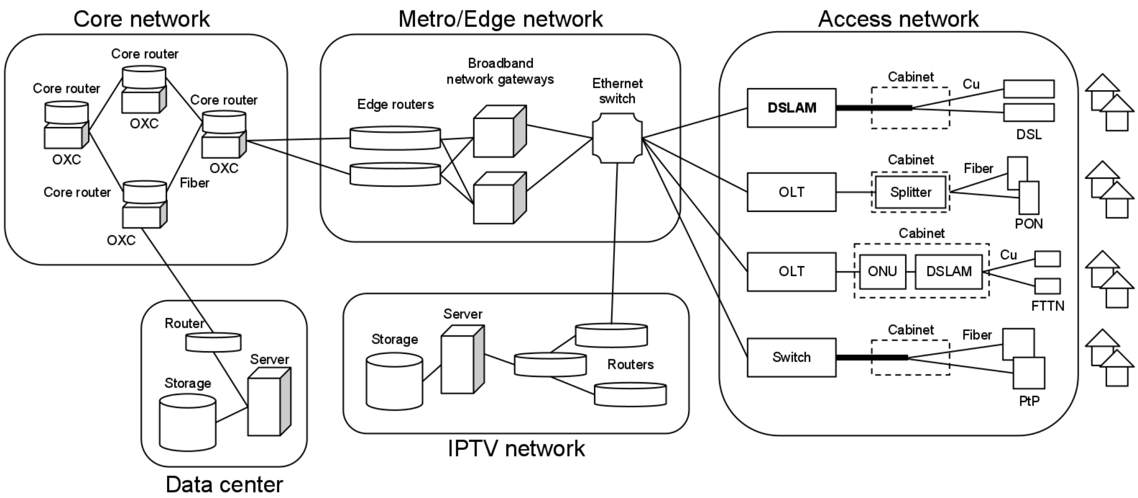

Figure 2.1.: General topology of an ISP network [12]

2.1.2. DSL standards

As a straightforward evolution of the Plain Old Telephone Service (POTS) copper wireline network, DSL grew out of the Integrated Services Digital Network (ISDN) standard developed in the 1980's [13].

High bit rate Digital Subscriber Line (HDSL) was the first DSL version to emerge in the early 1990. HDSL supported payload transfer rates of up to 2048 kbit/s per twisted pair (TP) [14]. The technology was primarily intended for use by business customers and did not allow POTS on the same twisted pair.

HDSL modems used high-speed Digital Signal Processor (DSP) circuits. These circuits were implemented on a single integrated circuit chip using Very-large-scale integration (VLSI). These also executed adaptive echo cancelation, equalization, and filtering in real-time, as required to compensate for the impairments of the transmission cables [13].

The successor to HDSL was Single-pair High-speed Digital Subscriber Line (SHDSL). SHDSL supported payload bit rates of up to 2312 kbit/s per twisted pair [15].

Asymmetric Digital Subscriber Line (ADSL) was developed for residential customers requiring both POTS and DSL over a single twisted pair. Its standardization occurred concurrently with HDSL and is today by far the most widely deployed type of DSL.

ITU-T G.992.1 (ADSL1) specifies a maximum downstream data rate of 8 Mbit/s. Its successor, Asymmetric Digital Subscriber Line 2 (ADSL2) within ITU-T G.992.5 Annex M increased this figure to 24 Mbit/s [16].

The target technology of this work, VDSL2, was standardized as ITU-T G.993.2 (VDSL2) in 2006 [17]. It was made similar to the ADSL2 standard in terms of features and management, for allowing them to be implemented on the same platform.

Operators had demands on VDSL2 covering wide ranges in bandwidths, loop lengths and deployment environments, so the standard introduced the concept of parameter profiles. A profile incorporates a set of parameters which optimizes the system for a specific deployment scenario. For example, one profile can make the system optimized for long reach but low bandwidth (hence low data rate), while another profile enables data rates of up to 100 Mbit/s over short distances. Eight profiles were included in ITU-T G.993.2 (VDSL2), named 8a, 8b, 8c, 8d, 12a, 12b, 17a, and 30a, and are illustrated in Figure 2.8.

2.2. Self-Organizing Networks

The SON concept aims to reduce Operator Expenditures (OPEX) by minimizing the requirement of human involvement in network operational tasks. Some guidelines on how to deploy self-organization into an existing wireless cellular network are available [18]. SON was initially described for use in next generation wireless communication networks, but may be adopted for use in fixed broadband access networks.

The SOCRATES project aims to enhance the operations of wireless access networks by "integrating network planning, configuration and optimization into a single, mostly automated process requiring minimal manual intervention" [19, 20], illustrated by Figure 2.2. This involves development of novel concepts, methods and algorithms. The project is supported by the European Union and brings together for example Ericsson AB, Nokia Siemens Networks and several research organizations.

SON is divided into subtasks listed and described in Table 2.1. To perform self-optimization of wireless networks, a diverse set of radio parameters need to be continuously analyzed, predicted and adjusted. These regard for example transmit power, antenna characteristics or scheduling, and have intricate interdependencies. Major challenges exist in developing algorithms that are able to autonomously execute this task.

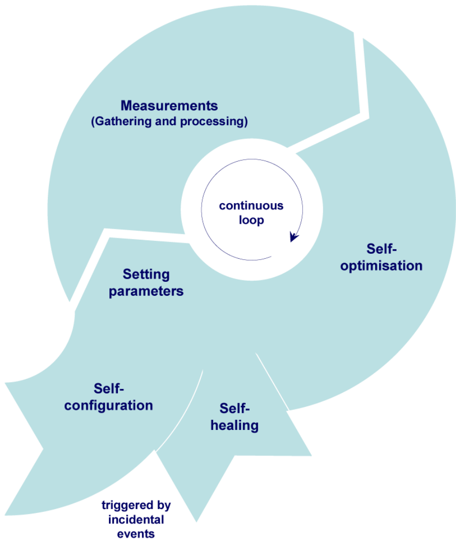

Figure 2.2.: SOCRATES SON concept [20]

Topic	**Description**
Self-Configuration	‘Plug and play´ behavior of new installed network elements to reduce costs and simplify installation procedure.
Self-testing and self-healing	System detects problems itself and mitigates or solves these to avoid user impact and to significantly reduce maintenance costs.
Self-optimization and self-tuning	Parameter optimization based on network monitoring and measurement data from terminals to minimize operational effort and increase quality and performance.

Table 2.1.: SON subtasks [19, 20, 18]

Lets observe Figure 2.2 and start at the measurements phase. A multitude of measurements of e.g. communication channel characteristics or traffic are collected at this stage. The data is processed in order to give the best indicators to the next phase. During self-optimization the previously processed data is used to derive an updated set of configuration parameters that in the ideal case leads to a fully optimized system.

The self-configuration phase in Figure 2.2 is entered if new hardware is installed (in the case of wireless networks: a new cell or radio base station) and involves adjusting the parameters of all the neighboring hardware devices according to the new 'whole picture'. If some hardware fails, the self-healing phase is entered in which the devices are configured to cover for the loss in capacity or performance.

Figure 2.3 illustrates the performance enhancement that is due to self-optimization: as the traffic load grows over time, a network applying self-optimization techniques manages to deliver better service quality than a network not utilizing self-optimization [19].

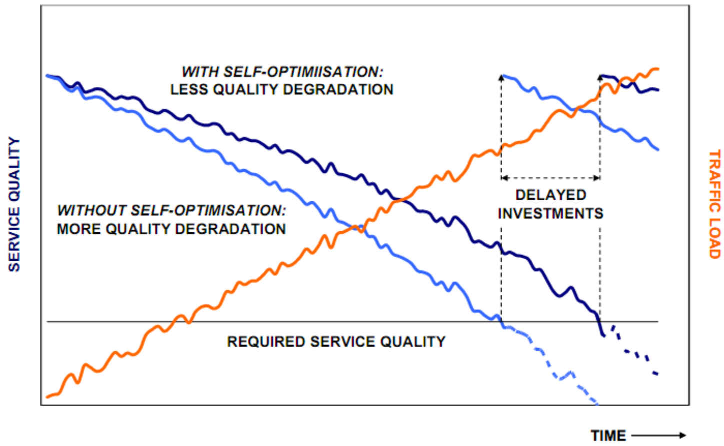

Figure 2.3.: Impact of 'self-optimization' [19]

2.3. DSL technology

In order to understand the following chapters it is important to know the basic workings of the technology that is under investigation. This chapter describes the IP DSLAM, how it works together with the CPE and how its configuration can be changed through management tools.

2.3.1. IP DSLAM

The IP DSLAM is the most essential equipment of a DSL network. It is located in a remote cabinet close to the customer or in a more distant central office building owned by the operator, and connects customers to the aggregation network and Internet backbone. It is common that a single IP DSLAM contains up to 24 DSL modems, each communicating with a modem housed at the customer premises (CPE). The size of the IP DSLAM device is about the same size as one CPE, despite its larger amount of lines.

An IP DSLAM consists of several components depicted in Figure 2.4. These include interfaces for communication with the backbone network, DSL interfaces, an NWP (Network Processor) with corresponding memory, an ethernet transceiver, one or more Digital Signal Processors (DSPs), an Analogue Front-End (AFE) including A/D and D/A converters for each line, line drivers, a power supply, fans, and other auxiliary systems. Each DSL line needs at least one AFE and one line driver, but the other systems can be shared by several lines.

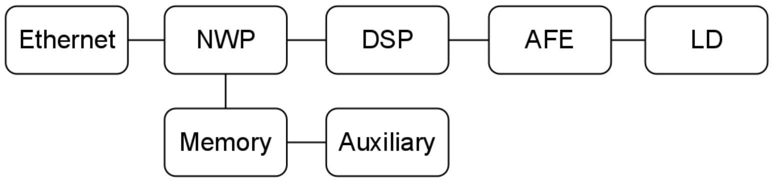

Figure 2.4.: General components of an IP DSLAM

2.3.2. DSL transmission mechanisms

The blocks in Figure 2.5 are all essential in the transmission of data across a DSL communications link.

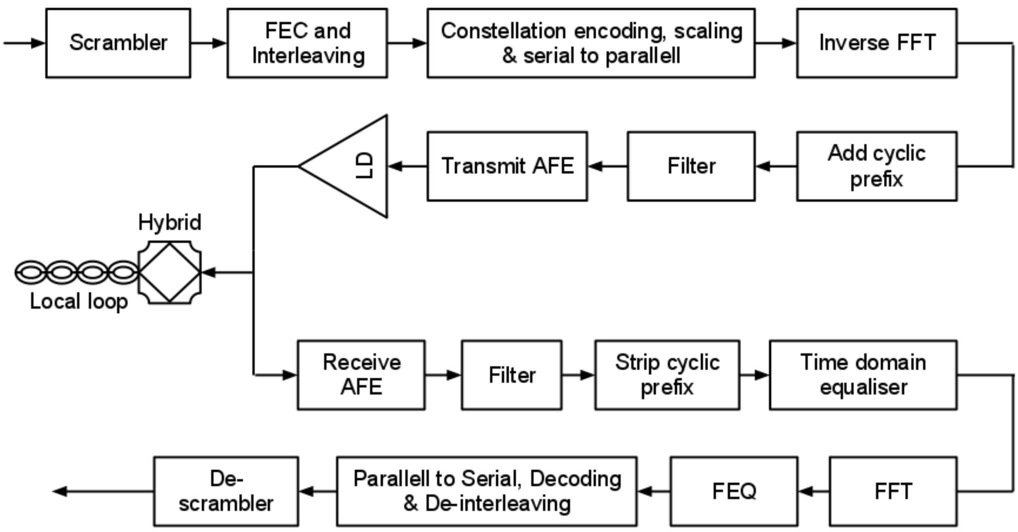

Figure 2.5.: Multi-carrier DMT based transceiver [21]

As telephone lines were not designed for digital data transmission and consist of pairs of long, unshielded copper wires, the transfer is prone to errors. Several methods exist to cope with this, most using some sort of coding of the data which makes it predictable. The common methods used in DSL is interleaving and Reed-Solomon coding which together provide a very robust error correction system.

Reed-Solomon coding works by introducing redundant information to the transmitted data, which makes each codeword more distinguished. When a codeword is decoded and an error is detected, the unaffected original message can be determined as the most likely one in a limited set. Reed-Solomon coding is used effectively against Gaussian noise, where all transferred codewords are affected similarly. Impulse noise could severely affect one part of a codeword, making it hard to distinguish from other codewords and thus preventing error correction.

In order to reduce the negative effects of impulse noise, interleaving is used. The principle is to spread out the information temporally, decreasing the likelihood of an impulse destroying a large portion of a message, and instead affecting several messages by a lesser amount.

Figure 2.6 illustrates an interleaver, essentially being a buffer memory into which outgoing data is put and read out by the transmitter which then performs the modulation and transmission. The interleaver is composed of several Reed-Solomon coded messages depicted as rows. The information is read and then sent in a left-to-right, top-to-bottom manner. At the receiving end, the process is reversed. In the figure, blocks of data that has been affected by impulse noise are indicated by crosses. As seen, the errors are spread out over several codewords, resulting in each having a higher probability of being reconstructed.

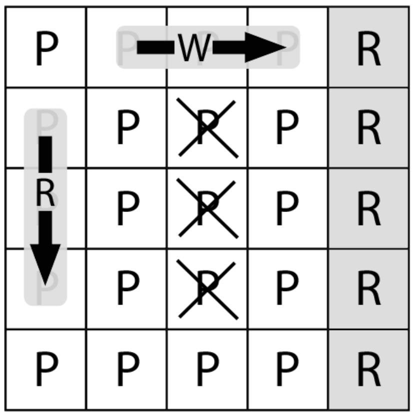

Figure 2.6.: Interleaver

2.3.3. Transmission parameters

Before the DSL link is established, a procedure called line initialization (Figure 2.7) determines optimal conditions for the physical layer. One set of parameters (Table 2.2, page 10) are used to steer this procedure by for example limiting the output power, which will affect e.g. the attainable bit rate.

Another set of parameters (Table 2.3, page 11) that are read-only represents the characteristics of the physical connection between the IP DSLAM and the CPE and are calculated during the initialization procedure.

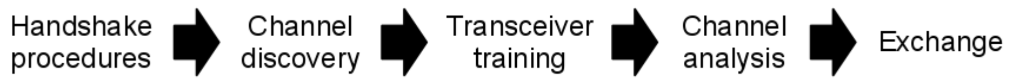

Figure 2.7.: DSL initialization procedure [22]

The most interesting adjustable parameters are listed in Table 2.2. They are all interconnected through relationships set by the software algorithms that controls the line initialization. The relationships are described by the ITU-T DSL standards, but extended by the equipment manufacturers within their proprietary software, and are thus hard to fully investigate.

Parameter name	**Description**
Maximum output power	Limits output power.
Minimum line rate	Line rate lower limit.
Maximum line rate	Line rate higher limit.
Target Signal-to-Noise Ratio (SNR) margin	The SNR margin that must be achieved for the line initialization to succeed.
Minimum SNR margin	SNR margin threshold below which the output power will be increased to maintain the target SNR margin.
Maximum SNR margin	SNR margin threshold above which the output power will be decreased.
INP	Impulse noise protection is defined as the number of consecutive Discrete multi-tone modulation symbols, or fractions thereof, as seen at the input to the de-interleaver, for which errors can be completely corrected by the error correcting code, regardless of the number of errors within the errored Discrete multi-tone modulation symbols (see Table 7-7 in [22]).
Interleaver delay	Improves the error correction capabilities of the ADSL connection, so that fewer retransmissions are required, long delay improves more than short delay.

Table 2.2.: Important adjustable transmission parameters

Parameter name	Description
Output power	The current output power on one line.
Actual line rate	The current attainable data transfer rate.
SNR margin	The difference between the SNR required to maintain an accepted quality of service and the actual SNR.

Table 2.3.: Important parameters characterizing an established line.

As mentioned in Section 2.1.2 there are, in addition to the parameters mentioned above, eight profiles defined for VDSL2 (Figure 2.8) intended for optimizing the line for different deployment scenarios. Contained in these profiles are settings related to for example maximum output power and which frequencies the devices are allowed to transmit on.

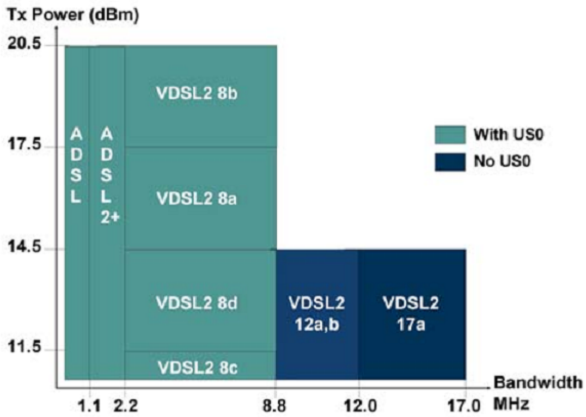

Figure 2.8.: VDSL2 profiles

2.3.3.1. Parameters closely related to SNR margin

As mentioned in Table 2.3, the SNR margin is related to the quality of service, and thus the Bit Error Ratio (BER). The SNR is measured continuously to ensure a Bit Error Ratio of 10^{-7} or better. If the Bit Error Ratio drops below this threshold, actions are taken to improve the line quality. If the improvement fails, the line is disconnected. Aiming for an SNR margin at 6 dB improves the Bit Error Ratio, and makes the line more robust, to cope with the varying line conditions that can occur.

Target SNR margin is the SNR margin which always must be achieved for successful training. Target SNR and other parameters related to SNR margin are listed in Table 2.4 (page 12).

Parameter name	**Comment**
Target SNR margin	The bit rates can be selected with priority to higher bit rates if the Target SNR margin is easily achieved. After the line comes up, the actual SNR margin will not always be the same as the target SNR margin. If the target SNR margin cannot be achieved, the line will be closed and a trap will be issued.
Maximum SNR margin	If the actual SNR rises above the maximum SNR margin, the output power will be reduced, if possible. The maximum SNR margin is absolute, and must be equal to or greater than the target SNR margin.
Minimum SNR margin	If the actual SNR falls below the minimum SNR margin, the output power will be increased. If this is not possible, the line will be retrained, if 1 minute has elapsed and the SNR is still below the minimum SNR margin. The minimum SNR margin is absolute, and must be equal to or less than the target SNR margin.

Table 2.4.: Parameters closely related to SNR Margin

2.3.3.2. Transmit PSD modes

For prioritizing either higher data rates or lower power consumption, a parameter exists that acts as a guideline to what PSD (Power Spectral Density) levels should be set at line training for the Showtime state. The parameter is called 'Transmit PSD' and the modes related to it are listed in Table 2.5.

2.3.3.3. Rate adaptation modes

In addition to the transmit PSD modes, there exists rate adaptation modes. When rate adaptation at runtime is enabled the IP DSLAM will dynamically adjust the data rate according to the current SNR on the line during Showtime.

When rate adaptation at runtime is enabled, the parameters downshift/upshift noise margin and downshift/upshift minimum time are available. If the actual SNR falls below the downshift margin for more than the downshift minimum time, the line rate will be decreased. If the actual SNR rises above the upshift margin for more than the upshift minimum time, the line rate will be increased.

Mode	Comment
Priority to rate	The line will be trained to have a rate between the minimum and maximum values, while meeting the target SNR. The transmit power that will be used is the power necessary to achieve the rate.
Priority to power	The line will be trained to use minimum possible transmit power between minimum and maximum, while meeting the target SNR. It means in practice that the line will be trained to the minimum data rate, but if increasing the data rate does not increase the power demand, the line will be trained to a higher data rate.
Fixed	The IP DSLAM will use all the available transmit power. The line will be trained to a point between minimum and maximum data rate. The line will be the most robust, since more power is used than what is normally needed.

Table 2.5.: Transmit PSD modes

2.3.4. Management

Market reviews have shown a great interest for SON, but operators are somewhat reluctant to hand over control of their networks to the network itself, and it is therefore important to have a basic understanding of the existing network management tools.

In addition to the tools described below, Ericssons Copper Plant Manager (CPM) product contains a feature called DSL Auto Optimizer (DAO). This feature enables the operator to choose a time window in which the lines can be tested with a chosen set of profiles. After the test has been run it makes a comparison of the service quality (e.g. bit rate) between the profiles and the best one is suggested to the operator [23].

2.3.4.1. EDA Management Proxy

Figure 2.9 shows a part of the page of Ericssons EDA Management Proxy (EMP) software that is used by operators to configure a DSL line. The EMP is accessible through an internet browser and is installed as a web service on an Ethernet Controller Node (ECN). As the ECN can have many IP DSLAMs connected, hundreds of DSL lines can be managed through this interface.

In this thesis work, the EMP was used in the initial investigations of what parameters could affect the power consumption of the IP DSLAM, as described in Section 4.1.2.1.

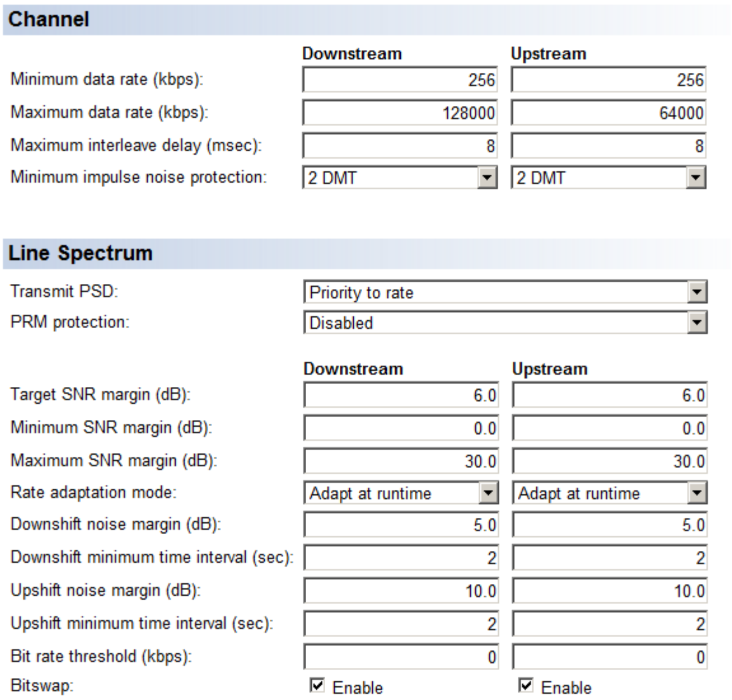

Figure 2.9.: A part of the VDSL2 line profile configuration page in the EMP web interface.

2.3.4.2. Management Information Base (MIB)

A MIB (Management Information Base) is a database used for managing the entities in a communications network. The database is tree-structured, and an entry is called MO (Managed Object) and is addressed through an OID (Object Identifier). Each type of equipment in the network has their own set of MOs, but some equipment can contain MOs that reports information about another connected piece of equipment. In Ericssons IP DSLAMs there are many MOs that reports data from the connected CPEs e.g. the downstream SNR margin etc.

In this work, Ericssons MIB descriptions were used. Ericsson has two documents describing the MIB for their IP DSLAMs, one containing MOs based on the standards [25] and one containing and extended set of proprietary MOs [26]. The standard-based document is based on the Internet Engineering Task Force (IETF) document RFC5650 which defines a MIB module for use with network management protocols for the purpose of managing VDSL2, ADSL, ADSL2, and Asymmetric Digital Subscriber Line 2 Plus (ADSL2plus) equipment [24].

2.4. Methods for measuring power consumption

Several methods of how to measure the power consumption of network equipment have been described in literature [3, 27, 28, 29]. When modeling the network there are two kinds of traffic configuration methods described in the following two paragraphs.

In the first method all the IP DSLAM ports are connected to CPEs through loop or line simulators, shown in Figure 2.10. By using this method the traffic can flow properly between IP DSLAM and CPE.

In the second method each port is individually trained (synchronized) on a certain loop and CPE, then its power consumption is "blocked" with the command ShowTime Lock or ShowTime Freeze and finally each port is connected to dummy loads with resistance of 100 Ohm. In this method there can be no traffic flowing, but the line drivers are active and consuming the same amount of power as it would do if the line was carrying traffic at maximum rate. In real networks there is traffic flowing through the IP DSLAM ports which requires the line drivers to be active. As the line driver's power consumption constitutes a large proportion of the total power consumption, it is important to take its function into consideration.

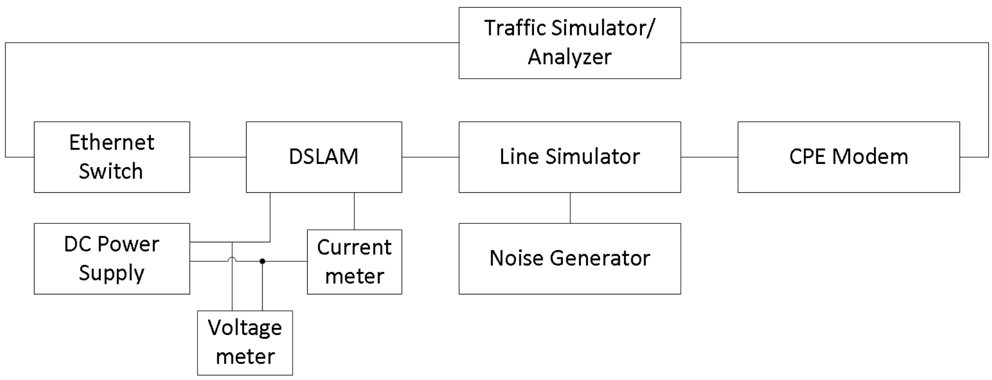

Figure 2.10.: Test Setup for power measurement for DSLAM

The following three definitions for the power consumption of network equipment are generally used [27] :

1. **PBBline**: Power consumption per line (in W/port) [3, 28].

$$PBBline = PBBeq \ / \ Nsubscrib\text{-}lines \tag{2.1}$$

Where PBBeq is the power consumption (in W) of fully equipped broadband equipment (IP DSLAM) connected to line simulators and CPE modems, measured at room temperature ($25 \pm 2°C$) and supply voltage -48 V DC. Nsubscrib-lines are the maximum number of subscriber lines served by the broadband equipment (IP DSLAM) under test. The smaller PBBline, the higher energy efficiency. [27]

2. **NPC**: Normalized Power Consumption (in mW/Mbps/km). It is an indicator of the amount of power required to transport 1 Mbps of data over a 1 kilometer distance [28].

$$NPC = 1000 * PBBline / (bitrate * line\ length) \tag{2.2}$$

   Where bitrate is in Mbps and loop length is in km. For IP DSLAM, the NPC shall be based on the bitrate and reach at full-power state. The smaller NPC, the higher energy efficiency.

   Using the NPC to compare the different working states (e.g. L0 with L2 or L3) is not recommended as the intention of some of these working states is to save energy at times of no or low-rate transmission - i.e. when there is no need to transmit high data rates.

3. **TEEER**: Telecommunication Equipment Energy Efficiency Rating defined by the North American operator Verizon [29]. This indicator considers the power consumption in 3 utilization conditions (at 0% load, 50% of maximum load and maximum load) to simulate the power consumption in actual network.

$$TEEER = (Access\ Lines / PTotal) + 1 \tag{2.3}$$

   Where $PTotal = (0.35\ x\ Pmax) + (0.4\ x\ P50) + (0.25\ x\ Psleep)$, Pmax is the average power measured at maximum load (100% duty cycle), P50 is the average power measured at 50% of duty cycle, and Psleep is the average power measured in a sleep or no activity mode. Access Lines are the maximum number of subscriber lines served by the broadband equipment (IP DSLAM) under test. The higher TEEER, the higher energy efficiency.

There are two aspects that influence the Energy Efficiency Index for the same type of equipment: one is the performance or functionality that equipment can provide, the other is the power consumption of the equipment. The more robust functionality and the lower power consumption, the higher energy efficiency. In fact , there exists balance between power and performance. If the power is reduced, then the performance may be lower than previous. The influencing factors are listed below [27].

1. The maximum numbers of access lines or the configuration.
2. The parameters of configuration including the Model of CPE, the loop diameter and length, the actual downstream and upstream data rate, actual transmit power and actual target noise margin etc.
3. The additional functions such as MELT (multi-ended line test), vectoring and bonding etc.

4. Power supply efficiency
5. Cooling strategy
6. Environment conditions such as measurement temperature, humidity etc.
7. Accuracy of Measurement Instruments
8. Power saving solutions such as low power state (L2 mode) and Standby (L3 mode) etc.

As suggested by the Environmental Engineering (EE) Measurement Methods and limits for Energy Consumption in Broadband Telecommunication Networks Equipment [28], the following details shall be included in a power measurement report:

- System configuration - in particular the number of active line boards and ports.
- List of hardware items used in the system under test, showing both the vendor type number and serial number.
- List of software/firmware modules used in the system.
- List of test equipment used to measure the power consumption.This also includes the CPE used for the measurement.
- Ambient temperature.
- Actual supply voltage.
- Voltage and current at interface "A".
- The status and number of all end-user interfaces.

2.5. Existing methods for reducing power consumption

There are already many opportunities to lower the power consumption of broadband networks. Some of the solutions are VDSL2 profiles, power management states, more efficient components, Dynamic Spectrum Management (DSM), Seamless Rate Adaptation (SRA) and PhyR.

2.5.1. Power management states

ITU-T recommendation ITU-T G.992.3 (ADSL2) defines a set of power management states for ADSL2 equipment [22] (see Table 2.6). To reduce both power consumption and interference the transmit power is lowered when bandwidth usage on a line falls below some threshold value for a certain amount of time. When bandwidth usage exceeds another threshold, the normal mode of operation is restored as fast as possible. Equipment at the operator (ATU-C) and customer (ATU-R) communicate regarding the conditions for making a transition between power states.

Table 2.6 defines the three basic power states for ADSL2 according to the ITU-T G.992.3 (ADSL2). The state of normal operation is called L0. By entering the low power state L2, in the case of a IPDSLAM (Internet Protocol Digital Subscriber Line Access Multiplexer) in Ericsson's EDA 1200 product family, transmit power is reduced by up to 25% [30]. A sufficient SNR margin is maintained to preserve the minimum data rate and service quality. When this same IP DSLAM is operating in the idle state L3, power consumption is reduced to 50% compared to the full on state [31]. In L3, no data can be transferred except for messages that brings the link state back to normal.

Link state	**Name**	**Description**
L0	Full on	ADSL link is fully functional
L2	Low power	ADSL link is active, but operating at low power
L3	Idle	There is no signal transmitted at the U-C and U-R reference points. The ATU may be powered or unpowered in L3.

Table 2.6.: Power management states according to ITU-T G.992.3 [22]

Transitions from state L2 or L3 to L0 can cause instability in other customers' connections, hence such schemes are permanently disabled by network operators [31]. The reason for this instability is that the transition induces noise into adjacent lines. This can have detrimental effects in the form of data transmission errors or in severe cases destroy the other link and require a time-demanding line re-train.

Figure 2.11 illustrates how transmit PSD is adjusted during the transition between states L0 and L2. When the L2 state is entered, transmit PSD is lowered in a stepwise fashion as to minimize the risk for service interruptions. Parameters that can be changed by equipment operators are the amount of transmit PSD decrease in each step (L2 Aggregate Transmit Power Reduction (L2ATPR)) and the minimum time between two consecutive steps (L2-TIME).

As power continues to be lowered, as seen in Figure 2.11, it eventually reaches a maximum total value of reduction specified by the parameter L2 Aggregate Transmit Power Reduction Total (L2ATPRT), which can also be changed. User data throughput is continuously monitored, and if it demands a higher bandwidth (thus transmit power), L0 is re-entered as fast as possible. A final parameter declares the minimum amount of time that L0 has to be maintained before L2 can be entered again. [32]

Guidelines have been set by Ofcom (a regulator in the UK) and the Broadband Forum for mitigating the bad aspects of ADSL2 power management [32, 33].

VDSL2 currently only supports the L3 mode, which disables transmission completely, but Ericsson has proposed and filed intellectual property rights on a low power state for VDSL2 with which power consumption can be lowered by 10-30 % [31, 5].

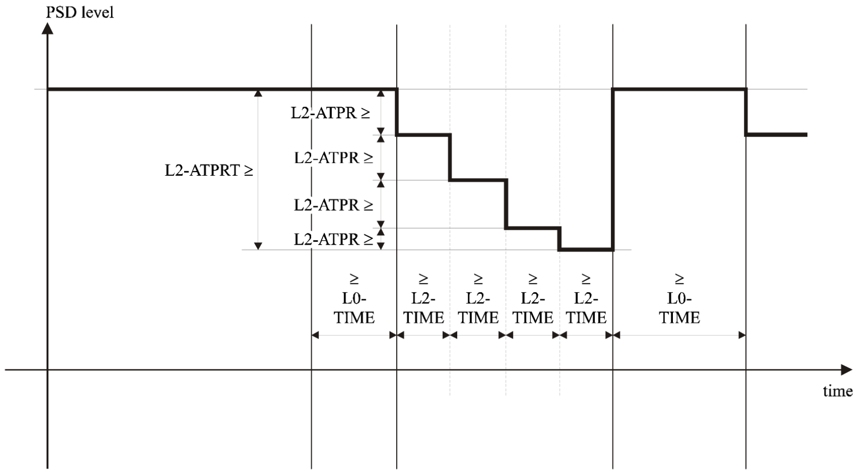

Figure 2.11.: Illustration of the L2 power state control parameters

2.5.2. Efficiency of electronics

The biggest opportunities for lowering the power consumption of the IP DSLAM seems to lie within the usage of newer hardware components. Ericsson has done research into how the power consumption of the IP DSLAM can be decreased substantially through the use of for example new and smarter line drivers [5].

Line drivers are responsible for 36% of the total power consumption of a VDSL2 line compared to 46 % for an ADSL2+ line [7, 8]. Most VDSL2 profiles are limited to 14.5 dBm output power, and the consumption of VDSL2 devices is more evenly distributed among the Network Processor, DSP, AFE, and line driver [5].

As described in Section 2.3.1 some of the IP DSLAM subsystems shown in Figure 2.4 are shared between several lines. In addition to upgrading the line driver, the Network Processor can be shared between more lines, hence reducing the power consumption per line.

For the IP DSLAMs investigated in this work, about half of the power consumption is still present even if the line is disabled since the network processor and some other subsystems are still active. The Network Processor cannot be disabled completely since it must be active waiting for management traffic. One idea for improvement is to decrease the Network Processor clock frequency and/or supply voltage when traffic intensity is low [5].

Ericsson has developed a low-power, 'green' IP DSLAM EDN 612nef. It has been optimized for using 14.5 dBm profiles to achieve total power savings of 30%, or 1 W per line compared to the preceding version [34]. These savings are mainly due to that its use of a different line driver [5].

In research performed by Alcatel-Lucent Bell Labs [7], it was discovered that "reducing the Aggregate Transmit Power (ATP) from the mandated 20 dBm maximum down to 17.5 dBm in case of ADSL2(plus) reduces the line driver power consumption by 20 to 25 %; hence reducing the total power consumption by about 10 %. Going down to 14.5 dBm (resp. 11.5 dBm) yields a 30 to 40 %(resp. 45 to 50 %) reduction of the line driver supply power, while reducing ATP below 11.5 dBm results in little further gain".

Chapter 3.

Development of a power optimization tool

This chapter outlines the development of a graphical tool called Mibber which provides the means to reach the goal of this work. The tool is capable of performing concurrent measurements of the power consumption and the configuration parameters of a device, as well as making it easier to develop algorithms which controls these parameters.

3.1. Purpose

In order to get a sufficient understanding of the device behavior and the complex relationships between its configuration parameters, as well as their effect on its power consumption, a tool which presents these parameters graphically is required.

The tool displays synchronized graphs of the power consumption and the values of any relevant configuration parameters of the device. It also provides easy ways to modify the parameters and control them through scripts. This allows for the development of algorithms which have the potential of lowering the power consumption of the device.

3.2. Description

Figure 3.1 shows the main view of Mibber. The left pane contains graphs of the power consumption and the values of some configuration parameters of an IP DSLAM. The horizontal axes of the graphs shows the time in seconds since the data started being fetched. All graphs are synchronized in time, which simplifies the discovery of any relationships between the behaviors of the parameters. A vertical scroll bar enables the monitoring of many parameters at the same time.

The thin pane at the bottom contains controls for changing the time interval from which values in the graphs are displayed, as well as controls for changing the height of the graphs. By adjusting these parameters through the controls, which affects the

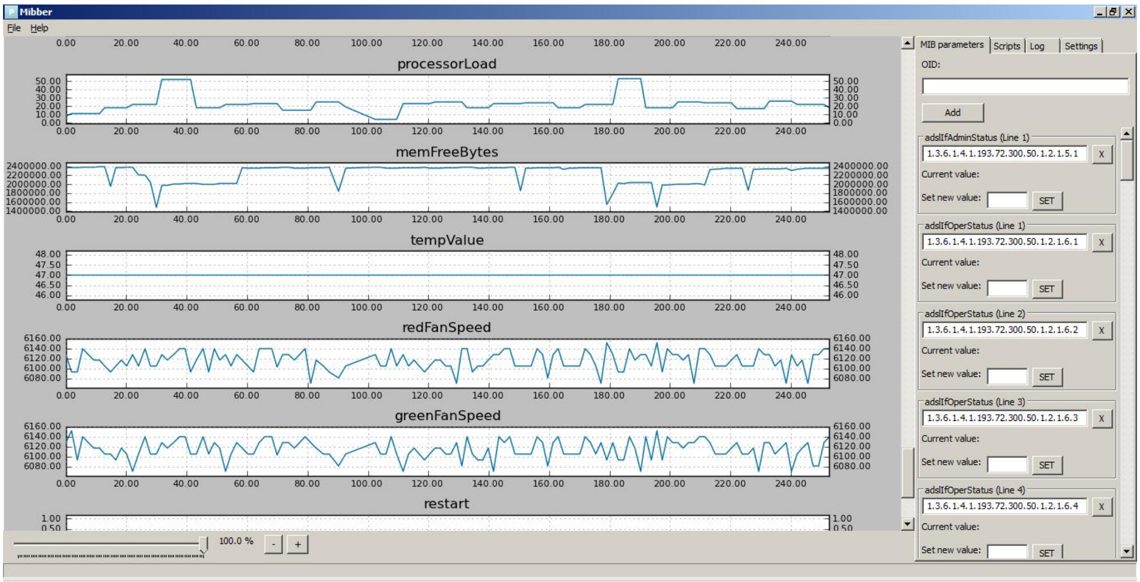

Figure 3.1.: Main view of Mibber

appearance of all graphs at the same time, relationships between parameters can be unveiled at both large scale and fine detail.

The right pane contains controls for adding a parameter to be monitored, and a list of all currently monitored parameters accompanied with controls for setting new values of these. The top menu and right pane tabs allows for saving the graphs to an image file, enabling or disabling logging of the data to text files, and activating scripts.

3.3. Development process

3.3.1. Choice of programming language and packages

Mibber was developed through the use of the programming language Python. The choice of language was made on the grounds of being previously used as well as of convenience towards the implementation of real-time data acquisition, monitoring and control functions.

A software package known as Matplotlib was already available and provided an Application Programming Interface (API) for embedding plots into the Mibber Graphical User Interface (GUI). Although the use of this package largely simplified the development of the tool, the package was not designed for real-time plotting of a large set of parameters, and many hurdles had to be overcome in order to make this possible.

In addition to Matplotlib, a number of other software packages were used (Table 3.1), for example allowing for communication with the hardware through Ethernet or GPIB (General Purpose Interface Bus), and allowing database storage of the measurement data.

Package name	**Application area**
wxPython [35]	User interface
matplotlib [36]	Graph drawing
net-snmp [37]	SNMP-connection to e.g. the IP DSLAM
PyVISA [38]	GPIB communication with e.g. the multimeter instrument
pysqlite [39]	Database storage of information retrieved by scripts
guppy [40]	Performance profiling and debugging

Table 3.1.: Required Python packages

3.3.2. The groundwork: a basic Telnet parser

The invention of Mibber was preceded by the development of a small Python application that could retrieve readings of the power consumption of each IP DSLAM connected to a Power over Ethernet (PoE)-enabled port of the ECN.

The PoE information was only retrievable from the ECN through Telnet and not from the IP DSLAM or Simple Network Management Protocol (SNMP). Telnet was originally intended for enabling manual configuration of the device through a text-based communications terminal. To automate this otherwise manual procedure, an understanding was acquired of the Command-Line Interface (CLI) of the Ericsson ECN330 ([44]) and the VT100 terminal emulator technology that it uses.

The application communicated with the ECN by simulating the use of a keyboard to enter commands into the terminal and then extracting the returned information. The purpose of the tool was to verify the measurements that the multimeter made of the power consumption of the IP DSLAM. Unfortunately, the Very high speed Digital Subscriber Line (VDSL) IP DSLAMs consumed more power than was possible to handle by the PoE technology, i.e. greater than 25 Watts, and these readings could only be collected for the ADSL equipment.

3.3.3. Measurement information retrieval

Initially, Mibber retrieved power readings from the multimeter and MIB parameters and displayed them in a text console. The most important part of the application code is that which handles the communication with the devices and polls these for information uninterruptedly and in a reliable manner. For this reason focus went into improving this part of the code before a graphical interface was introduced.

To enable concurrent retrieval of data from multiple devices, threads were used. Software which uses threads has to be designed carefully to prevent faults arising due to conflicts between different parts of the program, for example the part that communicates with the multimeter and the part which communicates with the IP DSLAM.

It was especially important to prevent Mibber from unexpectedly stopping to function during an unsupervised measurement and/or autonomous configuration procedure. Of equal importance was the ability of the software to cope with transient interruptions in the connections to the devices and not let such an event prevent the future readout of data collected over a long time period. A significant proportion of the development work went into ensuring the stability of the data retrieval.

3.3.4. The configuration file

A configuration file is read at startup that contains a list of MIB OIDs which are to be monitored. This file can be easily modified by using a text editor. An example of a configuration file follows:

```
POWINSTR_PROTO = PROTO.IP
POWINSTR_ADDR = "147.214.90.205"
POWINSTR_PORT = 3490
DSLAM_IPADDR = "147.214.90.152"
DSLAM_PORT = 161
VERBOSE = False

PARAMS = [
['adslAturCurrSnrMgn (Ds)' , '1.3.6.1.2.1.10.94.1.1.3.1.4.1'],
['adslAtucCurrSnrMgn (Us)' , '1.3.6.1.2.1.10.94.1.1.2.1.4.1'],
['adslAturPerfESs (Ds)', '1.3.6.1.2.1.10.94.1.1.7.1.4.1'],
]
```

The POWINSTR_PROTO variable is used to indicate which communications protocol should be used towards the multimeter instrument, and can be either Internet Protocol (IP) or GPIB. If the protocol used is IP the POWINSTR_ADDR variable contains an IP-address and the POWINSTR_PORT the port number. If the protocol used is GPIB the POWINSTR_ADDR variable contains the GPIB address of the instrument and the POWINSTR_PORT is unused.

The DSLAM_IPADDR variable contains the IP-address of the IP DSLAM that is to be monitored. The DSLAM_PORT variable contains the port number on which the IP

DSLAM SNMP server is listening. The VERBOSE variable is used to enable a higher degree of log messages that is written to the standard output, i.e. a terminal window. The PARAMS structure contains a list of parameter names and OIDs that is to be monitored.

3.3.5. Application startup

Mibber is started by executing the file `mibber.pyw` which by default is associated with the GUI-suited Python parser. After the configuration file has been loaded, the application automatically connects to the IP DSLAM and the multimeter instrument and then starts retrieving data. The data will also be stored in two separate log files, one for the data retrieved through SNMP and one for the readings of the IP DSLAM power consumption retrieved from the multimeter.

3.3.6. The support for scripts

The use of Python as the programming language made it easy to allow for separate instances of software to be executed in parallel within the Mibber tool. These instances can potentially in real-time give feedback to the user through the graphs and simultaneously act as the control unit of a device feedback loop.

Mibber provides an interface towards the scripts, which allows the script to read the current and previously retrieved measurement values, i.e. from IP DSLAM MOs and power consumption, and also set parameters through SNMP. A further development of the interface could be to make the changes made by the script be visualized in the graphs by changing the color of the corresponding parts of the plot lines.

When a parameter is changed either through the script or through the GUI of Mibber, the new value is put in an internal queue. Without this queue it would not be possible to set several parameters at the same time unless the SNMP client and server supported multiple connections. The queue is being read with a specific interval, and its contents is used as the input to the SNMP client. When the SNMP client connects to the IP DSLAM, it sets all the parameter values from the queue, after which the items are cleared from the queue.

Chapter 4.

Methods for Power Savings

This chapter describes the methods used in aiming to reach the goal of lowering the power consumption of a VDSL2 network. It is divided into two parts, describing an investigation (Section 4.1) of parameters and the implementation (Section 4.2) that uses these parameters.

4.1. Investigation

Before attempting to develop an algorithm that can perform autonomous configuration of a device and lower its power consumption, an investigation had to be made into how the device reacts to changes of individual parameters. A VDSL2 network must first be set up in accordance with real deployments and prepared for allowing measurement of the power consumption of the devices within it.

The tool Mibber that was created within the thesis work and described in Chapter 3 greatly simplified this investigation and also facilitated the development of algorithms.

4.1.1. Measurement setup

The equipment being investigated is listed in Table 4.1 and its basic topology illustrated in Figure 4.1. Table 4.1 also contains some relevant properties of the devices. The actual physical connections are described in the following section.

Figure 4.2 shows how the different tools connects to the Network Processor and DSP within the IP DSLAM. The EMP web interface, Mibber and MIB browsers connects through IP and SNMP to the Network Processor. The Broadcom GUI was used when investigating some parameters related to the DSP which could not be changed in a predictable manner through the EMP interface, as described in Section 4.1.2.1.

Device	Description
ECN330 [41]	Ethernet Controller Node Contains the EMP (see Section 2.3.4.1).
EDN 612p [42]	IP DSLAM, 12 lines, VDSL2 configurable band plans/profiles: 8a / 8b / 8c / 8d / 12a / 12b / 17a, Maximum transmit power: 20.5 dBm, Idle power consumption: 2.15 W/line
EDN 612nef [42]	IP DSLAM (low power variant), 12 lines, Maximum transmit power: 14.5 dBm, Idle power consumption: 1.47 W/line

Table 4.1.: Equipment under investigation.

4.1.1.1. Physical connections

Based on the methods proposed in Section 2.4, the setup in Figure 4.3 was used, with the line simulator replaced with an actual copper loop allowing lengths of 500, 1000, or 1500 meters.

The reasons to why an actual copper loop was used instead of the perhaps apparently more convenient line simulator were that multiple lines were required to investigate the effects of crosstalk between cable pairs, and that a demand never was arisen for changing the loop length dynamically.

The copper loop was connected to the IP DSLAM through a cable which at one end had a DSL ports connector and at the other end having individual pins soldered and then inserted into the connector of the cable binder (Figure 4.4). Care had to be taken to insert the pins into the correct holes of the connector, so as to have the DSL lines consist of twisted pairs of copper loops within the cable binder.

4.1.1.2. Data traffic setup

Traffic flow through the DSL network was required in order to see the effects of line noise on performance, and the relationship between data throughput and power consumption. The traffic generator was connected at one end to the switch through a 1000BASE-SX multi-mode fiber optical cable using an Small Form-factor Pluggable (SFP) connector, and at the other end to the CPE through a 100BASE-TX cable. The traffic generator had one 1000BASE-SX Upstream (US)/Downstream (DS) connection and eight 100BASE-TX US/DS connections, which allowed two IP DSLAMs each with four CPEs to have traffic flowing through them (Figure 4.3).

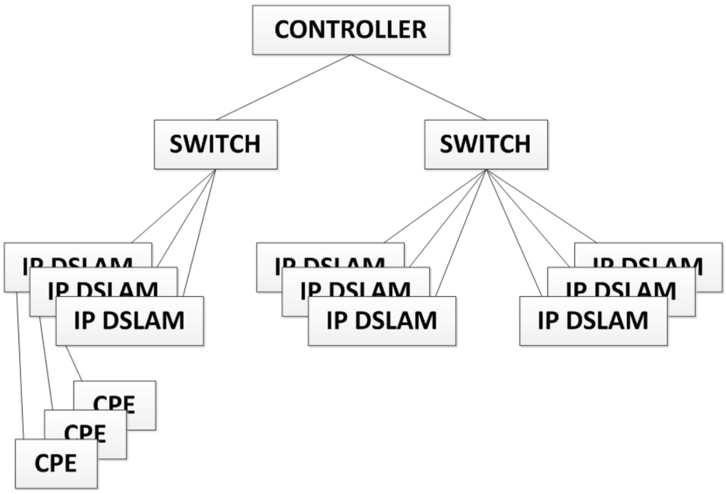

Figure 4.1.: Topology of the part of a DSL network seen in this work, constituting an Ethernet Access Node (EAN)

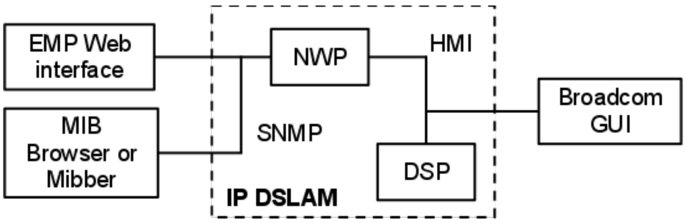

Figure 4.2.: The connections used for managing and getting information from the IP DSLAM.

Before any data traffic could flow through the equipment, configuration of the traffic generator, switch, IP DSLAMs and CPEs had to be made. For having the traffic to be redirected correctly and without unnecessary redundancy, VLAN (Virtual Local Area Network)s were used. Using a VLAN essentially means that each data packet is tagged with a VLAN ID number which enables equipment, particularly switches, to direct the packet to specific interfaces. When doing a manual configuration, it is essential to know that Permanent Virtual Circuit (PVC) 1-8 are reserved for ADSL while PVC 9 and upwards must be used when using the VDSL2 mode.

Firstly the traffic generator was configured for sending Ethernet frames both upstream towards the CPE and downstream towards the IP DSLAM through the switch. If payload data was embedded into the frames consisting of e.g. an Internet Protocol version 4 (IPv4) packet, the PVC might behave differently, which was apparent through for example the data rate monitor. For some combinations of IP DSLAM hardware and software, the traffic was stopped at the IP DSLAM due to the packet contents, where

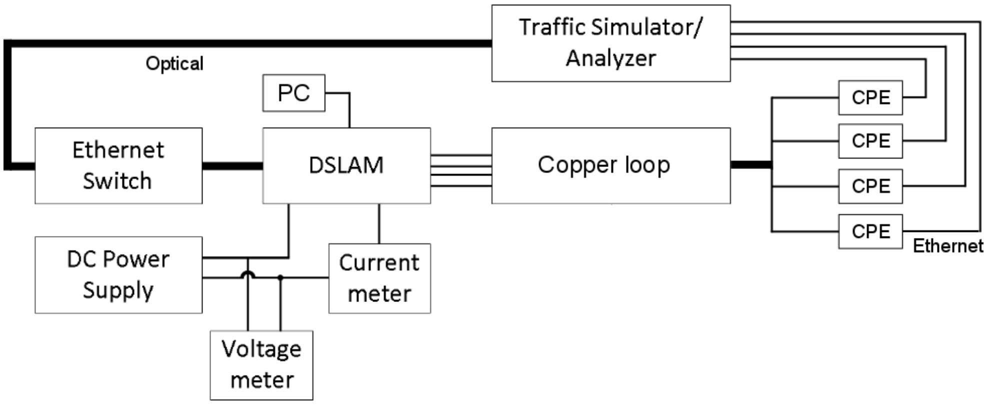

Figure 4.3.: The setup used for measuring the DSLAM power consumption.

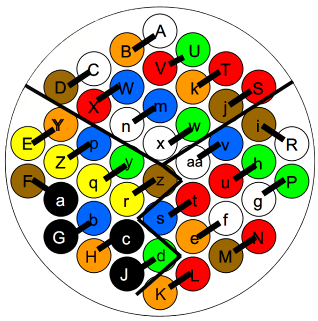

Figure 4.4.: Pin configuration of the connector for the copper loop binder cable.

having a MAC-address consisting of only zeros caused most problems. In addition to this erratic behavior, there were filters stopping the traffic, considered in the following paragraph.

Before setting up the IP DSLAMs, the switch was configured through a terminal interface to have two separate VLANs, one for each IP DSLAM. The IP DSLAMs were configured through SNMP for allowing traffic within their allocated VLANs. There are several parameters in the IP DSLAM which correspond to filters towards traffic either in the upstream or downstream direction and these had to be found and disabled. Lastly the VDSL2 link was enabled in the CPEs through their respective web interface.

The CPEs will at their startup either automatically be configured by the IP DSLAM through the Embedded Operations Channel (EOC), or fetch settings from the IP DSLAM through SNMP, to allow traffic flowing to and from the VLAN that was specified in the IP DSLAM.

Figure 4.5.: 1,500 metres of a copper loop binder containing 24 twisted pairs

4.1.2. Measurement preparations

VDSL2 was the focus of this thesis work and therefore the investigations mainly consisted of finding theoretical and empirical evidence of methods for power savings using the equipment and parameters associated with this technology.

There was only a small amount of work previously done in this field and only a few basic configuration parameters were known to affect the power consumption [5, 23, 10]. Documentation of the available parameters consisted of lists where each item was followed by a short description [25, 26].

Explanations of the relationships between parameters were found in [21, 13] and the customer-oriented user's guide to the ECN EMP interface (Section 2.3.4.1), but these only covered the general picture and did not reveal the actual inner workings of the algorithms and physical properties that govern their behavior in a real world scenario. A better picture of these inner workings was needed in order to be able to anticipate how the electronics and its power consumption behaved, and the work that followed gave reason to this section of the thesis.

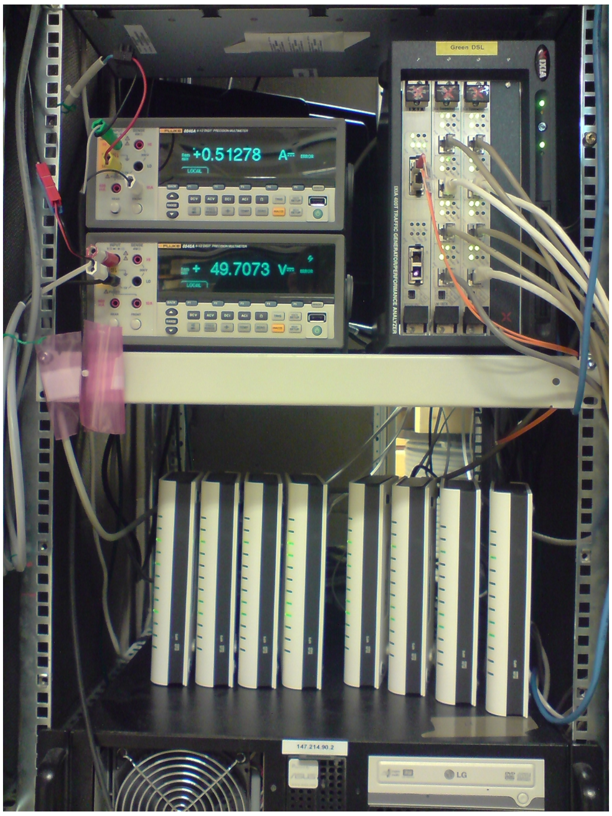

Figure 4.6.: Multimeters, traffic generator and CPEs

4.1.2.1. Initial investigations

Initial investigations into the potential for power savings was made by using the graphical configuration interface of the ECN, called EMP. This interface gave a first view of the available configuration parameters. EMP is used primarily by the owner of the DSL equipment, e.g. the ISP, and simplifies the management of any large set of IP DSLAMs.

Each parameter in EMP corresponds to one Managed Object in the MIB, with a few exceptions. When searching the MIB, the previously stated fact was considered in order to more easily find the most basic parameters. When it was uncertain whether one parameter in the EMP affected several instead of one Managed Object, the EMP was used to investigate the effects of changing the parameter instead of changing it through the Mibber tool or a MIB browser.

There were some issues in trying to modify some parameters. For example, when setting a value for an Managed Object manually the data type has to be correctly specified in accordance with the MIB. Some MOs had a data type like e.g. "BITS" where each binary digit in a number corresponded to a sub-parameter. Even with the MIB browser

([43]) these kinds of parameters took extra time to investigate compared to parameters with e.g. simple integer data types.

When a parameter is changed through SNMP (with e.g. Mibber or EMP), the corresponding Managed Object is updated in the MIB. Some MOs are mapped to a parameter in the DSP and that parameter then also needs to be updated, and this is done automatically by the EMP through an interface called Human Machine Interface (HMI).

For certain parameters the DSP configuration had to be changed manually through the Broadcom GUI. This GUI connects to the DSP through the HMI interface and gives the user some additional information and choices compared to what the EMP does. For example, parameters for new features like SRA and PhyR could only be changed through the Broadcom GUI, or only had an effect when changed through this instead of through SNMP and the MIB.

Other certain parameters could not be changed through their MOs after the IP DSLAM was started but instead had to be set through a file that was read at its startup. These included parameters related to the line driver and thus the power consumption but were not investigated thoroughly.

As mentioned in Section 2.3.1, the lines in the IP DSLAM shares some components, for example the Network Processor and one or several DSPs. In the case of EDN 612p, the 12 lines share 1 Network Processor and 3 DSPs. To investigate the power consumption of the Network Processor and DSPs when using VDSL2 the following procedure was used:

1. All the lines are turned off
2. Measure the total power consumption.
3. Turn on the first 4 lines (line 0,1,2,3)
4. Turn on the traffic generator for these 4 lines
5. Measure the total power consumption
6. Turn on 1 more line (line 4)
7. Turn on traffic for this line with the same data rate as the others
8. Measure the total power consumption
9. Repeat the steps but without traffic on the lines

During these measurements it was also discovered that the Network Processor consumes power if traffic is sent downstream even when all lines' operational status is off.

4.1.2.2. Candidate parameters

The lists of the available configuration parameters for Ericssons current VDSL2 equipment were read. Each parameter's name and description was evaluated of whether being useful in an algorithm controlling the device's power consumption. The initial list can be found in A.

Each candidate parameter was prioritized, whereafter the effects of changing them, first individually and then in combinations, was studied through the Mibber tool. As some parameters used special data types or formats that Mibber does not support, they had to be changed through either a command line interface or a graphical tool (table 4.2).

Tool name	**Description**
Mibber	Graphical plotting and configuration tool developed within the thesis work, described in section 3.
MG-SOFT MIB-browser [43]	Graphical MIB-browser in which entire MIBs can be loaded so that the tree of parameters can be browsed, and the parameters be read and written with ease.
Net-SNMP	Command-line tools for working with MIBs. Used by the Mibber software in addition to being used for manual parameter changes.

Table 4.2.: Tools used to configure the IPDSLAM

Table 4.4 lists the parameters that were found to have a direct effect on the power consumption of the device. Note that there are no parameters related to power management schemes, as these are only available for ADSL2plus.

Parameter name	**Comment**
Maximum SNR margin	If the actual SNR rises above the maximum SNR margin, the output power will be reduced, if possible.
Minimum SNR margin	If the actual SNR falls below the minimum SNR margin, the output power will be increased.
Target SNR margin	Target SNR margin is the SNR margin which always must be achieved for successful training. The output power will be changed to achieve the desired SNR margin.
Maximum downstream transmit power	Limits the output power of the IP DSLAM

Table 4.3.: Configuration parameters possibly affecting power consumption

4.1.3. Measurement execution

At first the ADSL power management states described in Section 2.5.1 were enabled and configured according to the specification [33] which was thereafter verified by making an analysis through the Mibber tool.

The power measurements made with the multimeter were confirmed by using the command line tool described in Section 3.3. This tool fetched information from the ECN about the power consumption of individual Ethernet ports that were PoE enabled, thus it revealed the power consumption of the IP DSLAMs connected to each port.

4.1.3.1. Power readings

The power readings done by the ECN and the command line tool had a precision of 0.5 Watts which was a disadvantage if these measurements were used to analyze the changes in power consumption caused by small changes in configuration parameters. Changes done to configuration parameters mostly lead to changes in power consumption of less than tenths of watts.

4.1.3.2. Candidate parameters

Parameter name	**Comment**
Maximum SNR margin	If the actual SNR rises above the maximum SNR margin, the output power will be reduced, if possible.
Target SNR margin	Target SNR margin is the SNR margin which always must be achieved for successful training. The output power will be changed to achieve the desired SNR margin.
Maximum downstream transmit power	Does this really affect power consumption directly???

Table 4.4.: Configuration parameters directly affecting power consumption

4.2. Implementation

With hopes of finding at least one good parameter for indicating quality of service and one parameter for affecting the power consumption, an idea for an algorithm was developed. The algorithm was not finished, and failed to lower the power consumption of a VDSL2 network. It is believed that the algorithm is a starting point from which further development can be made in order to reach the initial goals set by the project proposal and it is for that reason here described.

The algorithm uses statistics of past events to improve decisions about the future. If no statistics are available each parameter needs to be investigated separately and the algorithm then represents a Single-Input and Single-Output (SISO) system. With enough statistics it represents a Multiple-Input and Multiple-Output (MIMO) system because given the collected statistics of multiple parameters, a state can be determined in which it is possible to estimate the results of changing one or several parameters. The following steps describes the proposed algorithm:

1. Collect Quality-of-Service data (e.g. bit rate) and power consumption values over a long time period and while the line is in use.
2. During a period of no usage, change one or several parameters known to affect power consumption. This is done while collecting Quality of Service (QoS) and power consumption data.
3. Make statistics on how the change of a parameter changed the QoS and/or power consumption.
4. Use the statistics to make a better prediction on how to faster and more accurately reach an optimized state.

Chosen as initial target input and output parameters were, respectively, the number of Forward Error Correction seconds, i.e. seconds in which at least one Forward Error Correction has been made, and Maximum SNR margin. If the number of Forward Error Correction (FEC) seconds increase, the Maximum SNR margin is increased which allows the output power to be increased and signal quality increase. If the number of FEC seconds decreases, the Maximum SNR margin is lowered and thus the output power is also lowered.

The expected behavior of lowering output power is that the number of transmission errors increase. No predictable relationship was ever found between the FEC seconds count and the output power, by doing experiments. It is believed that the increase in errors could be mitigated by increasing the amount of error correction.

Tool name	**Description**
Mibber	Graphical plotting and configuration tool developed within the thesis work, described in Section 3.
SQLite Administrator	Database management tool which was used when developing scripts.

Table 4.5.: Tools used to develop scripts

The following are key features of the developed algorithm:

- Input: Errored Seconds and Power consumption
- Script executed within Mibber which provides interfaces to the data that it collects, e.g. IP DSLAM parameters and power.
- Uses an SQLite relational database for storage of data used in the statistics.
- Learns important basic parameters e.g. at average how long it takes for the DSL line to initialize - an indicator of stability.

- Script can detect changes in the operational state caused by external events and therefore cope with interruptions.
- Change the Maximum and Target SNR margin parameters with one of the following methods:
    1. By an amount proportional to the average of the rate of change in FEC seconds, if no statistics are available.
    2. Based on statistics over how the change in SNR margin parameters previously have affected the FEC seconds.
- Store in the database the FEC seconds before the change of SNR margin parameters, and info on how the SNR margin parameters were modified, and relate these entries.

Figure 4.7 shows statistics calculated from the data gathered by the script.

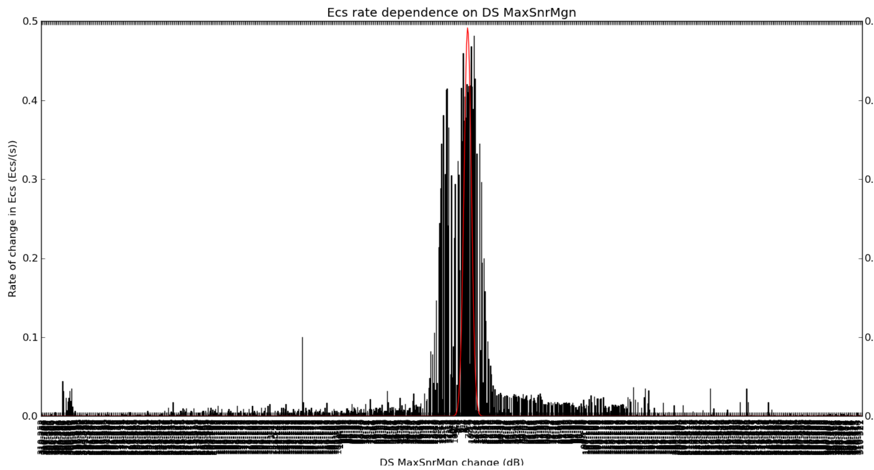

Figure 4.7.: Plot presenting statistics calculated from data gathered by the script.

Chapter 5.

Conclusions and future work

Following the inability of finding methods to lower the power consumption of a VDSL2 network without having any significant decrease in quality of service, the conclusions in this chapter are accompanied by suggestions of theoretical solutions.

5.1. Conclusions

This work has mainly consisted of through experiments gaining knowledge of how Ericssons EDA product suite works and behaves. By having decreased the amount of parameters needed to be investigated, and by developing a tool that greatly simplifies the task of understanding the intricate relationships between the many parameters of a IP DSLAM device, future work into this area has been given a good starting point.

The proposed algorithm that is described in Section 4.2 could not be applied in order to lower the power consumption of the Ericsson EDN612p or EDN612nef IP DSLAMs due to that no good input and output parameters were found during the investigations.

Possibilities to continue further within this area exist because there are configuration parameters that affects the power consumption as described in 4.1.3.2, and because it follows from the standards how the power should be affected by changing the basic parameters like Maximum SNR margin (Section 4.1.2.2). Also, there are believed to be enough margins in the relationship between power consumption and data rate that the power consumption can be decreased if the amount of error correction is increased.

5.2. Future work

Within the work described in the thesis many hurdles have been overcome, and these are described in the previous chapters. Additionally the tool Mibber has been developed and should be utilized in future ventures within this and other areas. Judging by the original thesis proposal, the contents of this section would have constituted the majority of the work. It is believed that a future project can reach the initial goals. Based on the conclusions some possible ways of reaching these original goals are here proposed.

One improvement of Mibber that could be made is to separate the main application into two applications; one client application that consists of a GUI, and one controller application that performs the measurements and logging. Another suggested improvement is to let Mibber indicate how a script modifies a parameter by e.g. changing the color of the part of the plot that corresponds to the change.

Further investigations should be made into the new technologies DSM, SRA and PhyR and their combinations. Further investigate the possibilities of changing the DSP configuration through HMI.

Future projects should focus better on documenting the behavior of the IP DSLAM, e.g. the results of enabling PhyR and whether it requires restart of the CPE or not, and for which firmware versions this applies. They should also further investigate the relations between MIB parameters, by use of a tool like e.g. Mibber.

Future projects should also investigate why disabling Reed-Solomon encoding did not result in increased errors, why enabling SRA or changing PowerAdaptivityMode was not effective for VDSL2 modes.

5.2.1. Possible triggers and actions

An algorithm can be pro-active or reactive. A pro-active algorithm tries to predict the future, as the algorithm proposed in Section 4.2 does. A reactive algorithm looks at the current (past) state and continuously corrects it towards being on the right path. An algorithm needs an input source (trigger), parameters, actions and expected results [45].

A system using the algorithm can be put in "sharp mode" or "dry mode". In sharp mode the algorithm is autonomous, corresponding to the goals of this work. In dry mode the algorithm doesn't perform any changes itself but instead proposes a change to be made manually by an operator.

The following list presents suggestions of input parameters and actions for an algorithm that was not implemented in this work:

1. Time of day - reduce maximum line rate if during time of low usage.
2. Type of traffic, e.g. IPTV, VoIP, Web or Torrent - optimize maximum line rate to meet the requirements of service quality.
3. QoS information (see the SHARQ project) - use more advanced info about the quality of service to optimize the line.
4. Distance between the IP DSLAM and the CPE - Optimize the downstream and upstream transmit power of the devices instead of using the maximum.

5.2.2. PID-controller

This work has shown that it is hard to predict the resulting behavior of the VDSL2 equipment after modifying one of its parameters related to power consumption. A good mechanism for controlling a system like this is the Proportional-Integral-Derivative mechanism. An algorithm utilizing the PID feedback control mechanism would use power consumption its output (process variable) and a Key Performance Indicator (KPI) as its input (manipulated variable).

Equation (5.1) describes the general form of the PID algorithm. The most important term is the error $e(t) = SP - PV$ which is the difference between the desired value (setpoint) and the current value of the output, here the power consumption.

The first term in equation (5.1), the proportional term, makes a change to the output that is proportional to the current error. The integral term contribution is proportional to both the magnitude of the error and the duration of the error and accelerates the movement towards the setpoint. The derivative term slows the rate of change of the controller output and improves the algorithm stability.

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \tag{5.1}$$

The choice of the values of the three parameters K_p, K_i and K_d are important in deciding how fast the algorithm will react to a change in an input and how stable its output is. The values of these three parameters, called tuning parameters, also emanates from the relationship between the input and output parameters. The parameters have to be decided for each state of the IP DSLAM configuration because the relationship between the input and output depends on other configuration parameters and the DSL line condition (e.g. loop length).

Appendix A.

Initial candidate parameters

This appendix contains a list of those Managed Objects for Ericssons EDA IP DSLAMS that were deemed as interesting for being used to decrease the power consumption of the IP DSLAM. For proprietary parameters, only the OID is mentioned.

A.1. Line parameters - status

OID: 1.3.6.1.4.1.193.72.300.50.1.2.1.5
Name: adslIfAdminStatus

OID: 1.3.6.1.4.1.193.72.300.50.1.2.1.6
Name: adslIfOperStatus

A.2. Line parameters - bit rate

OID: 1.3.6.1.4.1.193.72.300.50.1.2.1.3
Name: adslIfSpeed

OID: 1.3.6.1.4.1.193.72.300.10.1.14.1.5

OID: 1.3.6.1.4.1.193.72.300.10.1.15.1.5

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.6.1
Name: adslAtucPhysXPreviousAttainableRate

OID: 1.3.6.1.2.1.10.94.1.1.14.1.14
Name: adslAtucChanConfInterleaveMaxTxRate

OID: 1.3.6.1.2.1.10.94.1.1.14.1.12
Name: adslAtucChanConfInterleaveMinTxRate

OID: 1.3.6.1.2.1.10.94.1.1.14.1.26
Name: adslAturChanConfInterleaveMinTxRate
Note: Upstream

A.3. Line parameters - Signal-to-noise ratio

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.75

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.74

OID: 1.3.6.1.2.1.10.94.1.1.3.1.4
Name: adslAturCurrSnrMgn **Note**: Downstream SNR margin

OID: 1.3.6.1.4.1.193.72.300.80.1.60.1.100
Name: snrMarginDS1
Note: Downstream, only for VDSL modes

OID: 1.3.6.1.4.1.193.72.300.10.1.2.1.2
Name: adslAturPhysXPreviousSnrMgn
Note: Downstream

OID: 1.3.6.1.2.1.10.94.1.1.14.1.18
Name: adslAturConfTargetSnrMgn
Note: Downstream SNR margin, Unit: 0.1 dB

OID: 1.3.6.1.2.1.10.94.1.1.14.1.20
Name: adslAturConfMinSnrMgn
Note: Downstream

OID: 1.3.6.1.2.1.10.94.1.1.14.1.19
Name: adslAturConfMaxSnrMgn

OID: 1.3.6.1.2.1.10.94.1.1.2.1.4
Name: adslAtucCurrSnrMgn
Note: Upstream SNR margin

OID: 1.3.6.1.4.1.193.72.300.80.1.60.1.85
Name: snrMarginUS1
Note: Upstream, only for VDSL modes

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.1
Name: adslAtucPhysXPreviousSnrMgn
Note: Upstream

OID: 1.3.6.1.2.1.10.94.1.1.14.1.4
Name: adslAtucConfTargetSnrMgn
Note: Upstream SNR margin, Unit: 0.1 dB

OID: 1.3.6.1.2.1.10.94.1.1.14.1.6
Name: adslAtucConfMinSnrMgn

OID: 1.3.6.1.2.1.10.94.1.1.14.1.5
Name: adslAtucConfMaxSnrMgn

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.75

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.74

OID: 1.3.6.1.4.1.193.72.300.80.2.5.1.5
Name: vdsl2SCStatusSnr

A.4. Line parameters - Attenuation

OID: 1.3.6.1.2.1.10.94.1.1.3.1.5
Name: adslAturCurrAtn

OID: 1.3.6.1.2.1.10.94.1.1.2.1.5
Name: adslAtucCurrAtn
Note: Upstream loop attenuation

OID: 1.3.6.1.4.1.193.72.300.10.1.2.1.6
Name: adslAturPhysXLoopAtn
Note: Downstream loop attenuation

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.5
Name: adslAtucPhysXLoopAtn
Note: Upstream loop attenuation

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.7.1
Name: adslAtucPhysXPreviousLoopAtn

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.8
Name: adslAtucPhysXPreviousSigAtn

A.5. Line parameters - power

OID: 1.3.6.1.4.1.193.72.300.10.1.28
Name: adslTxPowerCalibration

OID: 1.3.6.1.4.1.193.72.300.10.1.27
Name: adslPowerModes

OID: 1.3.6.1.2.1.10.94.1.1.2.1.7
Name: adslAtucCurrOutputPwr
Note: Downstream output power

OID: 1.3.6.1.2.1.10.94.1.1.3.1.7
Name: adslAturCurrOutputPwr
Note: Upstream output power

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.2.1
Name: adslAtucPhysXPreviousOutputPwr
Note: Downstream output power

OID: 1.3.6.1.4.1.193.72.300.10.1.19.1.15
Name: adslLineXStatusActPsdDs
Note: Downstream average PSD

OID: 1.3.6.1.4.1.193.72.300.10.1.19.1.20
Name: adslLineXStatusActPsdUs
Note: Upstream average PSD

OID: 1.3.6.1.4.1.193.72.300.10.1.14.1.9

OID: 1.3.6.1.4.1.193.72.300.10.1.15.1.9

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.1

OID: 1.3.6.1.4.1.193.72.300.80.1.8.1.2
Name: miscVdslConfMaxTxPowerDn
Notes: Downstream, only for VDSL2 modes

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.19

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.90

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.4

OID: 1.3.6.1.4.1.193.72.300.10.1.80.1.5.1
Name: adslLineConfPhysAdslPboPsdDnEsel

OID: 1.3.6.1.4.1.193.72.300.10.1.80.1.50
Name: adslLineConfPhysAdslPboPsdDnEPsd

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.24

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.23

A.6. Line parameters - Power management

OID: 1.3.6.1.4.1.193.72.300.10.1.1.1.15.1
Name: adslAtucLineStatusPwrMngState

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.70

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.71

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.72

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.73

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.64

A.7. Performance/error indicators

OID: 1.3.6.1.4.1.193.72.300.10.1.20.1.2

OID: 1.3.6.1.2.1.10.94.1.1.6.1.5
Name: adslAtucPerfESs

OID: 1.3.6.1.4.1.193.72.300.10.1.16.1.30

OID: 1.3.6.1.4.1.193.72.300.10.1.60.1.32.1.1
Name: adslAturChan1DayIntervalXRtxCorrectedCw

OID: 1.3.6.1.4.1.193.72.300.10.1.6.1.1
Name: adslAtucPerfXEcs

OID: 1.3.6.1.4.1.193.72.300.10.1.45.1.25
Name: adslAtuc1DayIntervalXEcs

OID: 1.3.6.1.4.1.193.72.300.10.1.50.1.15
Name adslAtur1DayIntervalXLprs

OID: 1.3.6.1.4.1.193.72.300.10.1.45.1.10
Name: adslAtuc1DayIntervalXLoss

OID: 1.3.6.1.4.1.193.72.300.10.1.14.1.3

OID1.3.6.1.4.1.193.72.300.10.1.14.1.13

OID: 1.3.6.1.4.1.193.72.300.10.1.7.1.1 **Name**: adslAturPerfXEcs **Note**: Downstream forward error correction seconds

OID: 1.3.6.1.4.1.193.72.300.10.1.6.1.1
Name: adslAtucPerfXEcs **Note**: Upstream forward error correction seconds

A.8. Base configuration

OID: 1.3.6.1.4.1.193.72.300.10.1.3.1.5.1
Name: adslPowerManagementMode

OID: 1.3.6.1.4.1.193.72.300.10.1.19.1.3
Name: adslLineXTransAtucActual

OID: 1.3.6.1.4.1.193.72.300.10.1.14.1.2.1

OID: 1.3.6.1.4.1.193.72.300.80.1.60.1.5
Name: miscPhysStatusVdslProfileBitmap

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.31

OID: 1.3.6.1.4.1.193.72.300.10.1.18.1.32

A.9. Signal parameters

OID: 1.3.6.1.4.1.193.72.300.10.1.85.1.5
Name: adslLConfProfRfiBands

OID: 1.3.6.1.4.1.193.72.300.10.1.3.1.2
Name: adslConfXAtucFrequencyBins

OID: 1.3.6.1.4.1.193.72.300.10.1.3.1.3
Name: adslConfXAturFrequencyBins

A.10. System status and control

OID: 1.3.6.1.4.1.193.72.600.1.1.9.0
Name: restart

OID: 1.3.6.1.4.1.193.72.600.1.1.3.2.0
Name: tempValue

OID: 1.3.6.1.4.1.193.72.600.1.1.3.1.0
Name: tempControlState

OID: 1.3.6.1.4.1.193.72.600.1.1.2.1.0
Name: processorLoad

OID: 1.3.6.1.4.1.193.72.600.1.1.4.4.0
Name: redFanSpeed

OID: 1.3.6.1.4.1.193.72.600.1.1.4.3.0
Name: greenFanSpeed

Glossary

Symbols

1000BASE-SX A computer networking standard for communication over multi-mode fiber optical cables with data rates up to 1000 Mbit/s..]page17

100BASE-TX A computer networking standard for communication over twisted pair cables with data rates up to 100 Mbit/s..]page17

A

ADSL Asymmetric Digital Subscriber Line.]page4,]page6,]page10,]page13

ADSL2 Asymmetric Digital Subscriber Line 2.]page4,]page6,]page9, 10

ADSL2plus Asymmetric Digital Subscriber Line 2 Plus.]page6

AFE Analogue Front-End.]page6

AFEs Analogue Front-Ends.]page6

API Application Programming Interface.]page13,]page24

ATU ADSL Transceiver Unit.]page24

ATU-C ADSL Transceiver Unit at the Central Office (i.e. network operator).]page9,]page24

ATU-R ADSL Transceiver Unit at the remote terminal (i.e. customer premises).]page9,]page24

C

Cable Broadband access through cable television infrastructure..]page3

Central Office telco building with equipment.]page22

CPE Customer Premises Equipment.]page6, 7,]page9,]page17

D

Digital Signal Processors .]page6

DS Downstream.]page17

DSL Digital Subscriber Line.]page3, 4,]page6,]page15–18

DSLAM Operator equipment....]pageiv,]page7–9,]page12–14,]page16,]page18

DSM Dynamic Spectrum Management.]page9

DSP Digital Signal Processor.]page3

E

EMI electromagnetic interference.]page25

Ethernet A technology allowing for computers to be connected to eachother via a LAN..]page13

Ethernet Controller Node .]page13,]page18,]page25

F

Fiber To The x Generic term for any broadband network architecture that uses optical fiber to replace all or part of the usual metal local loop used for last mile telecommunications..]page3

G

GPIB A short-range digital communications bus specification..]page13

GUI Graphical User Interface.]page13

H

HDSL High bit rate Digital Subscriber Line.]page3, 4

I

IETF Internet Engineering Task Force.]page6

IPDSLAM Operator equipment....]page6,]page17, 18

ISDN Was the first....]page3

ISP Internet Service Provider.]page18

ITU-T International Telecommunications Standardization organization.]page3,]page9

ITU-T G.992.1 (ADSL1) Recommendation.]page4

ITU-T G.992.3 (ADSL2) Recommendation.]page9,]page24

ITU-T G.992.5 Annex M Recommendation.]page4

ITU-T G.993.2 (VDSL2) Recommendation.]page4

L

L0 Full on power state.]page9, 10

L2 Low power state.]page9, 10

L2ATPR L2 Aggregate Transmit Power Reduction.]page10

L2ATPRT L2 Aggregate Transmit Power Reduction Total.]page10

L3 Idle power state.]page9

LAN Local Area Network.]page23

link state According to ITU-T G.992.3 (ADSL2) p. 217 (229) link state should not be confused with ADSL Transceiver Unit (ATU) state..]page9

M

Matplotlib A Python software library providing an object-oriented programming API allowing plots to be embedded into applications..]page13

MIB Management Information Base.]page6,]page13,]page18

Mibber Measurement tool.]page12–14,]page16

MO Managed Object.]page18

Modem Modulator Demodulator.]page3

N

Network Processor Incorporating PHY functionality..]page6

O

OPEX Operator Expenditures.]page4

P

payload The essential data that is being carried within a packet or other transmission unit. The payload does not include the "overhead" data required to get the packet to its destination. The payload is the bits that get delivered to the end user at the destination..]page3, 4

PoE Power over Ethernet.]page13

POTS Plain Old Telephone Service.]page3, 4

PSD transmit energy per tone.]page10

R

re-train The ATU-C and ATU-R communicate, optimizing parameters to establish the best possible link..]page10

RFC5650 IETF RFC5650 - Definitions of Managed Objects for Very High Speed Digital Subscriber Line 2 (VDSL2).]page6

S

Self-Optimisation and self-ConfiguRATion in wirelEss networkS SOCRATES is a....]page5

self-optimization A part of SON which incorporates....]page2,]page5

SFP Small Form-factor Pluggable.]page17

SHDSL Single-pair High-speed Digital Subscriber Line.]page4

SNMP Simple Network Management Protocol.]page17

SNR Signal-to-Noise Ratio.]page9

SON Self-Organizing Networks.]page2,]page4, 5,]page25

T

telco telephone company.]page2

Telnet A network protocol used to provide a text-oriented communications facility using a virtual terminal, for the purpose of accessing the inner workings of network-connected computer devices..]page13,]page25

twisted pair A type of wiring in which two conductors are twisted together for the purposes of canceling out electromagnetic interference (EMI) from external sources, and crosstalk between neighboring pairs..]page3, 4

U

US Upstream.]page17

V

VDSL Very high speed Digital Subscriber Line.]page13

VDSL2 Very high speed Digital Subscriber Line 2.]page2,]page4,]page6,]page9,]page16, 17

Very-large-scale integration VLSI is....]page4

VLAN Virtual Local Area Network.]page17

VT100 A video terminal introduced in 1978 that is emulated in the ECN to enable a virtual terminal to be connected through Telnet and used for configuring the device and getting information from it..]page13

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