DETERMINATION OF ADSL CAPACITY IN A GENERIC EXCHANGE ENVIRONMENT

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ABSTRACT

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Asymmetric Digital Subscriber Line (ADSL) is a high speed transmission technology, supporting up to 8 Mbps to the customer, over existing twisted-pair local loops, as described in the background chapter of this dissertation. ADSL is considered a transition technology between the existing copper network and an all-fiber network.

A common problem facing telecommunication service providers (Telcos) is to determine beforehand how many customers could be upgraded from existing plain analog services to ADSL, subject to the access network topology and data rate required. Secondly, when developing new geographical areas, Telcos would like to know how far customers may be located from the exchange, in order to guarantee a minimum data rate.

The purpose of this dissertation is to determine how many customers could be upgraded/supported, as a function of the type of services available in the network, consisting of ADSL, ISDN, E1 and *High-bit-rate DSL* (HDSL), as well as the data rate required.

In this dissertation, capacity was determined as a function of the number of interferers present, in contrast to capacity versus bandwidth available/used. Secondly, maximum reach was determined as a function of the number of interferers present. Different combinations of 0.4 or 0.5 mm wire gauges, echo-cancelled hybrid or frequency division multiplexed spectral allocation, and the presence or absence of a bridged tap are considered.

A bit loading algorithm developed by Campello [1] was used to optimize the allocation of bits/symbol/subchannel and energy/subchannel, by using the signal-to-noise ratio profile of the twisted-pair channel and the total available energy (power).

Keywords:

A*symmetric* **D***igital* **S***ubscriber* **L***ine* (**ADSL**), **B**it **L**oading, **B**it **A**llocation, **C**ampello, **C**apacity, **T**wisted-pair **C**hannel **M**odelling, **D***iscrete* **M***ulti*-**T***one* (**DMT**) **M**odulation, **E**nergy **O**ptimization, **G**eneric **E**xchange, **L**ocal **L**oop **N**etwork **T**opology, **T**wisted-pair.

SAMEVATTING

Bepaling van ADSL Kapasiteit in ’n Generiese Sentrale Omgewing

deur

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A-simmetriese Digitale Huurderslyn (ADSL) is ’n hoëspoed transmissietegnologie, met ’n datatempo tot 8 Mbps na die kliënt oor bestaande gedraaide-paar telefoonlyne, soos beskryf in die agtergrondhoofstuk van hierdie verhandeling. ADSL word beskou as ’n oorgangstegnologie tussen die bestaande kopernetwerk en ’n totale veselnetwerk.

’n Algemene probleem wat telekommunikasieverskaffers (Telkoms) ondervind is om vooraf te bepaal hoeveel kliënte omgeskakel kan word van bestaande analoogdienste na, of bedien kan word deur ADSL, onderhewig aan die topologie van die toegangsnetwerk en die vereiste datatempo. Tweedens, wanneer nuwe geografiese areas ontwikkel word, wil Telkoms weet hoe ver kliënte vanaf die sentrale geleë kan wees om ’n minimum datatempo te waarborg.

Die doel van hierdie verhandeling is om hierdie probleem te probeer aanspreek vir verskillende dienste beskikbaar in die netwerk, bestaande uit ADSL, ISDN, E1 en *Hoë bisspoed DSL* (HDSL), terwyl die vereiste datatempo in ag geneem word.

In hierdie verhandeling word kapasiteit bereken as ’n funksie van die aantal steurseine teenwoordig, in teenstelling met kapasiteit as ’n funksie van die bandwydte wat beskikbaar is of gebruik word. Tweedens word maksimum reikafstand as ’n funksie van die aantal steurseine teenwoordig bereken. Verskillende kombinasies van 0.4 of 0.5 mm draaddiktes, eggo-gekanselleerde of frekwensie-divisie-gemultiplekseerde spektrale allokasie, en die

teenwoordigheid of afwesigheid van ’n stomplyn, word geïmplementeer.

’n Bis-allokasie-algoritme, ontwikkel deur Campello [1], word gebruik om die toekenning van bisse/simbool/subkanaal en energie/subkanaal te optimeer, deur gebruik te maak van die sein-tot-ruis-verhoudingprofiel van die gedraaide-paar kanaal en die totale drywing beskikbaar.

Sleutelwoorde:

A*simmetriese* **D***igitale* **H***uurderslyn* (**ADSL**), **B**is-allokasie, **B**is-toekenning, **C**ampello, **D***iskrete* **M***ulti*-**T***oon* (**DMT**) **M**odulasie, **E**nergie-optimering, **G**edraaide-paar, **G**edraaide-paar **K**anaalmodellering, **G**eneriese **S**entrale, **H**uurderslyn **N**etwerktopologie, **K**apasiteit.

To my loving family

who supported me through my years of study

and

to God Almighty for giving me talents,

and the opportunities to use them.

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CONTENTS

1 INTRODUCTION **1**

1.1 The problem 2

1.2 Related research 2

1.3 Aim 3

1.4 Objectives 4

1.5 Dissertation Overview 4

2 BACKGROUND **5**

2.1 Chapter Overview 5

2.2 The Access Network 5

2.3 What is ADSL? 9

2.4 Why ADSL? 16

3 CHANNEL MODELLING **18**

3.1 Chapter Overview 18

3.2 Primary and Secondary Parameters 18

3.3 Two-port networks and ABCD parameters 22

3.4 Impairments for ADSL 25

3.4.1 Noise 25

3.4.2 Crosstalk 25

3.4.3 Power Spectral Density of Disturbers 26

3.4.4 NEXT Noise Models 31

3.4.5 FEXT Noise Models 33

3.4.6 Radio Frequency Interference 35

4 BIT LOADING **36**

4.1 Chapter Overview . . . 36

4.2 Introduction . . . 36

4.3 Rate-Adaptive Loading Algorithm (RALA) . . . 37

4.4 Demonstration of algorithm operation . . . 42

4.4.1 Changing the line length . . . 42

4.4.2 Changing the length of a bridged tap . . . 46

4.4.3 Introducing frequency selective interference . . . 46

5 IMPLEMENTATION AND SIMULATION **53**

5.1 Chapter Overview . . . 53

5.2 Basic description . . . 53

5.3 Block diagrams . . . 53

5.4 Specifications . . . 59

6 RESULTS **61**

6.1 Chapter Overview . . . 61

6.2 ADSL downstream capacity . . . 61

6.3 ADSL maximum reach . . . 68

6.3.1 2.048 Mbps downstream data rate . . . 68

6.3.2 6.144 Mbps downstream data rate . . . 74

6.3.3 8.192 Mbps downstream data rate . . . 79

7 CONCLUSION **84**

REFERENCES **87**

LIST OF FIGURES

2.1 Basic elements of the public switched telephone network 6
2.2 Main network topology 7
2.3 Illustration of twisted pair and binder group location within a 500 pair cable 8
2.4 Digital Loop Carrier architecture 8
2.5 Frequency division multiplexing and echo-cancelled hybrid PSD 11
2.6 General ADSL architecture 12
2.7 Splitterless ADSL architecture 14
2.8 ADSL PSD when implementing DMT modulation 16

3.1 Resistance vs. Frequency 20
3.2 Inductance vs. Frequency 20
3.3 Characteristic Impedance vs. Frequency 21
3.4 Propagation constant vs. Frequency 21
3.5 Two-port networks in series 22
3.6 Echo generation in a bridged tap 23
3.7 NEXT and FEXT generation between pairs in a binder group 26
3.8 Power spectral density of an ISDN interferer 27
3.9 Power spectral density of a HDSL interferer 28
3.10 Power spectral density of an E1 interferer 29
3.11 Power spectral density of a downstream ADSL interferer 30
3.12 Power spectral density of an upstream ADSL interferer 31
3.13 Power spectral density of 1, 10 and 49 ISDN NEXT interferers 32
3.14 Power spectral density of 1, 10 and 49 HDSL NEXT interferers 33
3.15 Power spectral density of 1, 10 and 49 E1 NEXT interferers 34

3.16 Power spectral density of 1, 10 and 49 downstream ADSL NEXT interferers 34
3.17 Power spectral density of 1, 10 and 49 upstream ADSL NEXT interferers . 35

4.1 Line topology to simulate line length changes 42
4.2 Demonstration of RALA for a 1 km length of 0.4 mm twisted-pair 43
4.3 Demonstration of RALA for a 3 km length of 0.4 mm twisted-pair 44
4.4 Demonstration of RALA for a 5 km length of 0.4 mm twisted-pair 45
4.5 Line topology to simulate bridged tap length changes 46
4.6 Demonstration of RALA for a 0.4 mm twisted-pair bridged tap with a length of 100 m 47
4.7 Demonstration of RALA for a 0.4 mm twisted-pair bridged tap with a length of 200 m 48
4.8 Demonstration of RALA for a 0.4 mm twisted-pair bridged tap with a length of 300 m 49
4.9 Demonstration of RALA for a 10 dB interference level at 400 kHz 50
4.10 Demonstration of RALA for a 30 dB interference level at 400 kHz 51
4.11 Demonstration of RALA for a 50 dB interference level at 400 kHz 52

5.1 User input 54
5.2 Determination of ADSL capacity 55
5.3 Determination of maximum reach 56
5.4 Multiplying ABCD matrixes 57
5.5 Determination of SNR / data rate for each subchannel 58

6.1 ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with no bridged tap, using ECH allocation 64
6.2 ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with no bridged tap, using FDM allocation 64
6.3 ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with no bridged tap, using ECH allocation 65
6.4 ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with no bridged tap, using FDM allocation 65

6.5 ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with maximum length bridged tap, using ECH allocation 66
6.6 ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with maximum length bridged tap, using FDM allocation 66
6.7 ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with maximum length bridged tap, using ECH allocation 67
6.8 ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with maximum length bridged tap, using FDM allocation 67
6.9 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with no bridged tap, using ECH allocation 70
6.10 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with no bridged tap, using FDM allocation 70
6.11 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with no bridged tap, using ECH allocation 71
6.12 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with no bridged tap, using FDM allocation 71
6.13 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with maximum length bridged tap, using ECH allocation . . . 72
6.14 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with maximum length bridged tap, using FDM allocation . . . 72
6.15 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with maximum length bridged tap, using ECH allocation . . . 73
6.16 ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with maximum length bridged tap, using FDM allocation . . . 73
6.17 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire with no bridged tap, using ECH allocation 75
6.18 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire with no bridged tap, using FDM allocation 75
6.19 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire with no bridged tap, using ECH allocation 76

6.20 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire with no bridged tap, using FDM allocation 76
6.21 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire maximum length bridged tap, using ECH allocation 77
6.22 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire maximum length bridged tap, using FDM allocation 77
6.23 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire maximum length bridged tap, using ECH allocation 78
6.24 ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire maximum length bridged tap, using FDM allocation 78
6.25 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with no bridged tap, using ECH allocation 80
6.26 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with no bridged tap, using FDM allocation 80
6.27 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with no bridged tap, using ECH allocation 81
6.28 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with no bridged tap, using FDM allocation 81
6.29 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with maximum length bridged tap, using ECH allocation . . . 82
6.30 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with maximum length bridged tap, using FDM allocation . . . 82
6.31 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with maximum length bridged tap, using ECH allocation . . . 83
6.32 ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with maximum length bridged tap, using FDM allocation . . . 83

LIST OF TABLES

2.1 COMPARISON BETWEEN XDSL, T1/E1 PRIVATE LINES AND ANALOG MODEMS 10

3.1 CABLE PARAMETERS FOR DIFFERENT WIRE TYPES 19

List of Abbreviations

2B1Q	2 Binary to 1 Quaternary modulation
ADSL	Asymmetric Digital Subscriber Line
AMI	Alternate Mark Inversion
ANSI	American National Standards Institute
ATU-C	ADSL Terminal Unit - Central office side
ATU-R	ADSL Terminal Unit - Remote (customer) side
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CDSL	Consumer Digital Subscriber Line
CO	Central Office
CSA	Carrier Serving Area
DLC	Digital Loop Carrier
DMT	Discrete Multi-Tone
Downstream	From the Central Office to the Customer
DP	Distribution Point
DS-1	1.544 Mbps service
DSLAM	Digital Subscriber Line Access Multiplexer
E1	Symmetric 2.048 Mbps service using HDB3 modulation
ECH	Echo-cancelled Hybrids
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FEXT	Far-end Crosstalk

FSI	Frequency Selective Interference
FTTH	Fiber to the Home
HDB3	High Density Bipolar Order 3 Encoding - It is based on AMI, but extends this by inserting violation codes whenever there is a run of 4 or more 0's.
HDSL	High-bit-rate Digital Subscriber Line
HPF	High Pass Filter
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ITU	International Telecommunications Union
LAN	Local Area Network
LPF	Low Pass Filter
MALA	Margin Adaptive Loading Algorithm
MDF	Main Distribution Frame
NEXT	Near-end Crosstalk
NGDLC	Next Generation Digital Loop Carrier
PCM	Pulse Coded Modulation
PCP	Primary Cross-connection Point
POTS	Plain Old Telephone Services
PSD	Power Spectral Density
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
RADSL	Rate-adaptive Asymmetric Digital Subscriber Line
RALA	Rate Adaptive Loading Algorithm
RFI	Radio Frequency Interference
RS	Reed Solomon
RT	Remote Terminal
SAC box	Serving Area Concept box
SAI	Serving Area Interface
SCP	Secondary Cross-connection Point

SDMT	Synchronized Discrete Multi-Tone
SDSL	Single-line Digital Subscriber Line
SNR	Signal-to-Noise Ratio
SP	Service Provider
T1	Symmetric 1.544 Mbps service using AMI modulation
TCP/IP	Transfer Control Protocol / Internet Protocol
UADSL	Universal Asymmetric Digital Subscriber Line
Upstream	From the customer to the Central Office
UTP	Untwisted Pair
VDSL	Very-high-bit-rate Digital Subscriber Line
VoD	Video-on-Demand
xDSL	x-type of Digital Subscriber Line

CHAPTER ONE

INTRODUCTION

"ADSL technology can literally transform the existing public information network from one limited to voice, text and low-resolution graphics to a system capable of bringing simultaneous switched digital video and other advanced, interactive services to everyone's office or home ...A home office worker receiving ADSL-based services could simultaneously tap into the corporate server, hold a meeting via video phone and field an important call from a prospective client — all on the same line [1]*."*

Debbie Sallee, Broadband Strategic Marketing Manager,
Motorola Semiconductor Prod.

"ADSL ...makes more sense than any service I've seen since frame relay debuted back in the late 80s ...If it sounds like ADSL is the perfect vehicle for curing your Internet access woes, it is — not to mention a potential option for high-speed access to frame relay and ATM services [2]*."*

Paul Desmond, Features Editor, Network World.

[1] *Source: editorial contribution in the June 3, 1996 issue of "Network World", p. 35*
[2] *Source: editorial published in the September 16, 1996 issue of "Network World", p. 86*

1.1 The problem

A common problem facing telecommunication service providers (Telcos) is to determine beforehand how many customers could be upgraded from plain voice services to ADSL within the existing network. Secondly, when developing new geographical areas, Telcos would like to know how far the customer may be located from the exchange, in order to guarantee a minimum data rate. *Additive white Gaussian noise* (AWGN) is inherent to the network, while other services (like ADSL, ISDN, E1 (2.048 Mbps symmetric) and HDSL) can also be found in the network.

Two methods are available in order to solve this problem: Practical implementation and theoretical simulation. The theoretical simulation only requires a computer and models implemented in software. A practical implementation becomes too costly when considering the number of modems needed, as well as the amount of processing power needed to transmit data over the network.

1.2 Related research

Messerschmitt [2] developed a Transmission Line Modelling Program , called LINEMOD. The program can generate the input impedance, attenuation profile and impulse response for any line configuration, including bridged taps. Kessler *et al*. [3] explained the shortcomings of the ADSL standard for ADSL over ISDN (simultaneous transmission of ADSL and ISDN). Reach reduction is shown to be 10-15%, while the pilot must be moved. Kalet *et al*. [4] examined the performance of a twisted-pair channel, assuming a *near-end crosstalk* (NEXT) dominated environment using a Gaussian model. It is shown that the capacity is independent of the transmitted power spectral density. Capacity of a twisted-pair channel, with both NEXT and white Gaussian noise, is also addressed. Van der Velde *et al*. [5] investigated *bit error rate* (BER) performance of a passband single-carrier *quadrature amplitude modulated* (QAM) transceiver for ADSL with AWGN and *self far-end crosstalk* (self-FEXT) as the main disturbances. An analytical expression for the *signal-to-noise ratio* (SNR) margin, clearly shows the effect of various cable and system parameters on ADSL performance. The optimum constellation size and maximum achievable bit rate is determined as a function of the loop length. Kerpez *et al*. [6] determined the performance of DS-1 rate (1.544 Mbps) passband ADSLs in the presence of background noise, self-FEXT, and NEXT from other digital transmission systems that share its spectrum. The performance of *forward error correction* (FEC) and Trellis codes in the presence of crosstalk and impulse noise is also found. Werner [7] gives special attention to the most damaging impairments that are encountered in subscriber lines, such as propagation loss, linear distortion, crosstalk, bridged taps, and impulse noise. Less important impairments are also described. The paper concludes with a discussion of the capacity of a twisted-pair channel in a crosstalk-dominated environment. Barton *et al*. [8] performed a performance study of high-speed ADSL in the presence of AWGN and crosstalk noise from existing services. Coverage of the existing *carrier service area* (CSA) is possible at transmission rates that are well above the existing T1 (1.544 Mbps) rate. Waring [9] provides a brief overview of ADSL technology, describing important technology considerations, including noise impairments, spectral compatibility, and ”data over voice” design challenges. Sistanizadeh [10] performed a computational study on the spectral compatibility of ADSL with other digital transport technologies that might coexist in the same binder group. Specifically, NEXT and FEXT effects of Basic Rate DSL, High-bit-rate DSL (HDSL), and T1 lines are investigated.

Most of the papers found in the literature determined the total capacity of an ADSL system as a function of the amount of bandwidth available/used. Capacity are thus plotted against *frequency*, in contrast to this dissertation which determined and plotted capacity as a function of the number of *interferers*.

1.3 Aim

Given the related research and relevant standards, configurations, equations and figures, the aim of this dissertation is threefold. The first is to combine some of the related research to simulate a generic exchange environment (especially multi-pair cables). The second is a computational study to determine the ADSL downstream data rate (for a specific pair) as a function of other services within the cable, specifically within the same binder group. The third is a computational study to determine the maximum reach possible (given a required data rate) as a function of other services within the same binder group. Specifically, the effects of other ADSL services, ISDN (Basic Rate DSL), HDSL and E1 will be pursued.

In the last two cases, a bit loading algorithm developed by Campello [1] was corrected and used to determine the capacity of the ADSL line under consideration.

1.4 Objectives

The objectives of this dissertation are:

- Downstream data rate vs. the number of interferers for every type of interferer separately over a fixed length of line with a certain topology.
- Maximum reach vs. the number of interferers for every type of interferer separately. Specified data rates of 2.048, 6.144 and 8.192 Mbps over a line with a certain topology will be used.

Please note that a practical comparison with the theoretical results were not possible because no ADSL modems were available in South Africa at the time.

1.5 Dissertation Overview

Chapter 2 provides a general overview of the current access network, ADSL technology and reasons for using ADSL technology. Chapter 3 describes the theory and mathematics used in modelling the physical channel of the access network. Chapter 4 gives a detailed description of Campello's Bit Loading Algorithm, used to optimize the data rate of the system, subject to the channel profile and a total energy constraint. Chapter 5 provides a description of the implementation and simulation of the formulas and algorithms of Chapter 3 and 4 in order to derive the results provided in Chapter 6. Chapter 6 shows the results of the simulation and discusses observations made from the graphs. Chapter 7 makes some concluding remarks about the dissertation.

CHAPTER TWO

BACKGROUND

2.1 Chapter Overview

Asymmetric Digital Subscriber Line (ADSL) is a high speed access technology which can be used for asymmetric multimedia and Internet applications. This chapter presents a basic description of the current distribution network, followed by an overview of ADSL technology, and reasons for using ADSL instead of analog modems and ISDN. Twisted-pair Channel Modelling is introduced in Chapter 3.

2.2 The Access Network

The *public switched telephone network* (PSTN) was put in place to handle basic telephone-to-telephone voice communication. The basic elements of the PSTN are shown in Figure 2.1 [11]. The telephone handset contains a small microphone which varies the electric signal sent through the local loop, according to the acoustic voice wave. It also includes a tiny speaker to convert the electric signal into an audible wave. The *central office* (CO) contains the CO switch that sets-up, maintains and terminates the temporary connections (calls) between any two end devices, using any combination of local loops and trunks. Trunks interconnect COs, consisting mainly of fiber-optic links. The introduction of computers and digital switches totally digitized the PSTN, introducing sampling of the analog voice at 8 kHz using 8 bits per sample. The samples are then quantized and coded.

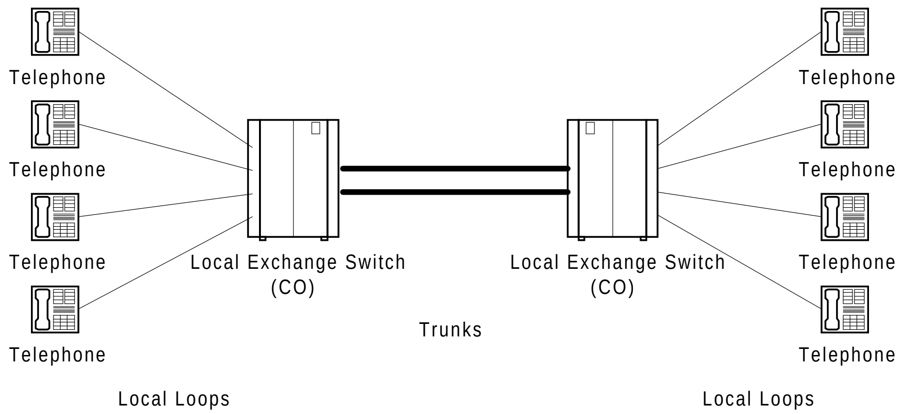

Figure 2.1: Basic elements of the public switched telephone network

This process is described as *pulse coded modulation* (PCM) [11].

The local loop needs some special attention. It is part of the main distribution network, as shown in Figure 2.2 [12]. The main network consists of large multi-pair cables which radiate out from the *main distribution frame* (MDF), located within the serving local exchange, to flexibility points known as *primary cross-connection points* (PCPs) [12], *serving area interface* (SAI) or *serving area concept box* (SAC box) [13]. The MDF permits any subscriber line to be connected to any port of any CO equipment. For ADSL the subscriber line will be connected to the CO switch and *DSL Access Multiplexer* (DSLAM, pronounced ”D-SLAM”) equipment. The MDF-PCP (E-side) cables are known as feeder cables containing up to 10 000 pairs. The PCPs are usually located in street cabinets and typically serve 1 500 to 3 000 customers within a certain area [13]. From the PCP, connections radiate out to *distribution points* (DPs), sometimes passing through secondary *cross-connection points* (SCPs). The PCP-(SCP)-DP (D-side) cables are known as distribution cables. The SCPs can be located within a street cabinet or mounted on a utility pole. The DPs are usually mounted on a utility pole, but for large office and residential complexes the SCP and/or DP are found in dedicated complex-installed cabinets. Overhead DPs typically serve four to six units [13]. Individual cable segments are joined together to form the link between the MDF and PCP [12]. These segments have typical lengths of 150 m [12, 14]. The feeder and distribution cables are bundled into binder groups. The crosstalk between pairs within a binder group is greater (about 10 dB higher) than the crosstalk between pairs in separate

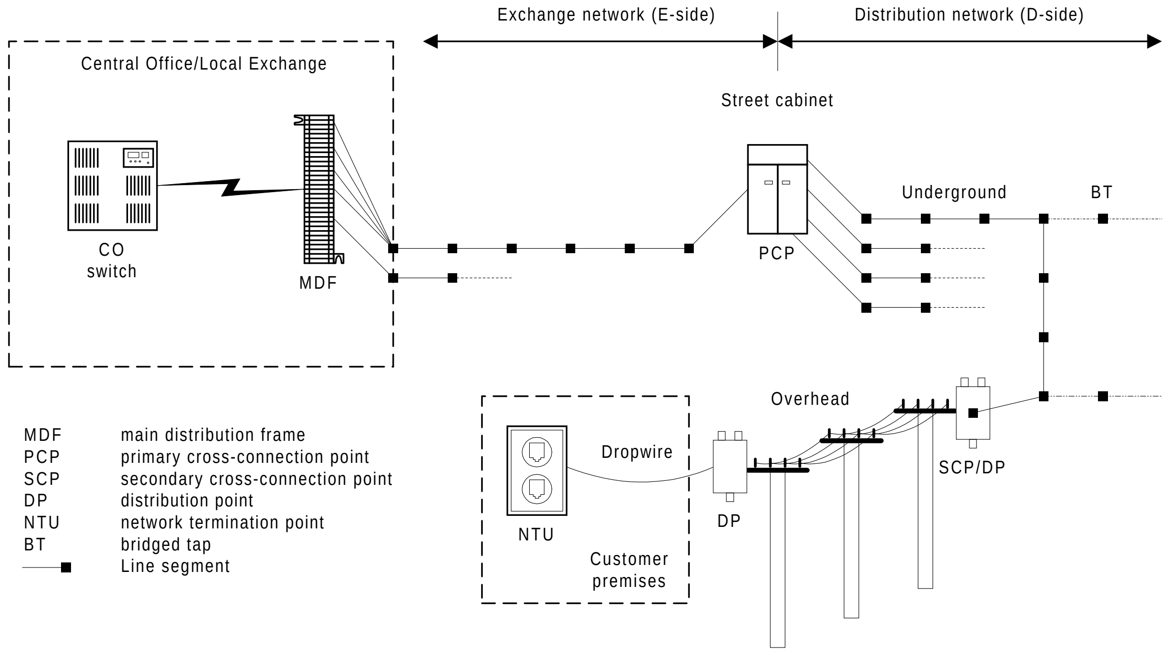

Figure 2.2: Main network topology

binder groups. A typical binder group in a multi-pair cable is shown in Figure 2.3. It should be noted that the distribution network may be overhead or underground. Underground feed is more reliable and is usually used in modern urban areas. Overhead feeds are more common in rural areas and for the last section of the PCP-(SCP)-DP connection, due to high civil engineering costs for underground feeds. From the DP a connection is made to the customer's premises via a dropwire. The dropwire consists of an untwisted copper pair of 0.9 mm gauge. Another connection is made to the network termination point (a familiar white RJ-45 socket) using quad (4-wire, untwisted) or UTP-Category 5 (5-wire, twisted) cable. UTP-Category 5 is preferred due to improved crosstalk performance (by as much as 20 dB) as compared to quad [12]. For loops longer than 5.5 km, the voice quality reached unacceptable levels, due to excessive signal loss in the 0-4 kHz region. 0.88 mH inductors are placed at 1.83 km intervals in order to improve frequency response across the voice band, but results in greater loss for higher frequencies [11, 13]. This extends the loop reach to 10 km [11]. However, ADSL will NOT operate on loaded loops. ADSL will operate over loops up to 5.5 km which contain bridged taps and are not loaded. In order to improve performance, the loop length should be reduced or thicker wire should be used. Also, in order to extend the working distance of copper loops, *Digital Loop Carriers* (DLCs), shown

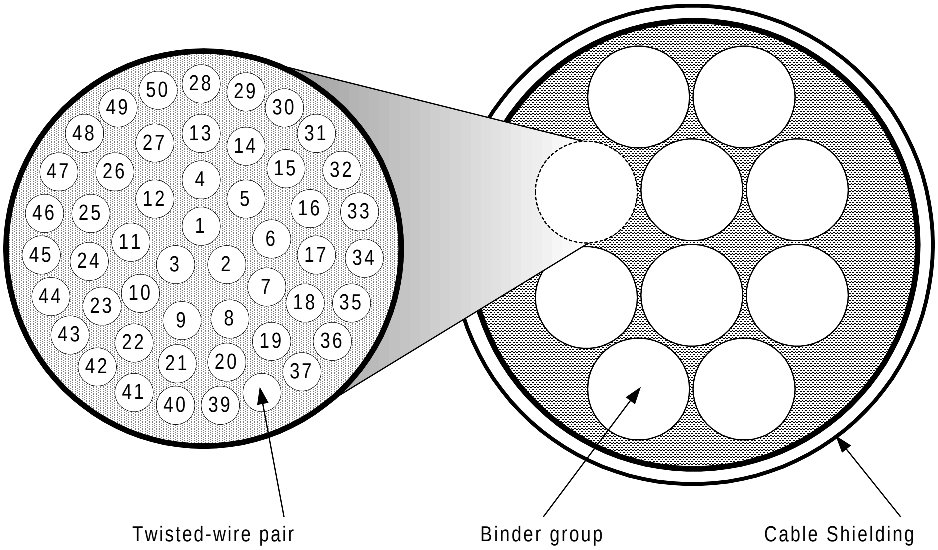

Figure 2.3: Illustration of twisted pair and binder group location within a 500 pair cable

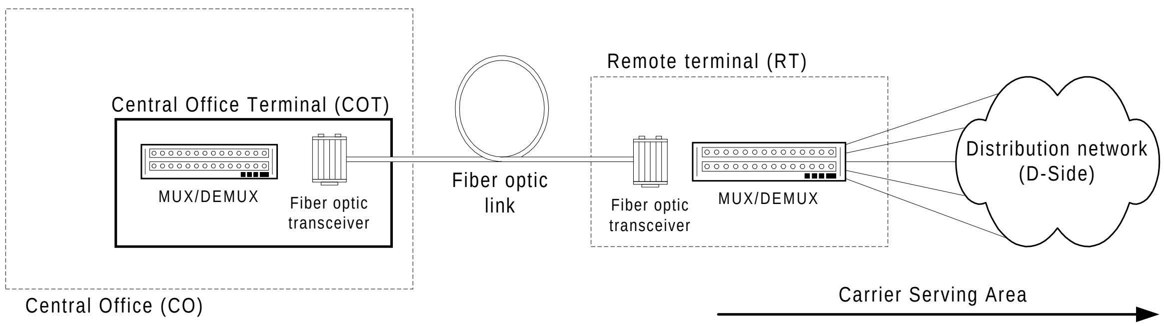

Figure 2.4: Digital Loop Carrier architecture

in Figure 2.4, are introduced into the feeder side (E-side), shown in Figure 2.2 [13]. The DLC replaces the large number of copper pairs in the feeder with a single multiplexed connection. The *Next Generation DLC* (NGDLC) is a fiber-fed connection, multiplexing up to 2 000 lines into one fiber cable. If NGDLC is implemented, the PCP is transformed into a *remote terminal* (RT) or mini CO, containing the multiplexing and modem equipment. Loops served by DLCs follow the *carrier serving area* (CSA) design rules, stipulating the following:

- Maximum loop length of 3.66 km for 0.5 mm gauge wire;
- Maximum loop length of 2.75 km for 0.4 mm gauge wire;
- Loops with a mixture of gauges are restricted to a length that corresponds to the

proportional length of each type of wire;

- Maximum loop resistance of 850 ohms;
- Cumulative length of bridged taps may not exceed 762 m, and
- The maximum loop length is reduced by the cumulative bridged taps on the loop [13].

2.3 What is ADSL?

ADSL is the acronym for *Asymmetric Digital Subscriber Line*, a local loop transmission technology. ADSL is part of the xDSL family, used mainly to provide high data rates over a twisted-pair channel. xDSL is considered as a transition technology towards an all-fiber network, commonly known as *fiber-to-the-home* (FTTH). ADSL is asymmetric because downstream (towards the customer) the data rate is higher than the upstream (towards the network) data rate. This has great benefits when compared with symmetric systems, in terms of higher downstream data rates and longer lines (extended reach) by reducing the *near-end crosstalk* (NEXT) between ADSLs [13, 15]. A comparison between the different xDSL members is given in Table 2.1 [13, 15, 16, 17, 18]. Although the transmission over the local loop is analog, the data being transmitted remains *digital*. This is in contrast to current analog modems where the local exchange requires the data to be converted to analog format before being digitized at the CO (64 kbps PCM). ADSL also allows the simultaneous transmission of *plain old telephone services* (POTS) by transmitting the data in the frequency band above voice-band, using upstream and downstream frequency bands.

The upstream and downstream frequency bands can be allocated using two methods: *Frequency division multiplexing* (FDM) and *echo-cancelled hybrids* (ECH), shown in Figure 2.5 [13, 15]. FDM has the advantage of separate frequency bands to prevent self-crosstalk (NEXT), with the disadvantage of reducing the downstream bandwidth (reduced downstream data rate). For ECH, upstream bandwidth resides within the downstream bandwidth, leading to self-crosstalk (self-NEXT), with higher downstream data rates. However, more complex digital signal processing is necessary. FDM ADSL offers better upstream performance than ECH ADSL, while ECH ADSL offers better downstream performance [13].

Table 2.1: COMPARISON BETWEEN XDSL, T1/E1 PRIVATE LINES AND ANALOG MODEMS

Feature	**ADSL**	**CDSL**	**HDSL**	**IDSL\ ISDN**	**SDSL**	**VDSL**	**Private Line**	**Analog Line**
Max. Downstream Speed (Mbps)	9	1.5	1.5/2	0.144	2	52	1.5/2	0.056
Max. Upstream Speed (Mbps)	1.5	0.512	1.5/2	0.144	2	13	1.5/2	0.033
Symmetric/Asymmetric	A	A	S	S	S	A/S	S	A
Modulation used	DMT	DMT	2B1Q	2B1Q	2B1Q	SDMT	AMI/ HDB3	PCM
Rate adaption after connection	Yes	Yes	No	No	No	TBA	No	No
Downstream Bandwidth (MHz)	1.104	0.552	0.392	0.08	1	30	3/4	0.004
Upstream Bandwidth (MHz)	0.276	0.138	0.392	0.08	1	30	3/4	0.004
Avg. spectral efficiency (bits/symbol/Hz)	8	2.7	2	2	2	1.7	0.5	14
Number of lines used	1	1	2	1	1	1	2	1
Maximum copper wire reach (km)	5.5	5.5	3.66	6.1	3.51	1.37	3.66	$<$18
Migration to Full Service Network	No	No	No	No	No	Yes	No	No
Migration to ADSL		Yes	Yes	Yes	Yes	N/A	Yes	Yes
Migration to VDSL	Yes	Costly	Costly	Costly	Costly		Costly	Costly
New infrastructure degree	Med	Low	Low	High	Low	High	Low	Low
Pricing method (Flat/Usage)	F/U	F/U	F	U	F	U	F	U
Switched/Dedicated	D	D	D	S	D	D	D	S
Interoperability	Yes	Yes	No	Yes	No	Yes	No	Yes
Simultaneous analog voice service	Yes	Yes	No	No	No	Yes	No	No
Power spectral density (dBm/Hz)			-38	-36	-43.2	-60	-50/-51	-23
Up	-38	-34.5						
Down	-40	-36.5						
Total power of transmitter[3] (dBm)			13.38	12.99	16.8	14.77	15.1	13
Up	16.4	16.9						
Down	20.43	22.9						
Maximum output voltage (V)	3.3	4.4	2.3	2.2	2.02	4-5	3.6	3.5
Line impedance (Ω)	100	100	135	135	135	100	100	600

[3] Assuming an utilization efficiency of 88% [18]

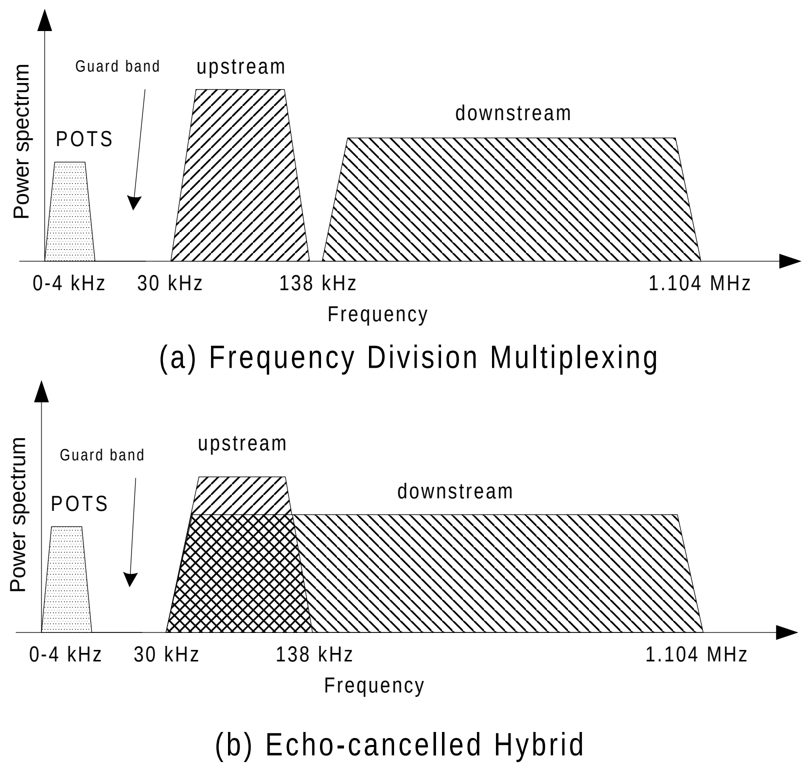

Figure 2.5: Frequency division multiplexing and echo-cancelled hybrid PSD

The conceptual definition of ADSL began in 1989 at Bellcore. Early development began at Stanford University and AT&T Bell Labs in 1990, with field trials in 1995. This also led to the ANSI T1.413-1995 standard, which was revised in December 1998 as ANSI T1.413-1998 (Issue 2) [19]. In October 1998 the ITU approved recommendation G.992.1 [20], specifying full-rate ADSL. ANSI T1.413-1998 has the capability for rate-adaptive ADSL, providing higher bit rates on loops with better transmission characteristics. The inherent rate-adaptive feature allows the *service provider* (SP) to adjust the bandwidth of the DSL link to fit the needs of the application and to account for the line length and quality. Through network management, the SP can pre-define the bandwidth or allow it to be self-adjusting. This feature is particularly attractive to telephone operators, as it allows them to tariff different rates for different bandwidths [11]. ADSL supports downstream and upstream bit rates up to 8 Mbps and 1 Mbps respectively [13], over 0.5 mm gauge wire up to 2.74 km [21]. ADSL has a maximum reach of 6 km for 0.5 mm gauge wire, with a reduced downstream rate of 1 Mbps [22]. The general ADSL architecture is shown in Figure 2.6 [11].

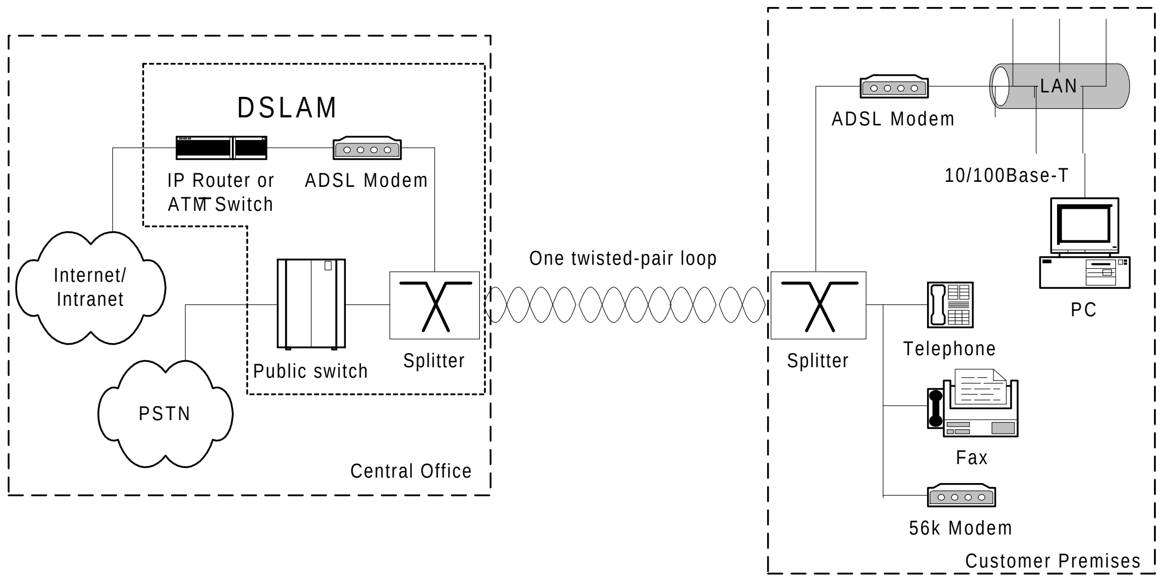

Figure 2.6: General ADSL architecture

The splitter is a device that comes between the local exchange and the customer premises — Its function is twofold. First, the splitter allows an existing analog telephone and other equipment (e.g., fax machines) to operate as before, without interference from the *ADSL terminal unit-Remote side* (ATU-R), by using a low-pass filter. A passive splitter is usually used, ensuring operation of the voice services even when the ATU-R should fail to operate. Second, the splitter allows the long holding time data traffic to be rerouted around the PSTN voice switch at the CO (where it is carried on circuits) onto an *Internet Protocol* (IP) router or *Asynchronous Transfer Mode* (ATM) switch network (where it is carried in packets). In the CO the ADSL modem and splitter are integrated into a slot-in card. This card is fitted into a DSLAM which handles the multiplexing and switching/routing of several DSL links. ADSL requires the installation and maintenance of a remote splitter. The splitter's main function at the premises was to allow the continued use of existing analog telephony and faxing devices in the home or small-office-home-office locations. However, besides introducing complexity, the presence of the splitter also raised issues about the premises wiring and configurations [11]. Pure ADSL involved the need for the service provider to make an appointment with the customer for splitter and possibly wiring installation. A further concern was the need to dispatch a truck and technician, which added considerable cost to service initiation and slowed deployment. In many cases, the remote splitter was provided as part of the service, adding to the service provider's capital costs. The associated wiring issues only added to the service delay, expense, and complexity. Clearly, if a way could be found to install and configure ADSL speeds and distances, and at the same time support existing analog devices without the need for the remote splitter, this would be a very attractive alternative to pure ADSL [11]. Near the end of 1997, Rockwell Semiconductor Systems introduced a splitterless ADSL variation it called *Consumer DSL* (CDSL), also known as splitterless ADSL, ADSL.Lite or *Universal ADSL* (UADSL), to address these concerns and limitations. Rockwell also proposed its method for standardization before the ITU, as something called "G.adsl lite", which shows the close relationship between ADSL/RADSL and ADSL.Lite. The only significant difference between ADSL/RADSL and ADSL.Lite, besides the absence of the splitter at the premises and wiring concerns, is a restricted operating speed range (most importantly 1.5 Mbps downstream as opposed to about 8 Mbps with ADSL) [11]. ADSL.Lite has been standardized by the ITU as G.992.2 [23].

The major differences between ADSL (G.992.1) and ADSL.Lite (G.992.2) are:

- Added power saving modes for CDSL at the ATU-C and ATU-R;
- Added fast retrain mechanism for CDSL;
- The number of tones are reduced from 256 to 128. ADSL.Lite thus uses the bandwidth from 0 to 552 kHz ;
- The number of bits per tone is reduced from 15 to 8 [13];
- Downstream rate of 64 kbps to 1.5 Mbps (32 kbps increments) for ADSL.Lite and
- Upstream rate of 32 kbps to 512 kbps (32 kbps increments) for ADSL.Lite [23].

By the end of 1997, Nortel, Microsoft, Compaq and Intel had all made ADSL.Lite support announcements. The future of ADSL.Lite appears not only assured, but bright. The local exchange (CO) side of the link remains unchanged — a splitter is still needed in the CO to separate high-speed data packets from voice conversations. The overall architecture of

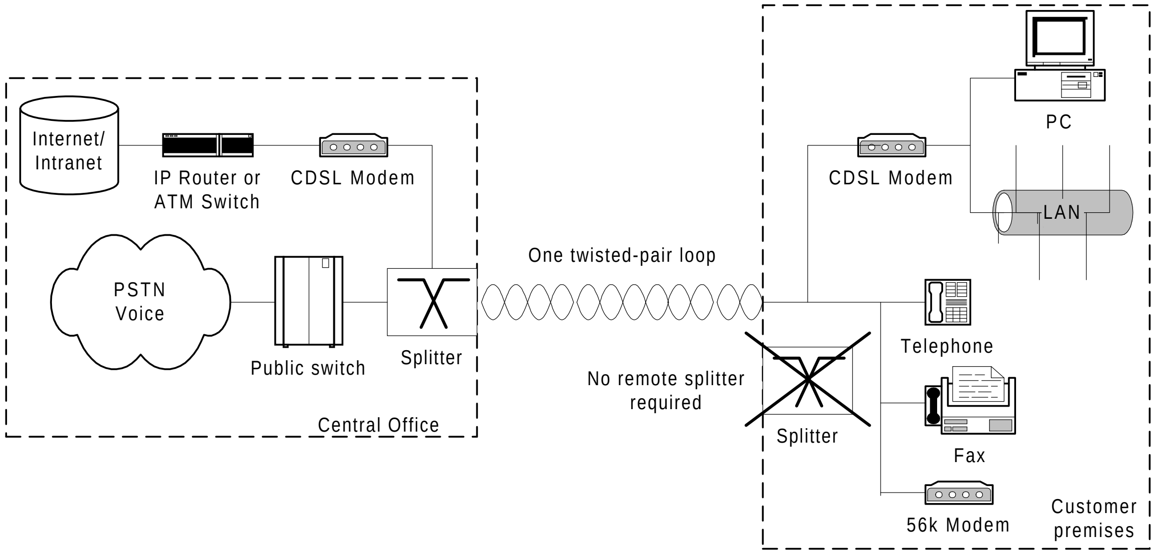

Figure 2.7: Splitterless ADSL architecture

ADSL.Lite is shown in Figure 2.7 [11]. In order to remove the splitter at the remote side of the network, the power of the upstream transmitter must be reduced by 6-9 dB within the voiceband region (corresponding to 4-7 dBm total power), in order to obtain the same interference level in the voice band as specified in ANSI T1.413. This power reduction leads to lower upstream data rates for a given loop. It should be noted that on-hook to off-hook state changes result in bursts of errors for the digital data. Signal processing techniques are required to adapt the demodulation process in order to counteract these state changes. However, the low frequency tones can still be used without affecting the voice-band interference level [24].

ADSL.Lite's intention is to complement service providers' ADSL deployment into places where higher speeds are not particularly mandated or feasible, and where there are concerns about remote splitter and wiring installation. ADSL.Lite still requires the same equipment arrangement as ADSL in the local exchange or central office. Because ADSL.Lite is a variation of ADSL, there should be minimal issues associated with tariffs or contracts for ADSL.Lite services [11].

The modulation used by both pure ADSL and splitterless ADSL is *Discrete Multi-Tone* (DMT) [13, 15]. Pure ADSL DMT divides the entire bandwidth range (0 to 1.1 MHz) into 256 equally spaced subchannels (also called tones), each occupying 4.3125 kHz. Subchannels #1 through #6 are reserved for the 4 kHz passband analog voice plus a wide guard-band. Subchannel #64 (276 kHz) is reserved for a pilot signal [3, 13, 19]. There are 26 upstream channels, starting at subchannel #7, 250 downstream channels when echo cancellation are used and 224 when FDM is used [15]. When the ADSL modem is activated, a complex handshaking procedure measures the gain (by sending unit energy in each subchannel) and noise present in each subchannel. These measurements are used to optimally adjust the spectral efficiency (measured in terms of bits/symbol/Hz) for each subchannel, up to 15 bits/symbol/Hz [13, 19]. The appropriate combination of energy and number of bits to be carried on each tone is then determined based on the desired detection symbol error probability [25]. Each subchannel employs its own coding technique based on QAM. All of the subchannels are constantly monitored for performance and errors. Upon detection of performance degradation in one or more tones, the receiver computes a modified bit distribution. The change is reported to the transmitter via a reliable low-speed control channel, where it is implemented. Information is usually transmitted in bytes, giving ADSL a linear granularity of 32 kbps [3, 11, 13]. DMT is an adjustable modulation technique used to combat various factors associated with local loops, such as line attenuation (a function of line length, wire diameter and bridged taps), frequency selective interference and impulse noise, and crosstalk between different twisted-pairs within the same binder group. These factors will be discussed in detail in Chapter 3. An illustration of DMT operation, in accordance with the ANSI T1.413 standard, is shown in Figure 2.8 [13, 19]. The *power spectral density* (PSD) is -40 dBm/Hz on average with tolerable variation over tones of $\pm$1.5 dB. The maximum transmit power is about 20 dBm (0.1104 W) [13, 19]. Bit allocation is performed in order to optimize the usage of the available transmit power [13]. A bit loading algorithm, developed by Campello, will be discussed in Chapter 4.

ADSL implements complex signal processing techniques to obtain coding gain. This enables ADSL to obtain efficiency close to the best possible performance (channel capacity), expressed as a function of the signal-to-noise ratio (SNR). With FEC, *Reed-Solomon* (RS) coding, Trellis coding and Viterbi decoding, ADSL can obtain a SNR gap as low as 1-2 dB [13]. The *SNR gap* is referred to as the amount by which the SNR (for channel capacity)

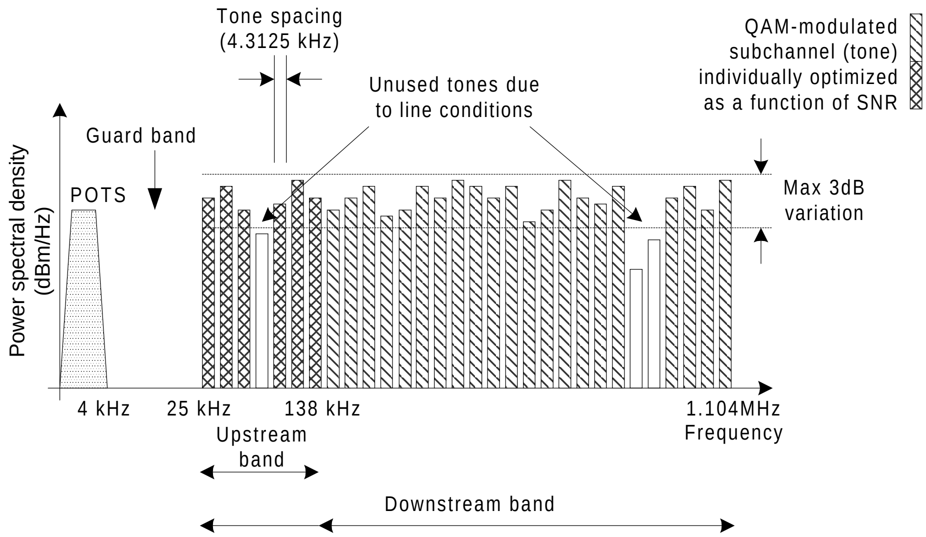

Figure 2.8: ADSL PSD when implementing DMT modulation

can be reduced to maintain a symbol error probability at or below the target P_e. Without coding, and a symbol error probability P_e of 10^{-7}, a SNR gap of 9.8 dB will be used [1]. Trellis codes are used to reduce the effect of steady-state wide-band noise. Radio frequency interference and narrow-band noise is counteracted by using adaptive equalizers. An interleaving depth of 20 ms protects against error bursts of up to 500 μs in duration. This causes slower throughput for TCP/IP protocols (which requires acknowledgement of packets) due to additional transport delay [13, 18].

2.4 Why ADSL?

Current analog modems, used mainly for remote access to service providers, approach speeds of 56 kbps downstream and 33 kbps upstream, using only a 3 kHz bandwidth. These data rates are inadequate for the transmission of real-time video and multimedia applications. However, the single advantage of current voice-band modems is their ubiquity. An analog modem can be connected to any phone line and call any other analog modem connected to the PSTN. Voice-band modems cost less than ADSL (and xDSL) modems and are easier to install. However, ADSL (and xDSL) modems solve some drawbacks of voice-band modems, such as blocked calls, inability to connect to multiple destinations simultaneously, high error rates and low data rates.

The rapid explosion of the Internet, multimedia applications and on-line services have forced telecommunication providers (Telcos) to provide faster access at lower cost, while making optimal use of the existing network. ADSL will play a crucial role over the next few years as Telcos enter new markets for delivering information, either video or multimedia. New broadband cabling, of which fiber is the most preferable, will take decades to reach all prospective subscribers, due to high deployment costs. Fiber provides low loss, high bandwidth and lightning fast transmission, but is too expensive to install for the last few hundred metres to the customer. ADSL is a member of the xDSL family [11, 16] of copper-based access solutions, which makes the transition from copper to fiber not only possible, but also cost-effective [14, 26]. It provides a means of reusing the existing copper network in order to provide broadband access to subscribers with minimal investment, while overcoming the inherent limitations of current analog modems.

ADSL allows the simultaneous transmission of high-speed data and conventional analog voice over the same local loop, as described in Section 2.3. This is in contrast to current situations, where high levels of Internet usage require an additional line to support simultaneous conventional voice services. Dial-up Internet access presents longer holding times to the network than voice services, leading to higher traffic loads. ADSL's asymmetric nature makes it ideal for Internet applications.

CHAPTER THREE

CHANNEL MODELLING

3.1 Chapter Overview

The purpose of this chapter is to describe the theory and mathematics necessary to obtain an insertion loss model for any line topology encountered in practice. Primary and secondary parameters are the main variables which can be measured and calculated, as described in Section 3.2. These parameters are used to obtain an ABCD matrix for the line, as described in Section 3.3. Section 3.4 describes the main impairments encountered in the ADSL environment, specifically NEXT and FEXT models, which will be extensively used in the simulation.

3.2 Primary and Secondary Parameters

Twisted-pair local loops are characterized by their primary parameters, *R* (resistance), *C* (capacitance), *L* (inductance) and *G* (conductance). These parameters vary with frequency for different cable types and wire gauges. According to the ANSI T1.413 standard, *G* is assumed zero, *C* is a constant for all frequencies, and the variation of *R* and *L* with frequency can be accurately modelled as:

$$R = \sqrt[4]{roc^4 + ac.f^2} \tag{3.1}$$

Table 3.1: CABLE PARAMETERS FOR DIFFERENT WIRE TYPES

Wire Type	**roc**	**ac**	**l$_o$**	**l$_\infty$**	**f$_m$**	**b**	**C(F/km)**
0.32mm	$0.4090 \cdot 10^3$	0.3822	$0.6075 \cdot 10^{-3}$	$0.5000 \cdot 10^{-3}$	$0.6090 \cdot 10^6$	5.2690	$40 \cdot 10^{-9}$
0.4mm	$0.2800 \cdot 10^3$	0.0969	$0.5873 \cdot 10^{-3}$	$0.4260 \cdot 10^{-3}$	$0.7459 \cdot 10^6$	1.3850	$49 \cdot 10^{-9}$
0.5mm	$0.1792 \cdot 10^3$	0.0561	$0.6746 \cdot 10^{-3}$	$0.5327 \cdot 10^{-3}$	$0.6647 \cdot 10^6$	1.1950	$50 \cdot 10^{-9}$
0.63mm	$0.1130 \cdot 10^3$	0.0257	$0.6994 \cdot 10^{-3}$	$0.4772 \cdot 10^{-3}$	$0.2658 \cdot 10^6$	1.0956	$45 \cdot 10^{-9}$
0.9mm	$0.0551 \cdot 10^3$	0.0090	$0.7509 \cdot 10^{-3}$	$0.5205 \cdot 10^{-3}$	$0.1238 \cdot 10^6$	0.9604	$40 \cdot 10^{-9}$
Dropwire 10”	$0.1809 \cdot 10^3$	0.0497	$0.7289 \cdot 10^{-3}$	$0.5434 \cdot 10^{-3}$	$0.7189 \cdot 10^6$	0.7558	$51 \cdot 10^{-9}$
Flat pair	$0.0412 \cdot 10^3$	0.0001	$1.0000 \cdot 10^{-3}$	$0.9110 \cdot 10^{-3}$	$0.1742 \cdot 10^6$	1.1950	$22.68 \cdot 10^{-9}$
UTP Cat.5	$0.1766 \cdot 10^3$	0.0500	$1.0908 \cdot 10^{-3}$	$0.5045 \cdot 10^{-3}$	$0.0326 \cdot 10^6$	0.7050	$48.55 \cdot 10^{-9}$

$$L = \frac{l_o + l_\infty . \left(\frac{f}{f_m}\right)^b}{1 + \left(\frac{f}{f_m}\right)^b} \tag{3.2}$$

where *R* is the resistance of the line [Ω/km] at a specific frequency *f* [Hz], *roc* is the copper DC resistance [Ω/km] and *ac* a constant characterizing the rise of resistance with frequency due to the ”skin effect”. *L* is the inductance of the line [H/km] at a specific frequency *f* [Hz], l_o and l_∞ are the low-frequency and high-frequency inductances [H/km] respectively, *b* is chosen to characterize the transition between low and high frequencies in the measured inductance values and f_m is in Hz [13, 19].

Several types of copper wire used in the main network have been characterized in terms of these parameters, as shown in Table 3.1 [13, 19]. The resistance *R* vs. frequency *f* is shown in Figure 3.1 and the inductance *L* vs. frequency in Figure 3.2. The twisted-pair secondary parameters can be expressed as:

$$Z_o = \sqrt{\frac{R + j\omega.L}{G + j\omega.C}} \tag{3.3}$$

$$\gamma = \sqrt{(R + j\omega.L)(G + j\omega.C)} \tag{3.4}$$

where $\omega = 2\pi f$, Z_o is the characteristic impedance and γ is the propagation constant of the twisted-pair at a specific frequency *f* [13, 7]. The characteristic impedance Z$_o$ vs. frequency is shown in Figure 3.3 and the propagation constant γ vs. frequency in Figure 3.4.

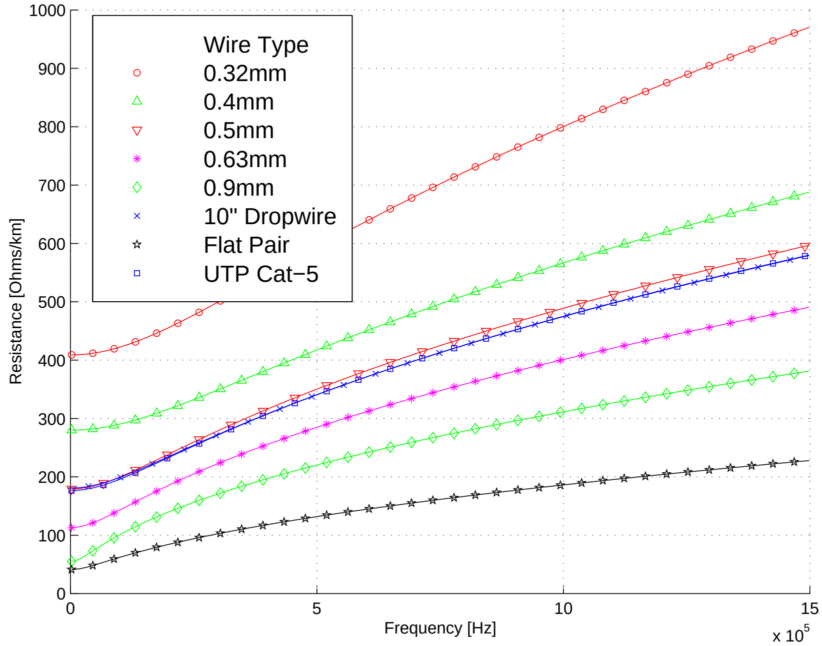

Figure 3.1: Resistance vs. Frequency

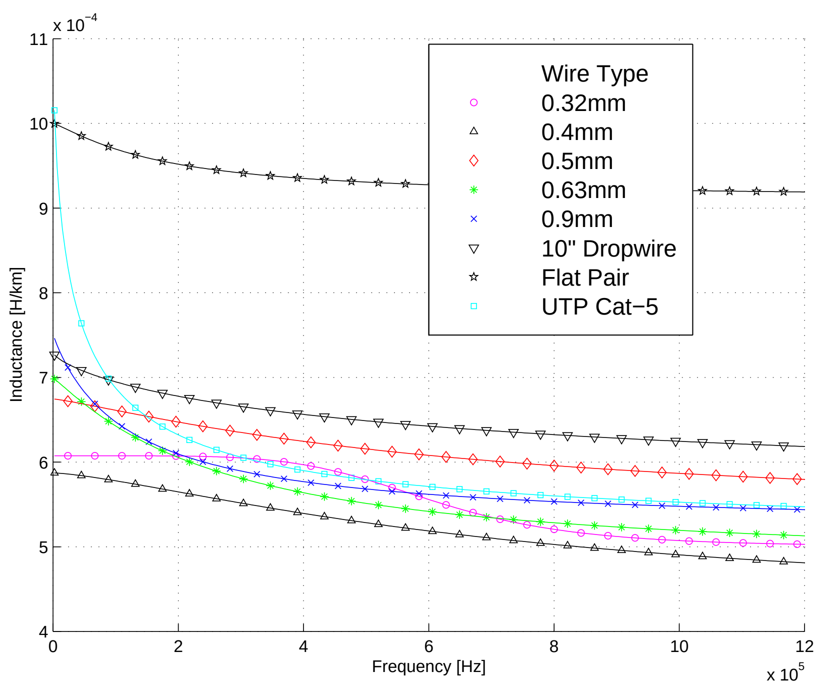

Figure 3.2: Inductance vs. Frequency

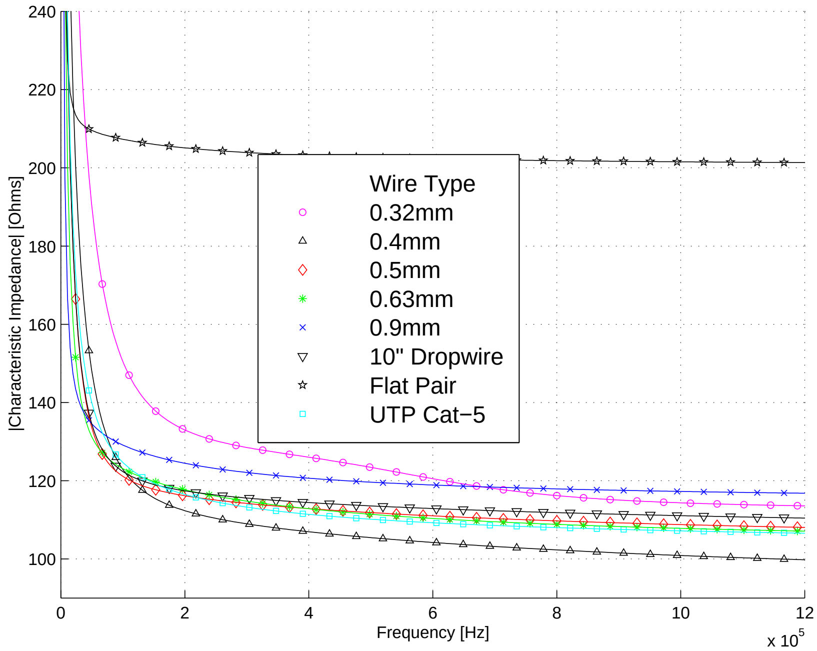

Figure 3.3: Characteristic Impedance vs. Frequency

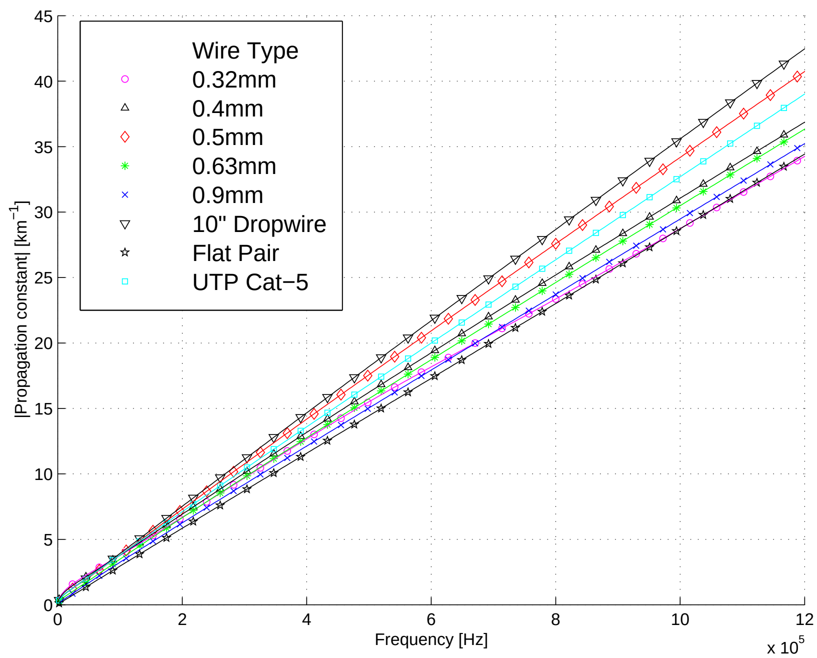

Figure 3.4: Propagation constant vs. Frequency

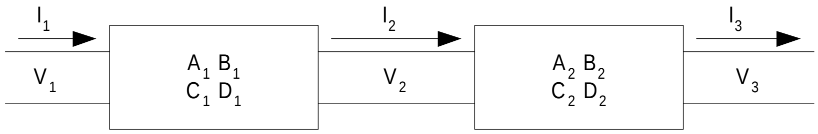

Figure 3.5: Two-port networks in series

3.3 Two-port networks and ABCD parameters

Local loops usually consist of several sections of cable with different lengths and wire gauges, with or without bridged taps, and terminated with resistive impedance. Two-port networks, and specifically ABCD matrixes can be used to represent each segment or section of a line. By multiplying the ABCD matrixes of each segment, an ABCD matrix is obtained which represents the complete line.

For a series impedance *Z*, the ABCD matrix is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \tag{3.5}$$

For a shunt impedance *Z*, the ABCD matrix is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Z^{-1} & 1 \end{bmatrix} \tag{3.6}$$

For two-port networks in series, shown in Figure 3.5, the ABCD matrix is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1A_2 + B_1C_2 & A_1B_2 + B_1D_2 \\ C_1A_2 + D_1C_2 & C_1B_2 + D_1D_2 \end{bmatrix} \tag{3.7}$$

Bridged taps are open-circuited twisted pairs, which are connected in shunt with working twisted pairs. Bridged taps create reflections of the main signal which affect both the

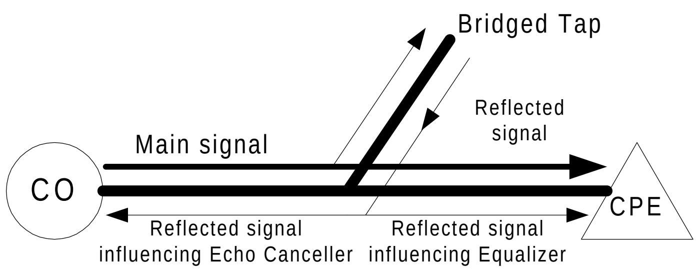

Figure 3.6: Echo generation in a bridged tap

transmitter and the receiver [7, 15], shown in Figure 3.6.

When a signal is transmitted from the CO to the customer, some of its energy deflects from the main signal path into the bridged tap and is reflected back by the open-circuited twisted pair. The delayed and distorted reflection of the main signal create two types of interference. First, part of it is added to the main signal and will appear as a noisy component to the customer's transceiver. Second, part will be reflected back to the transceiver at the CO and will appear as an echo. A third damaging effect of bridged taps is a net loss in power for the main signal. This loss can be explained by the fact that part of the main signal's power is dissipated in the bridged tap. Loss of power is also related to the "nulls" that are introduced by bridged taps in the transfer function of the loop. For loops with only one bridge tap, nulls occur at frequencies f_i for which the bridged tap's length d_{bt} is equal to an odd multiple of one quarter of the wavelength. The condition for the first null can be expressed as

$$f_o = \frac{1}{4 \cdot d_{bt} \cdot \tau_\phi(f_o)} \tag{3.8}$$

where $\tau_\phi(f_o) = Im\{\gamma(f_o)\}/f_o$ is the phase delay of the loop at frequency f_o. Other nulls occur at frequencies which are equal to $(2k + 1)\cdot f_o$, $k = 1, 2, 3, \ldots$. For working loops with several bridged taps, the location of the nulls can be heuristically determined by superposition. Equation (3.8) is a highly non-linear function of f_o. Typical bridged taps introduce "nulls" in the loop's transfer function at odd multiples of

$$f_o = \frac{45}{d_{bt[km]}}[kHz] \tag{3.9}$$

where $d_{bt[km]}$ represents the length of the bridged tap expressed in kilometers. Equation (3.9) is valid for bridged taps with lengths smaller than a few hundred meters. The loops transfer function is independent of the bridged tap's location when the loop is perfectly terminated. However, tap location becomes a factor when the terminations are mismatched or when the working portion of the loop has mixed gauges [7].

A bridged tap is treated as an impedance in parallel, with the ABCD matrix expressed as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ {Z_{bt}}^{-1} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{C_{\mathrm{bt}}}{A_{\mathrm{bt}}} & 1 \end{bmatrix} \tag{3.10}$$

where A_{bt} and C_{bt} are calculated from Equation (3.11) and (3.13), with d the length of the bridged tap [km].

The ABCD parameters are related to the characteristic impedance Z_o and propagation constant γ as follows:

$$A = D = \cosh(\gamma.d) \tag{3.11}$$

$$B = Z_o.\sinh(\gamma.d) \tag{3.12}$$

$$C = \frac{1}{Z_o}.\sinh(\gamma.d) \tag{3.13}$$

where d is the length [km] of the line segment under consideration [18].

The insertion loss function of the twisted-pair loop with source impedance Z_s and terminal impedance Z_t is [13, 18]:

$$H_{ins}(f) = \frac{Z_s + Z_t}{A.Z_t + B + C.Z_s.Z_t + D.Z_s} \tag{3.14}$$

The attenuation through the cable, in [dB], is expressed as [18]:

$$L_{dB}(f) = 10.log_{10}|\ H_{ins}(f)\ |^2 \tag{3.15}$$

3.4 Impairments for ADSL

3.4.1 Noise

Intrinsic noise impairments include thermal noise, echoes and reflections, attenuation, and crosstalk. Other sources of noise, due to the cable infrastructure, include surge protectors, *radio frequency interference* (RFI) filters, bridged taps, loading coils, split pairs, bunched pairs, leakage to ground, low insulation resistance, battery or earth contacts, and high-resistance joints [27].

Extrinsic impairments include impulsive noise originating from lightning strikes, electric fences, power lines, machinery, arc welders, switches, flourescent lighting, other equipment generating abrupt state changes (such as the on-hook to off-hook change of the telephone), and radio interference from broadcasting and radio transmitters [27].

The *capacity* of ADSL is usually limited by thermal noise and crosstalk, while the *performance* of ADSL is usually limited by impulses and RFI, which is intermittent in nature. ADSL uses advanced signal processing techniques (such as error correction coding with interleaving and adaptive line codes) to mitigate performance limiting noise [13, 27].

3.4.2 Crosstalk

Crosstalk refers to interference that enters a communication channel, such as a local loop, through some coupling path. Individual wires within a cable radiate electro-magnetically, inducing small currents in neighboring twisted pairs. This leads to an undesired crosstalk signal on the other pairs, which is treated as crosstalk noise [13]. The effect of crosstalk is minimized by using different twist distances among different pairs in a binder group (consisting of up to 50 pairs). Binder groups are also twisted such that no two groups are adjacent for long runs. Crosstalk is the main factor limiting the transmission throughput [3]. Two types of crosstalk are generated in a multi-pair cable: *Near-end crosstalk* (NEXT) and *Far-end crosstalk* (FEXT), as shown in Figure 3.7. A signal $v_s(t)$ is generated at the input to pair j. This signal, when propagating through the loop, generates two types of crosstalk

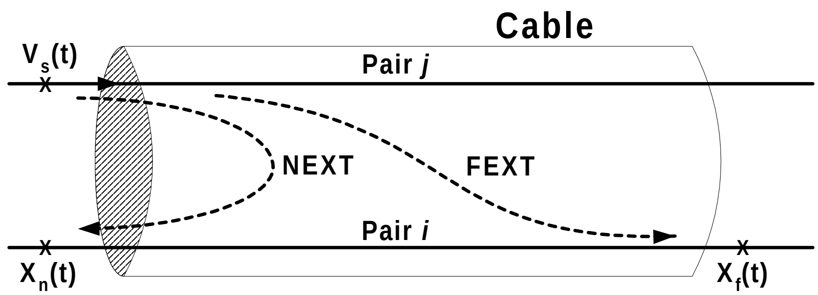

Figure 3.7: NEXT and FEXT generation between pairs in a binder group

in pair *i*. The crosstalk signal $x_n(t)$ is called NEXT and $x_f(t)$ is called FEXT. NEXT, if it exists, is generally more damaging than FEXT. This is because NEXT, unlike FEXT, does not propagate through a long loop and thus does not experience the corresponding propagation loss. A receiver on the left side, will thus see transmitters on the left side as NEXT-noise and transmitters on the right side as FEXT-noise [11].

3.4.3 Power Spectral Density of Disturbers

ISDN Disturber

The PSD of a typical ISDN disturber is expressed as [Annex B of [19]] :

$$\begin{aligned} PSD_{ISDN} &= K_{ISDN} \cdot \frac{2}{f_o} \cdot \frac{\left[\sin\left(\frac{\pi f}{f_o}\right)\right]^2}{\left(\frac{\pi f}{f_o}\right)^2} \cdot \frac{1}{1+\left(\frac{f}{f_{3dB}}\right)^4} \\ K_{ISDN} &= \frac{5}{9} \cdot \frac{V_p^2}{R}, \quad V_p = 2.50V, \quad R = 135\Omega \\ f_o &= f_{3dB} = 80kHz, \quad 0 \leq f < \infty \end{aligned} \tag{3.16}$$

PSD_{ISDN} is the single sided PSD of an 80 kbaud 2B1Q signal with random equiprobable levels, with full-baud square-topped pulses with 2^{nd} order Butterworth filtering (f_{3dB} = 80 kHz). The ISDN disturber PSD is shown in Figure 3.8.

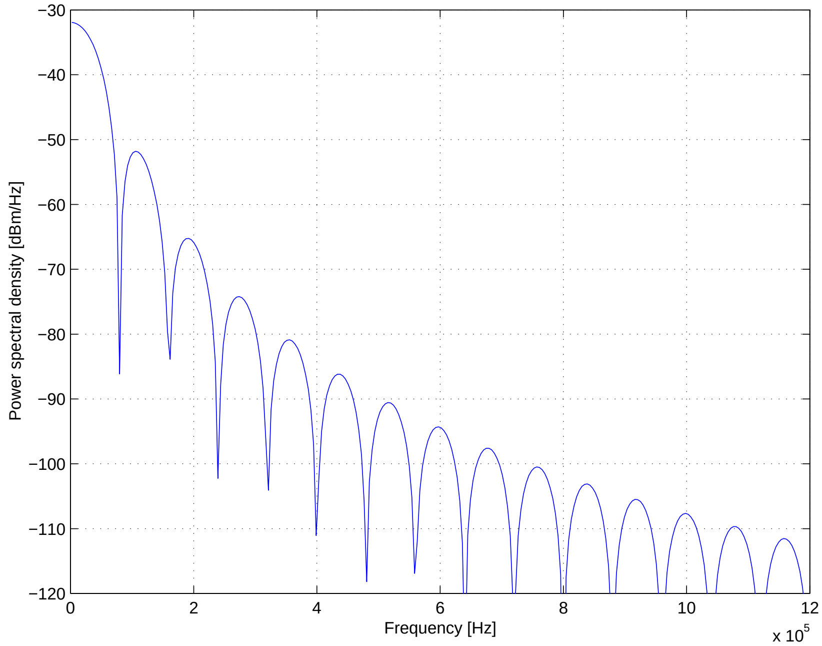

Figure 3.8: Power spectral density of an ISDN interferer

HDSL Disturber

The PSD of a typical HDSL disturber is expressed as [Annex B of [19]] :

$$\begin{aligned}
&PSD_{HDSL} = K_{HDSL} \cdot \frac{2}{f_o} \cdot \frac{\left[\sin\left(\frac{\pi f}{f_o}\right)\right]^2}{\left(\frac{\pi f}{f_o}\right)^2} \cdot \frac{1}{1+\left(\frac{f}{f_{3dB}}\right)^8} \\
&K_{HDSL} = \frac{5}{9} \cdot \frac{V_p^2}{R}, \quad V_p = 2.70V, \quad R = 135\Omega \\
&f_o = 392kHz, \quad f_{3dB} = 196kHz, \quad 0 \leq f < \infty
\end{aligned} \tag{3.17}$$

PSD_{HDSL} is a single-sided PSD of an 392 kbaud 2B1Q signal with random equiprobable levels, with full-baud square topped pulses with 4^{th} order Butterworth filtering (f_{3dB} = 196 kHz). The HDSL disturber PSD is shown in Figure 3.9.

E1 Disturber

The PSD of a typical E1 disturber is expressed as [Annex B of [19]] :

$$\begin{aligned}
&PSD_{E1} = K_{E1} \cdot \frac{2}{f_o} \cdot \frac{\left[\sin\left(\frac{\pi f}{f_o}\right)\right]^2}{\left(\frac{\pi f}{f_o}\right)^2} \cdot \sin^2\left(\frac{\pi f}{2.f_o}\right) \cdot \mid H_{Shaping}(f) \mid^2 \cdot \mid H_{Trans}(f) \mid^2 \\
&K_{E1} = \frac{V_p^2}{R}, \quad V_p = 3.60V, \quad R = 100\Omega \\
&f_o = 2.048MHz, \quad , 0 \leq f < \infty
\end{aligned} \tag{3.18}$$

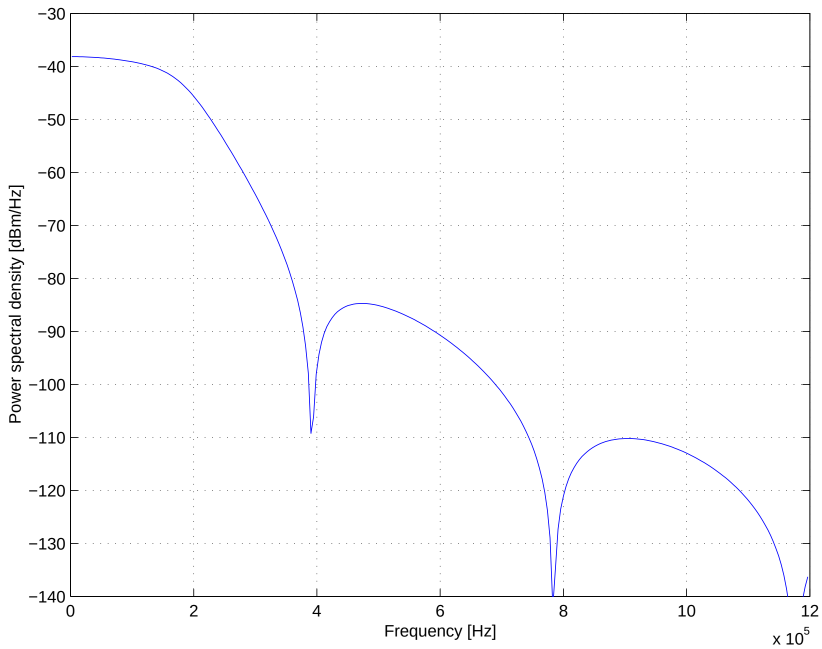

Figure 3.9: Power spectral density of a HDSL interferer

PSD$_{E1}$ is the single-sided PSD of a E1 line disturber with 50% duty-cycle random *Alternate Mark Inversion* (AMI) at 2.048 Mbps. The transmitted pulse passes through a 3rd order low-pass Butterworth filter ($f_{3dB-Shaping}$ = 4 MHz). This shaping filter's magnitude squared transfer function is:

$$\begin{aligned} \mid H_{Shaping}(f)\mid^2 &= \frac{1}{1+\left(\frac{f}{f_{3dB-Shaping}}\right)^6} \\ f_{3dB-Shaping} &= 4MHz \end{aligned} \tag{3.19}$$

In addition, the coupling transformer is modelled as a high-pass filter ($f_{3dB-Trans}$ = 40 kHz). This coupling transformer's magnitude squared transfer function is:

$$\begin{aligned} \mid H_{Trans}(f)\mid^2 &= \frac{f^2}{f^2+{f_{3dB-Trans}}^2} \\ f_{3dB-Trans} &= 40kHz \end{aligned} \tag{3.20}$$

The PSD of an E1 disturber is shown in Figure 3.10.

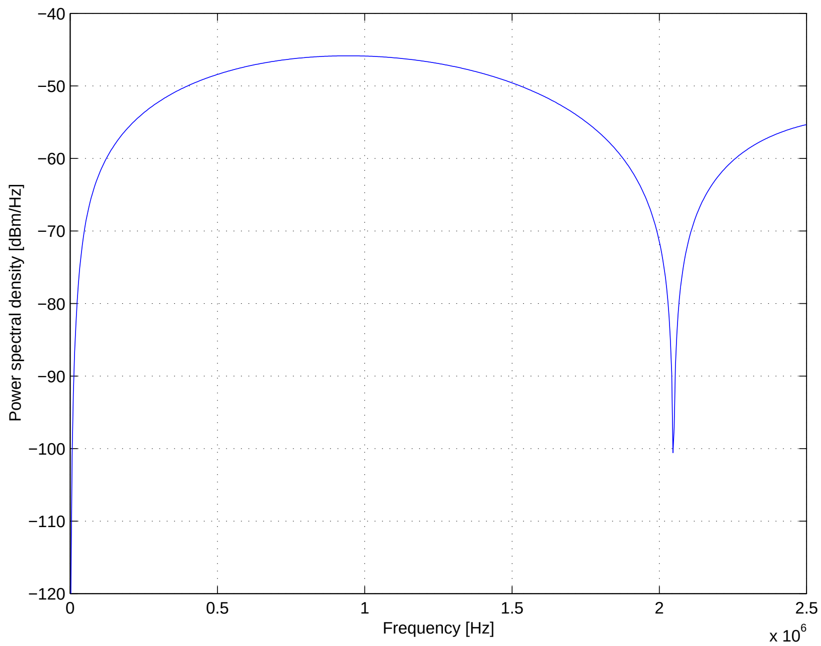

Figure 3.10: Power spectral density of an E1 interferer

ADSL Downstream Disturber

The power spectral density of a downstream ADSL disturber is expressed as [Annex B of [19]] :

$$PSD_{ADSL-down} = K_{ADSL-down} \cdot \frac{2}{f_o} \cdot \frac{\left[\sin\left(\frac{\pi f}{f_o}\right)\right]^2}{\left(\frac{\pi f}{f_o}\right)^2} \cdot \mid LPF(f) \mid^2 \cdot \mid HPF(f) \mid^2 \qquad (3.21)$$
$$K_{ADSL-down} = 110.4mW, \quad f_o = 2.048MHz, \quad ,0 \leq f < \infty$$

$K_{ADSL-down}$ is the total transmitted power in milliwatt for a downstream ADSL transmitter before shaping filters, with f_o the sampling frequency. *LPF* is a low-pass filter with f_{3dB} = 1.104 MHz and 36 dB/oct roll-off, expressed as:

$$\mid LPF(f) \mid^2 = \frac{{f_h}^\alpha}{f^\alpha + {f_h}^\alpha} \qquad (3.22)$$
$$f_h = 1.104MHz, \quad \alpha = 11.96$$

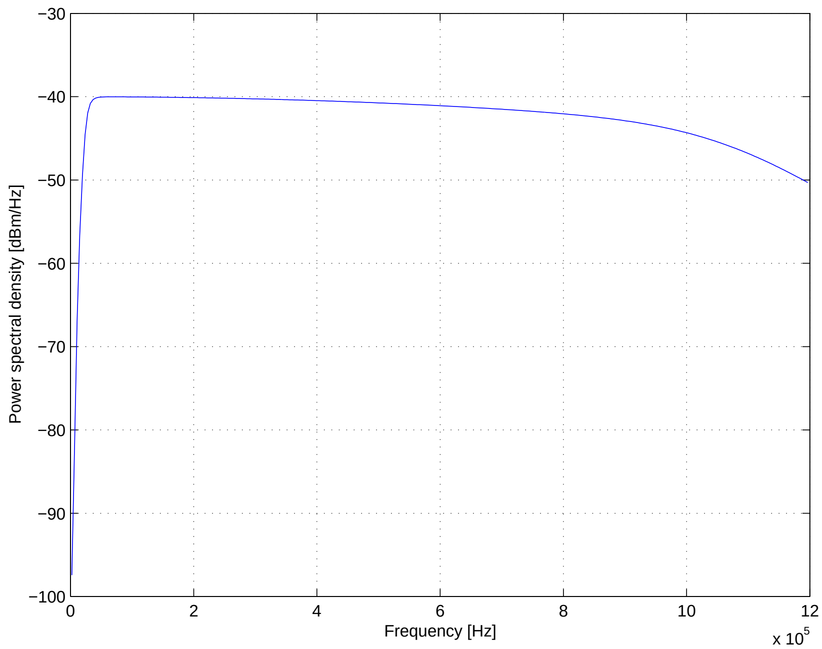

Figure 3.11: Power spectral density of a downstream ADSL interferer

HPF is a band-pass filter with f_{3dB} = 4 kHz and 25.875 kHz with 57.5 dB attenuation in the voice band, expressed as:

$$\begin{aligned} &\mid HPF(f) \mid^2 = \tfrac{f^\alpha + {f_l}^\alpha}{f^\alpha + {f_h}^\alpha} \\ &f_l = 4kHz, \quad f_h = 25.875kHz, \quad \alpha = 7.09 \end{aligned} \tag{3.23}$$

The PSD of an ADSL downstream disturber is shown in Figure 3.11.

ADSL Upstream Disturber

The power spectral density of an upstream ADSL disturber is expressed as [Annex B of [19]] :

$$\begin{aligned} &PSD_{ADSL-up} = K_{ADSL-up} \cdot \tfrac{2}{f_o} \cdot \tfrac{\left[\sin\left(\frac{\pi f}{f_o}\right)\right]^2}{\left(\frac{\pi f}{f_o}\right)^2} \cdot \mid LPF(f) \mid^2 \cdot \mid HPF(f) \mid^2 \\ &K_{ADSL-up} = 43.7mW, \quad f_o = 276kHz \quad 0 \le f < \infty \end{aligned} \tag{3.24}$$

$K_{ADSL-up}$ is the total transmitted power in milliwatt for a upstream ADSL transmitter before shaping filters, with f_o the sampling frequency. *LPF* is a low-pass filter with f_{3dB} = 138 kHz

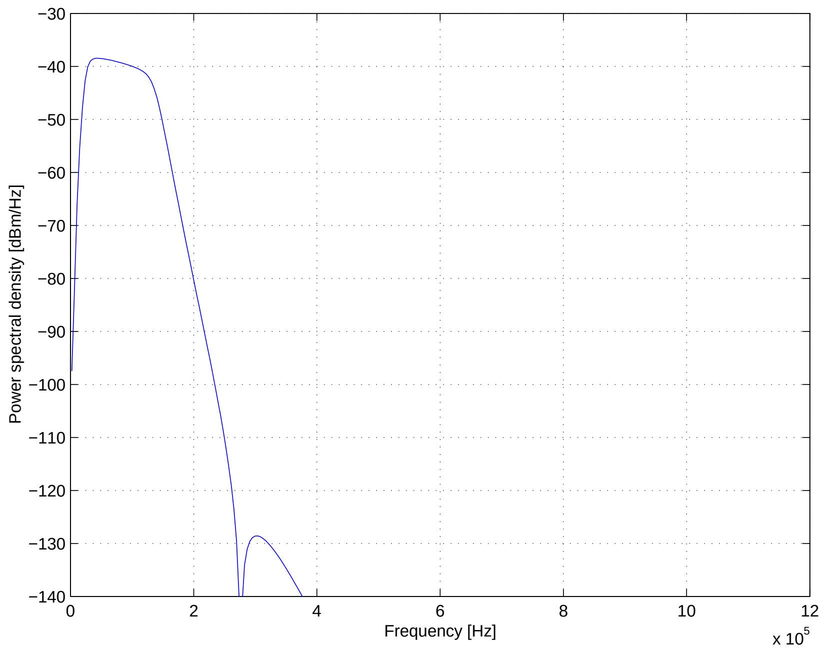

Figure 3.12: Power spectral density of an upstream ADSL interferer

with 24 dB attenuation at 181.125 kHz, expressed as:

$$\begin{aligned} &\mid LPF(f) \mid^2 = \tfrac{{f_h}^{\alpha}}{f^{\alpha}+{f_h}^{\alpha}} \\ &f_h = 138kHz, \quad \alpha = 20.32 \end{aligned} \tag{3.25}$$

HPF is a band-pass filter with f_{3dB} = 4 kHz and 25.875 kHz with 57.5 dB attenuation in the voice band, expressed as:

$$\begin{aligned} &\mid HPF(f) \mid^2 = \tfrac{f^{\alpha}+{f_l}^{\alpha}}{f^{\alpha}+{f_h}^{\alpha}} \\ &f_l = 4kHz, \quad f_h = 25.875kHz, \quad \alpha = 7.34 \end{aligned} \tag{3.26}$$

HPF are used to separate ADSL from the POTS. The PSD of an ADSL upstream disturber is shown in Figure 3.12.

3.4.4 NEXT Noise Models

NEXT noise models were empirically determined by measuring the pair-wise coupling transfer functions in a 50-pair cable. At any given frequency, only a few other pairs may contribute significantly, but over all frequencies, many lines contribute. Thus, to derive a

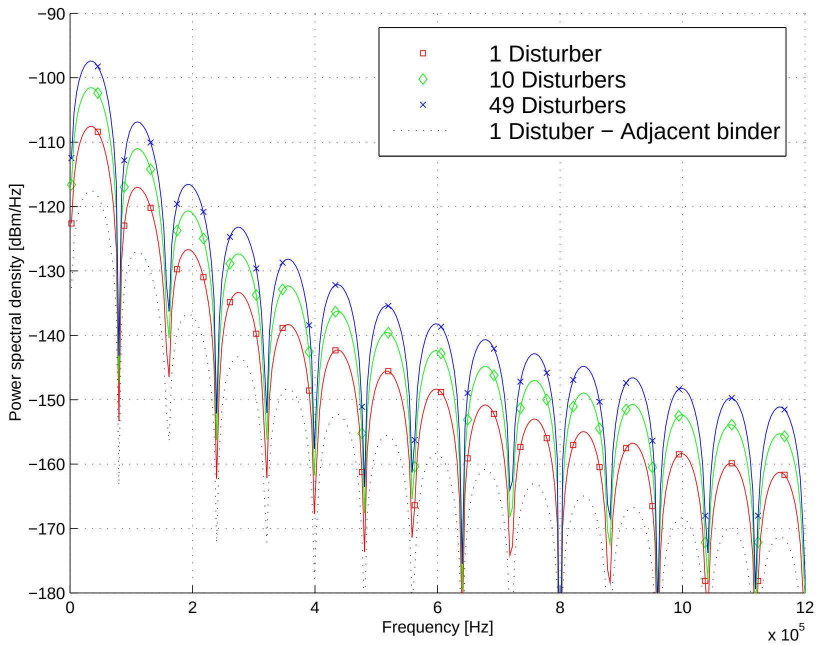

Figure 3.13: Power spectral density of 1, 10 and 49 ISDN NEXT interferers

model, the coupling average over many pairs was determined. The value determined by the model is referred to as the 99% worse case. This means that 99% of twisted-pairs found in practice will actually perform better than the model and only 1% will perform worse [13, 27]. The power spectral density of NEXT noise, for the line under consideration, can be expressed as:

$$\begin{aligned} &PSD_{NEXT} = PSD_{Disturber} \cdot x_n \cdot f^{1.5} \\ &x_n = 8.814 \cdot 10^{-14} \cdot \left(\tfrac{n}{49}\right)^{0.6}, \quad n < 50, \quad 0 \leq f < \infty \end{aligned} \tag{3.27}$$

where n is the number of disturbers, and f is the frequency [Hz]. Equation (3.27) can be used for ADSL, ISDN, HDSL and E1 interferers. For crosstalk between binder groups, x_n is reduced by an additional 10 dB, i.e. $x_n = 8.814 \cdot 10^{-15} \cdot (n/49)^{0.6}$.

ISDN NEXT Noise

The PSD of 1, 10 and 49 ISDN NEXT interferers are shown in Figure 3.13.

HDSL NEXT Noise

The PSD of 1, 10 and 49 HDSL NEXT interferers are shown in Figure 3.14.

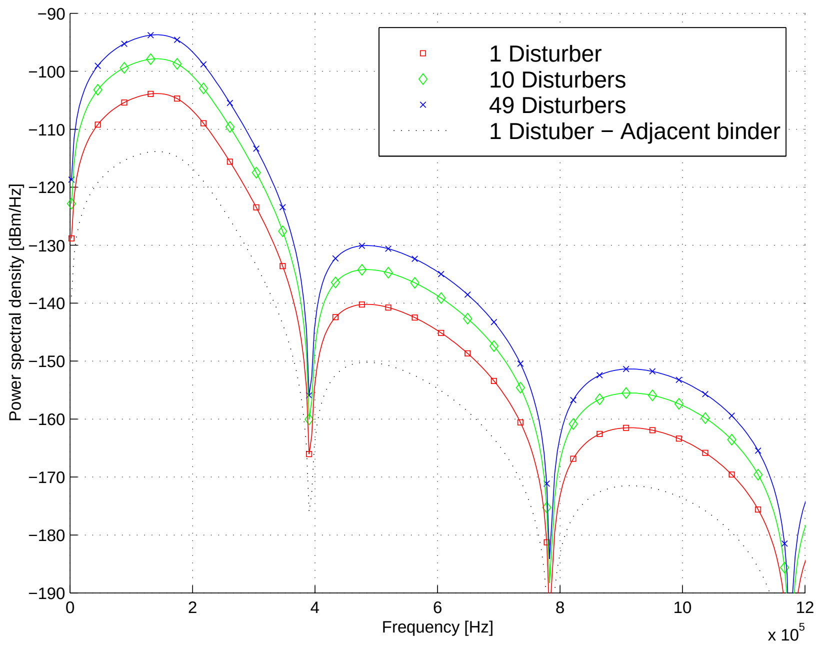

Figure 3.14: Power spectral density of 1, 10 and 49 HDSL NEXT interferers

E1 NEXT Noise

The PSD of 1, 10 and 49 E1 NEXT interferers are shown in Figure 3.15.

ADSL Downstream NEXT

The PSD of 1, 10 and 49 downstream ADSL NEXT interferers are shown in Figure 3.16.

ADSL Upstream NEXT

The PSD of 1, 10 and 49 upstream ADSL NEXT interferers are shown in Figure 3.17.

3.4.5 FEXT Noise Models

FEXT is dependent on the characteristics of the line. The original signal at the transmitter will be attenuated due to the inherent propagation loss of the line. In a real network, FEXT is not just a function of the crosstalk in the cable, but also of the cable topology [27], i.e.

$$\begin{aligned} &PSD_{FEXT} = PSD_{Disturber} \cdot x_n \cdot d \cdot \mid H_{ins}(f) \mid^2 \cdot f^2 \\ &x_n = 2.6247 \cdot 10^{-16} \cdot \left(\frac{n}{49}\right)^{0.6}, \quad n < 50, \quad 0 \leq f < \infty \end{aligned} \tag{3.28}$$

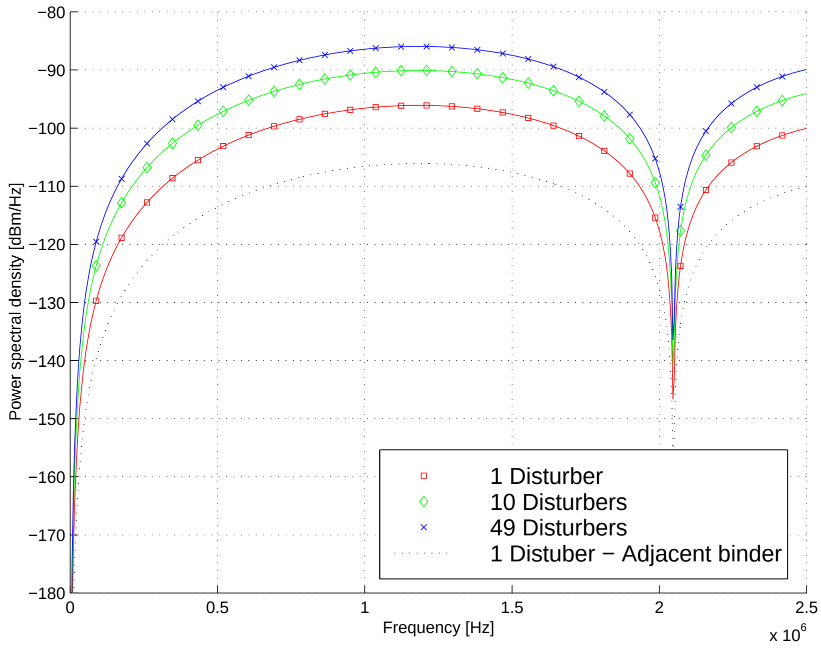

Figure 3.15: Power spectral density of 1, 10 and 49 E1 NEXT interferers

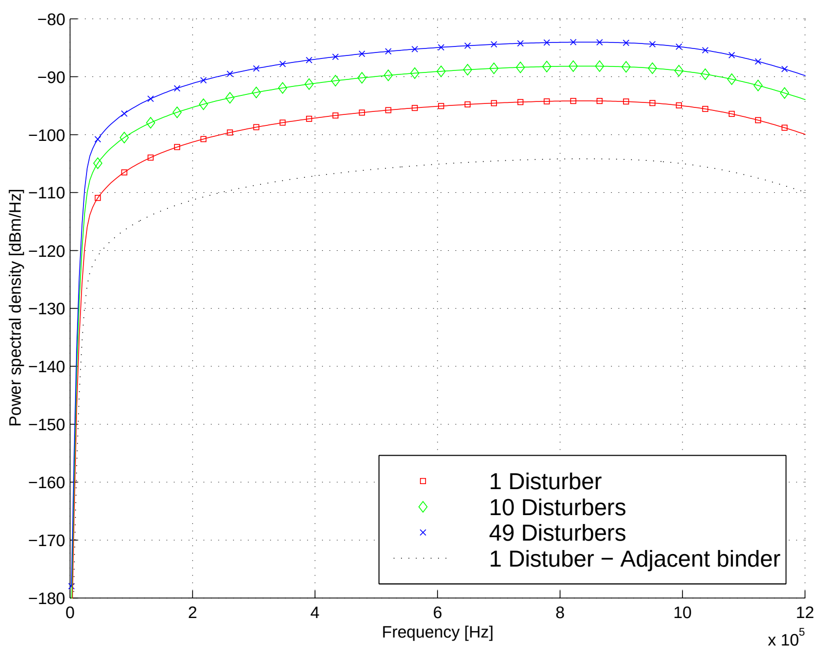

Figure 3.16: Power spectral density of 1, 10 and 49 downstream ADSL NEXT interferers

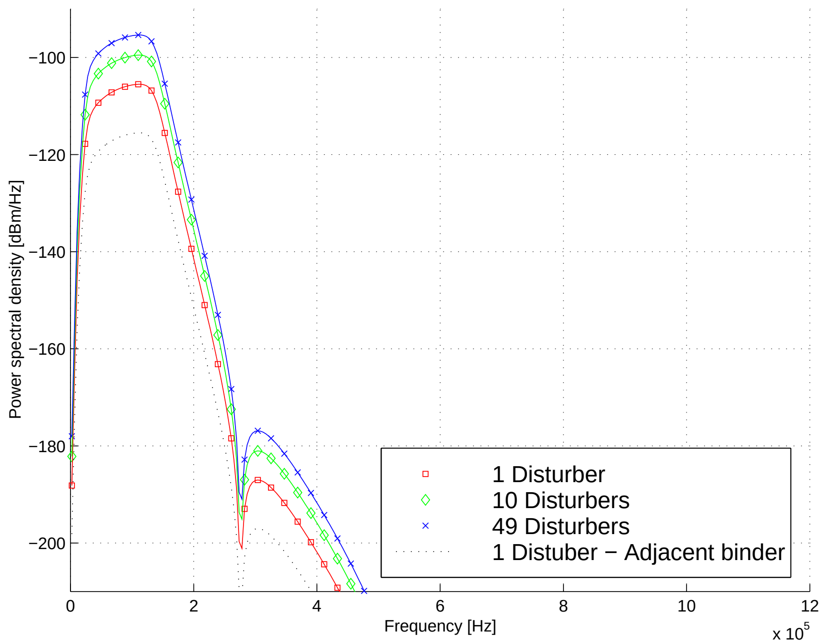

Figure 3.17: Power spectral density of 1, 10 and 49 upstream ADSL NEXT interferers

where *n* is the number of disturbers, *d* is the length of the disturbing line [km], $H_{ins}(f)$ is the insertion loss for the line under consideration, $|\cdot|^2$ is the modulus-squared function, and *f* is the frequency [Hz].

3.4.6 Radio Frequency Interference

ADSL local loops are exposed to RFI, particularly overhead or aerial loops. This is not a big problem for ADSL, because only AM transmitters can interfere with the transmission, and only when the transmitter is in close proximity with the local loop. RFI cause deep notches in the frequency spectrum of ADSL at the center frequency of the RF transmitter. The DMT modulation technique can eliminate the subchannels effected by RFI. RFI only becomes a problem for *Very-high-bit-rate DSL* (VDSL), where amateur bands must be considered.

CHAPTER FOUR

BIT LOADING

4.1 Chapter Overview

The purpose of this chapter is to give a detailed description of Campello's Bit Loading Algorithm [1], implemented in the simulation program. Section 4.2 gives an introduction to bit loading, while section 4.3 describes the rate-adaptive algorithm used in ADSL DMT modulation. Section 4.4 demonstrates the operation of the algorithm for line length changes, bridged tap length changes and frequency selective interference.

4.2 Introduction

Loading algorithms compute values for allocated bits b_n and energy ε_n for every subchannel in a parallel set of subchannels, equally divided over a total bandwidth *B*. There are two types of loading algorithms — those that try to maximize *data rate*, and those that try to maximize *performance*, given a certain error rate.

A **rate-adaptive** *loading algorithm* (RALA) maximize the data rate, by approximately maximizing the total number of integer bits, subject to a fixed energy constraint, i.e.

$$\max_{\varepsilon_n} b_{tot} = \sum_{n=1}^{N} log_2 \left(1 + \frac{\varepsilon_n \cdot SNR_n}{\Gamma}\right) \tag{4.1}$$

subject to:

$$\varepsilon_{tot} = \sum_{n=1}^{N} \varepsilon_n \tag{4.2}$$

where b_{tot} is the total number of allocated bits, N is the total number of used subchannels, SNR_n is the signal-to-noise ratio for subchannel n (determined when unit energy is applied to the subchannel), Γ is the SNR gap and ε_{tot} is the sum of unit energy available for the N subchannels. The *SNR gap* is referred to as the amount by which the SNR (for channel capacity) can be reduced to maintain a symbol error probability at or below the target P_e. Without coding, and a symbol error probability P_e of 10^{-7}, a SNR gap of 9.8 dB will be used [13]. Each subchannel has a transmit energy ε_n and a number of bits per symbol b_n [1].

A **margin-adaptive** *loading algorithm* (MALA) maximizes performance by approximately minimizing the energy, subject to a fixed bits per symbol constraint, i.e.

$$\min_{\varepsilon_n} \varepsilon_{tot} = \sum_{n=1}^{N} \varepsilon_n \tag{4.3}$$

subject to:

$$b_{tot} = \sum_{n=1}^{N} log_2 \left(1 + \frac{\varepsilon_n \cdot SNR_n}{\Gamma}\right) \tag{4.4}$$

The rate-adaptive loading algorithm distributes the total available energy amongst the subchannels in such a way that the overall bit rate is maximized. The margin-adaptive algorithm, on the other hand, determines the bit allocation that requires the least amount of energy, leaving the maximum amount of energy to combat performance variations [1]. Campello's bit loading algorithm, which is basically a rate adaptive loading algorithm, will be discussed in the following section.

4.3 Rate-Adaptive Loading Algorithm (RALA)

The ADSL DMT modulation technique uses the rate-adaptive loading algorithm to optimize bit allocation, as well as energy distribution, given a specified available transmit power and a channel SNR profile. The total number of bits per symbol that can be transmitted over a parallel set of subchannels must maximize the sum:

$$b_{tot} = \sum_{n=1}^{N} log_2 \left(1 + \frac{\varepsilon_n \cdot SNR_n}{\Gamma}\right) \tag{4.5}$$

SNR is a fixed function of the channel under consideration, but ε_n can be varied to maximize b_n, subject to an energy constraint

$$\sum_{n=1}^{N} \varepsilon_n = \varepsilon_{tot} \tag{4.6}$$

In order to solve the bit rate maximization problem, a maximum of *N+1* equations with *N+1* unknowns (ε_n, n = 1,. . . ,N and K) must be solved, i.e.

$$\begin{aligned}
\varepsilon_1 + \Gamma/SNR_1 &= K && (4.7)\\
\varepsilon_2 + \Gamma/SNR_2 &= K && (4.8)\\
\vdots &= \vdots && (4.9)\\
\varepsilon_n + \Gamma/SNR_n &= K && (4.10)\\
\varepsilon_1 + \cdots + \varepsilon_n &= \varepsilon_{tot} && (4.11)
\end{aligned}$$

The solution can produce negative energies. If it does, the equation with the smallest SNR_n should be eliminated, and the corresponding ε_n should be zeroed. The set of equations are solved recursively by eliminating the smallest SNR_n and zeroing the corresponding ε_n, until the first solution with no negative energies for all n occurs [1].

Firstly, the SNRs for the channel must be arranged from large to small. Thus, Equation (4.7) to (4.11) are pre-ordered in terms of SNR, with n=1 corresponding to the largest SNR and n=N corresponding to the smallest SNR. A solution to Equation (4.7) to (4.11) was obtained as:

$$K = \frac{1}{N^*} \cdot \left(\varepsilon_{tot} + \Gamma \cdot \sum_{n=1}^{N^*} \frac{1}{SNR_n}\right) \tag{4.12}$$

$$\varepsilon_n = K - \frac{\Gamma}{SNR_n} \qquad \forall n = 1, \ldots, N^* \tag{4.13}$$

where N^* is set equal to N before starting the recursive solution of Equation (4.7) to (4.11). N^* is now the number of subchannels *used* and N is the total number of subchannels. If ε_{N^*} is negative, then ε_{N^*} is zeroed and $N^* = N^* - 1$. Equation (4.12) and (4.13) are continually solved, until the first non-negative solution for ε_{N^*} is found. The number of subchannels used for modulation is then equal to N^* [1].

Recalling that QAM modulation is used on each of the two-dimensional subchannels, the allocation of bits per subchannel is given by:

$$b_n = log_2\left(1 + \frac{\varepsilon_n \cdot SNR_n}{\Gamma}\right) \tag{4.14}$$

where b_n is the number of bits per subchannel allocated for subchannel n. Clearly, there are many possible bit distributions that all sum to the same total b_{tot} [1].

Define a bit distribution vector $\bar{b}$ = $[b_1 \ b_2 \ \ldots b_{N^*}]$. The bit distribution vector $\bar{b}$ is said to be *efficient*, if

$$\max_m \left[e_n(b_n)\right] \leq \min_n \left[e_m(b_m + 1)\right] \tag{4.15}$$

where $e_n(b_n)$ is the incremental energy defined by Equation (4.16). Efficiency means that there is no movement of a bit from one subchannel to another that reduces the symbol energy. An efficient bit distribution also solves the rate adaptive loading problem for a total energy constraint. Campello has formalized an iterative algorithm (known as Campello's EF algorithm) that will translate any bit distribution into an efficient bit distribution [1]:

1. $m \Leftarrow arg\left\{\min_{1\leq i\leq N^*}[e_i(b_i+1)]\right\}$

2. $n \Leftarrow arg\left\{\max_{1\leq j\leq N^*}[e_j(b_j)]\right\}$

3. While $e_m(b_m+1) < e_n(b_n)$ do

(a) $b_m \Leftarrow b_m + 1$

(b) $b_n \Leftarrow b_n - 1$

(c) $m \Leftarrow arg\left\{\min_{1\leq i\leq N^*}[e_i(b_i+1)]\right\}$

(d) $n \Leftarrow arg\left\{\max_{1\leq j\leq N^*}[e_j(b_j)]\right\}$

Campello's EF Algorithm

m is assigned the index of the subchannel requiring the least amount of incremental energy to increase the bits per symbol to the next upper level. *n* is assigned the index of the subchannel which will 'return' the most energy to the system if the bits per symbol is decreased to the next lower level. The EF algorithm retains the total number of bits and converges to the best solution [28].

The *incremental energy* necessary to transmit b_n information units on a subchannel is the amount of additional energy necessary to send the current information unit b_n with respect to the previous information unit b_n-*1* [1]. Thus, the incremental energy is defined by:

$$e_n(b_n) \triangleq \varepsilon_n(b_n) - \varepsilon_n(b_n - 1) \tag{4.16}$$

Using the definition of Equation (4.14), ε_n is defined as:

$$\varepsilon_n = \frac{\Gamma}{SNR_n}\cdot\left(2^{b_n} - 1\right) \tag{4.17}$$

Using Equation (4.16), the incremental energy is the determined by:

$$e_n(b_n) = \frac{1}{2}\cdot 2^{b_n}\cdot\frac{\Gamma}{SNR_n} \tag{4.18}$$

Following the EF algorithm is an additional concept of *E-tightness*, which is necessary to solve the rate adaptive loading problem, defined as:

$$0 \leq \varepsilon_{tot} - \sum_{n=1}^{N^*} \varepsilon_n(b_n) \leq \min_{1 \leq i \leq N^*} [e_i(b_i + 1)] \tag{4.19}$$

E-tightness implies that no additional unit of information can be carried without violation of the total energy constraint of Equation (4.6) [1]. The E-tightening (ET) algorithm is given by:

1. Set $S = \sum_{n=1}^{N^*} \varepsilon_n(b_n)$
2. While $(\varepsilon_{tot} - S < 0)$ or $(\varepsilon_{tot} - S \geq \min_{1 \leq i \leq N^*} [e_i(b_i + 1)])$

If $(\varepsilon_{tot} - S < 0)$ then

(a) $n \Leftarrow arg \left\{ \max_{1 \leq j \leq N^*} [e_j(b_j)] \right\}$

(b) $S \Leftarrow S - e_n(b_n)$

(c) $b_n \Leftarrow b_n - 1$

else

(a) $m \Leftarrow arg \left\{ \min_{1 \leq i \leq N^*} [e_i(b_i + 1)] \right\}$

(b) $S \Leftarrow S + e_m(b_m + 1)$

(c) $b_m \Leftarrow b_m + 1$

Campello's ET algorithm

S is the defined as the *total* energy currently used in the system. This is in contrast to the *incremental* energy being used by Campello. The ET algorithm reduces the number of bits, when the energy exceeds the limit, by reducing the bits per symbol in the most energy-consumptive subchannel(s). Otherwise, the bits per symbol are increased in the least energy-consumptive subchannel(s) when energy is sufficiently below the limit [1].

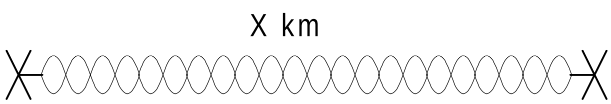

Figure 4.1: Line topology to simulate line length changes

4.4 Demonstration of algorithm operation

For the purpose of this demonstration, the effect of NEXT and FEXT will be ignored.

To demonstrate the operation of the algorithm, the following three scenarios will be used:

- Changing the line length
  - Vary the length from 1 km to 5 km (in 2 km increments)
- Changing the length of a bridged tap
  - The main line length is kept constant
  - Vary the bridged tap line length between 100 m and 300 m (in 100 m increments)
- Introducing frequency selective interference (FSI)
  - Use a Gaussian shaped interference level function with f_{center} = 400 kHz, σ = 28 kHz
  - SNR interference level of between 10 dB and 50 dB (in 20 dB increments)

**NOTE:

In the following subsections, subfigures are numbered left to right, top to bottom, i.e.

a b

c d

4.4.1 Changing the line length

The line topology is shown in Figure 4.1. Figure 4.2(a) shows the SNR [dB] vs. subchannels for a 1 km line. The SNRs are sorted from large to small, as shown in 4.2(b). The bit allocation is shown in Figure 4.2(c). The dashed line represents the maximum theoretical number of bits, given the SNR, for a specific subchannel. Due to inherent hardware

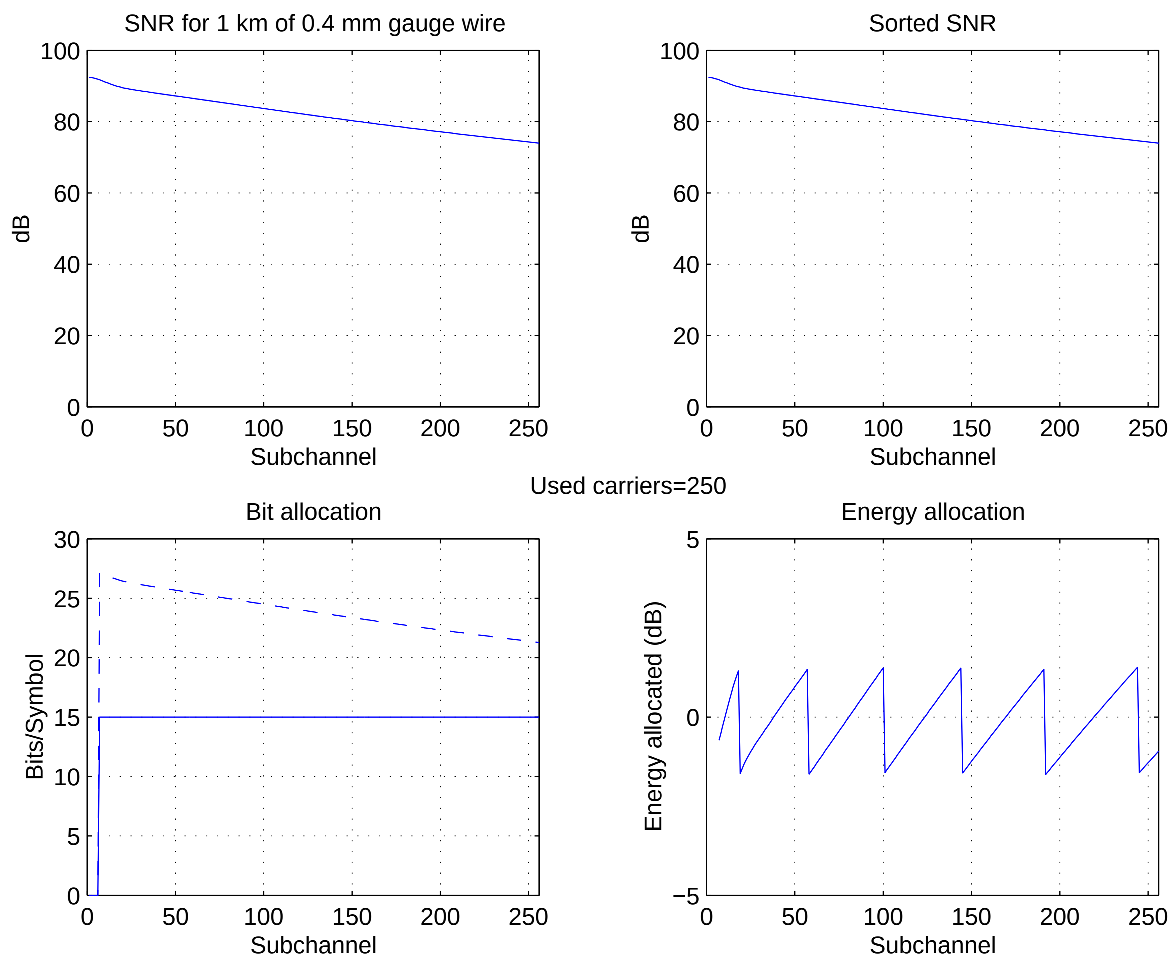

Figure 4.2: Demonstration of RALA for a 1 km length of 0.4 mm twisted-pair

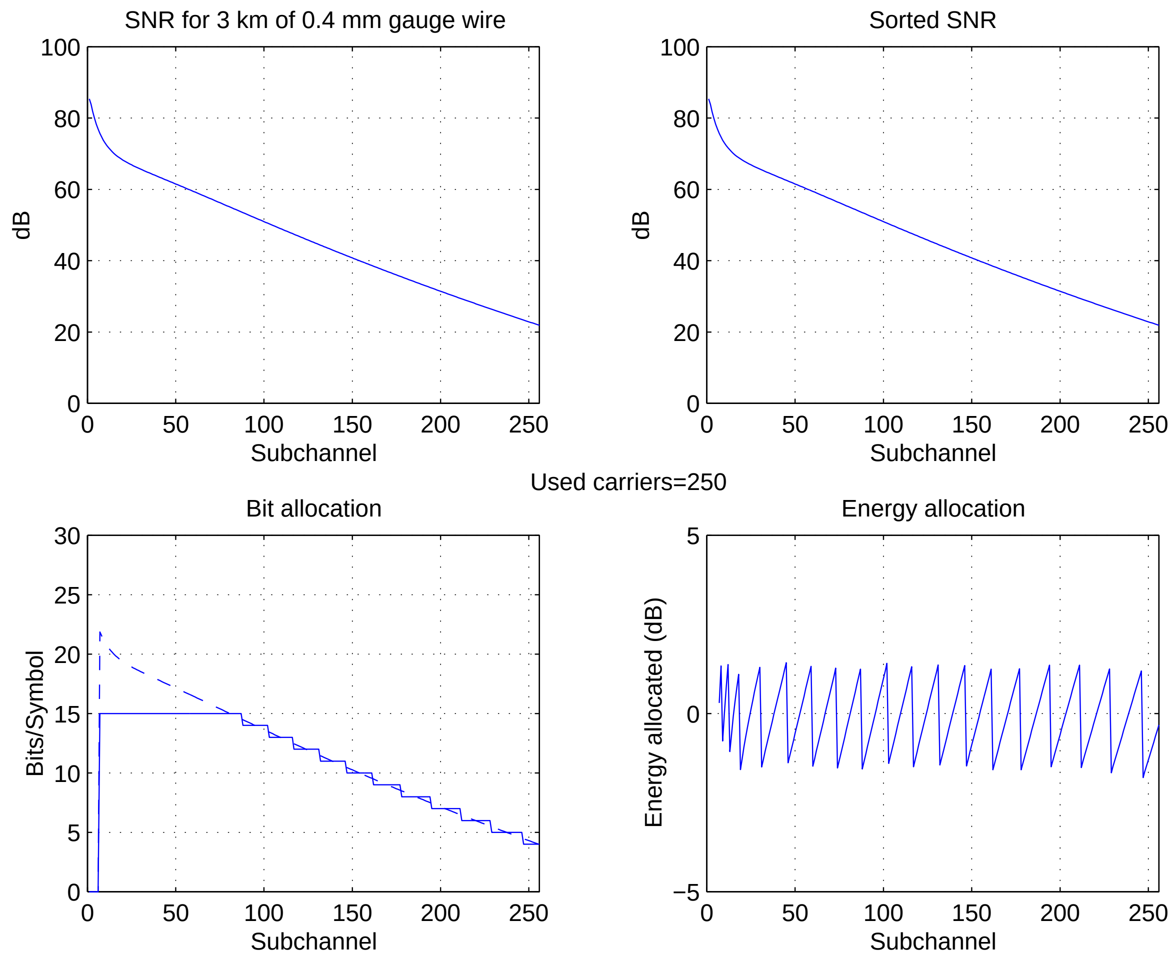

Figure 4.3: Demonstration of RALA for a 3 km length of 0.4 mm twisted-pair

limitations, the number of allocated bits/subchannel are limited to 15, as shown by the solid line. The near optimum allocation of energy [dB] vs. subchannel, is shown in Figure 4.2(d). Notice the characteristic sawtooth profile with a ±1.5 dB variation about the mean for this algorithm.

Figure 4.3(a) shows the SNR [dB] vs. subchannels for a 3 km line. The bit allocation is shown in Figure 4.3(c). All available subchannels are used, but the SNR at high frequencies starts to affect the allocation of bits from subchannel #88. Notice how the bit distribution follow the SNR profile.

Figure 4.4(a) shows the SNR [dB] vs. subchannels for a 5 km line. The bit allocation is shown in Figure 4.4(c). The number of subchannels used are reduced to the best 127. No

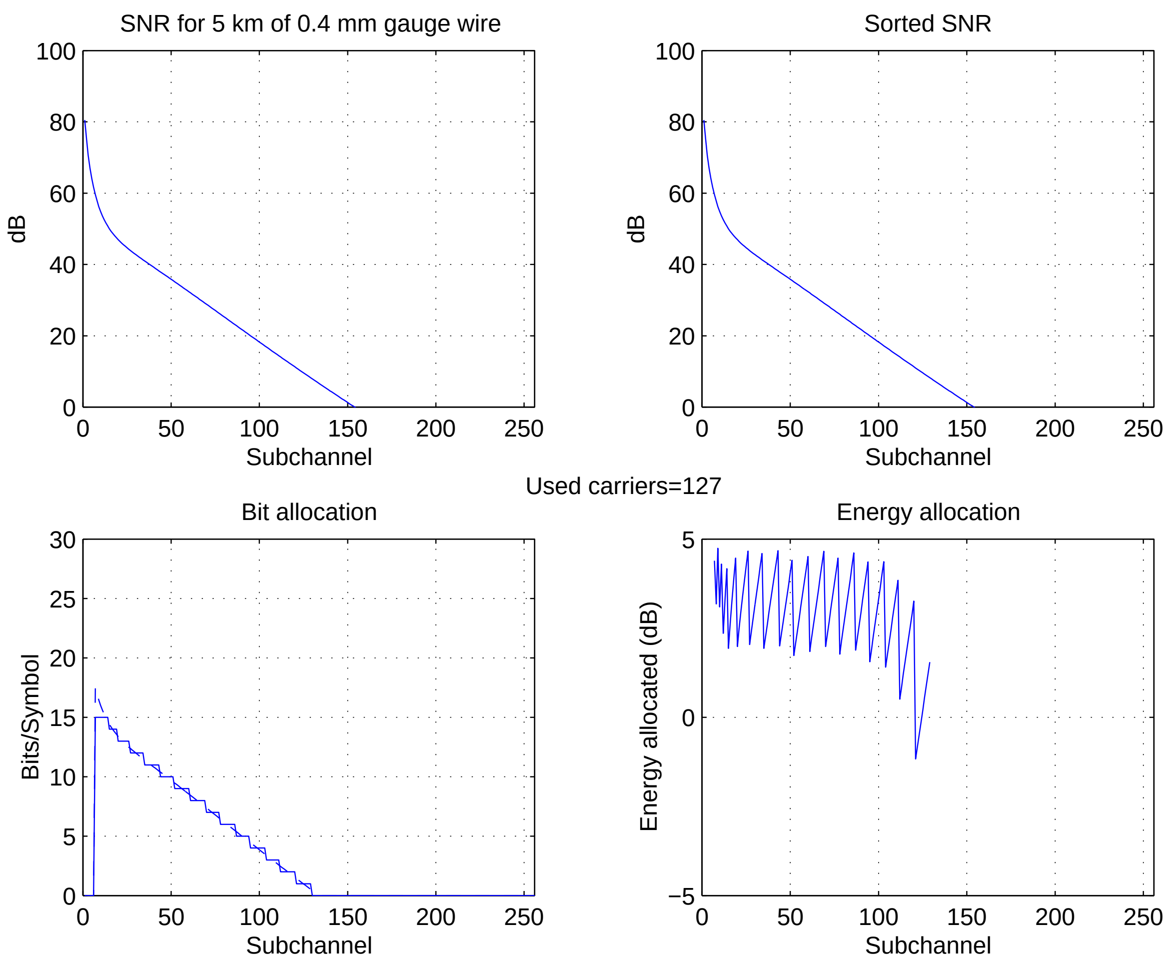

Figure 4.4: Demonstration of RALA for a 5 km length of 0.4 mm twisted-pair

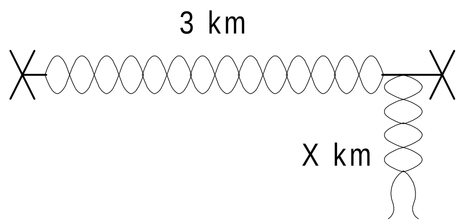

Figure 4.5: Line topology to simulate bridged tap length changes

energy and bits are allocated in subchannels #130 to #256, but are redistributed in lower subchannels, as can be seen from the increase in the mean in Figure 4.4(d).

4.4.2 Changing the length of a bridged tap

The line topology used is shown in Figure 4.5. Figure 4.6(a) shows the SNR [dB] vs. subchannels for a 100 m bridged tap. The SNRs are sorted from large to small, as shown in 4.6(b). The bit allocation is shown in Figure 4.6(c). The effect of the bridged tap can be seen around subchannel #120. Figure 4.7(a) shows the SNR [dB] vs. subchannels for a 200 m bridged tap. Once again the effect of the bridged tap can be seen around subchannel #60 and subchannel #180.

Figure 4.8(a) shows the SNR [dB] vs. subchannels for a 300 m bridged tap. The effect of the bridged tap can be seen around subchannels #40, #120 and #200.

The position of the notches can be estimated using Equation (3.8).

4.4.3 Introducing frequency selective interference

The line topology is shown in Figure 4.1 with a line length of 3 km. Figure 4.9(a) shows the SNR [dB] vs. subchannels for a 10 dB interference level at 400 kHz (Subchannel #93). The algorithm allocates less bits/symbol in the region around subchannel #93.

For a 30 dB interference level (Figure 4.10), the bits/symbol are reduced to 2 bits/symbol and the energy is minimized around subchannel #93.

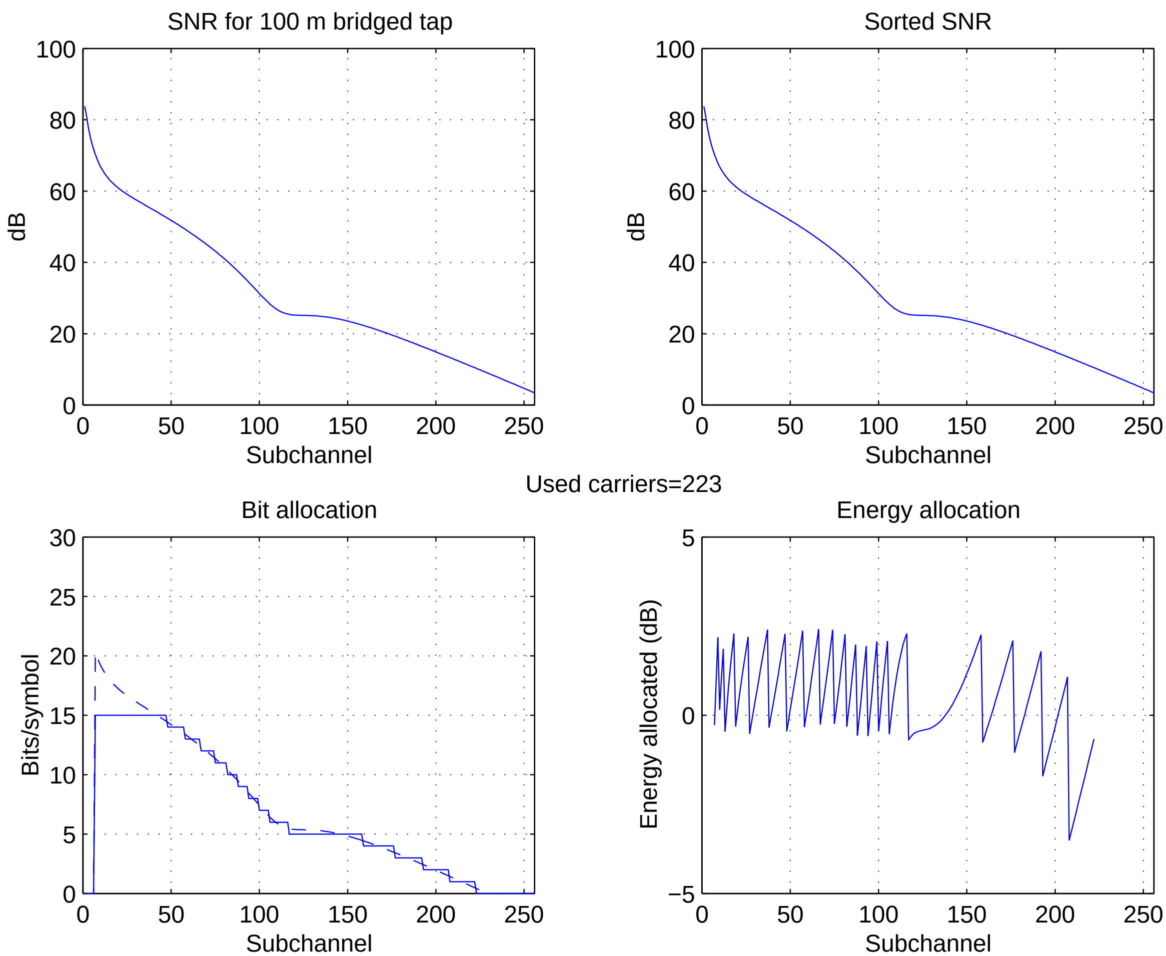

Figure 4.6: Demonstration of RALA for a 0.4 mm twisted-pair bridged tap with a length of 100 m

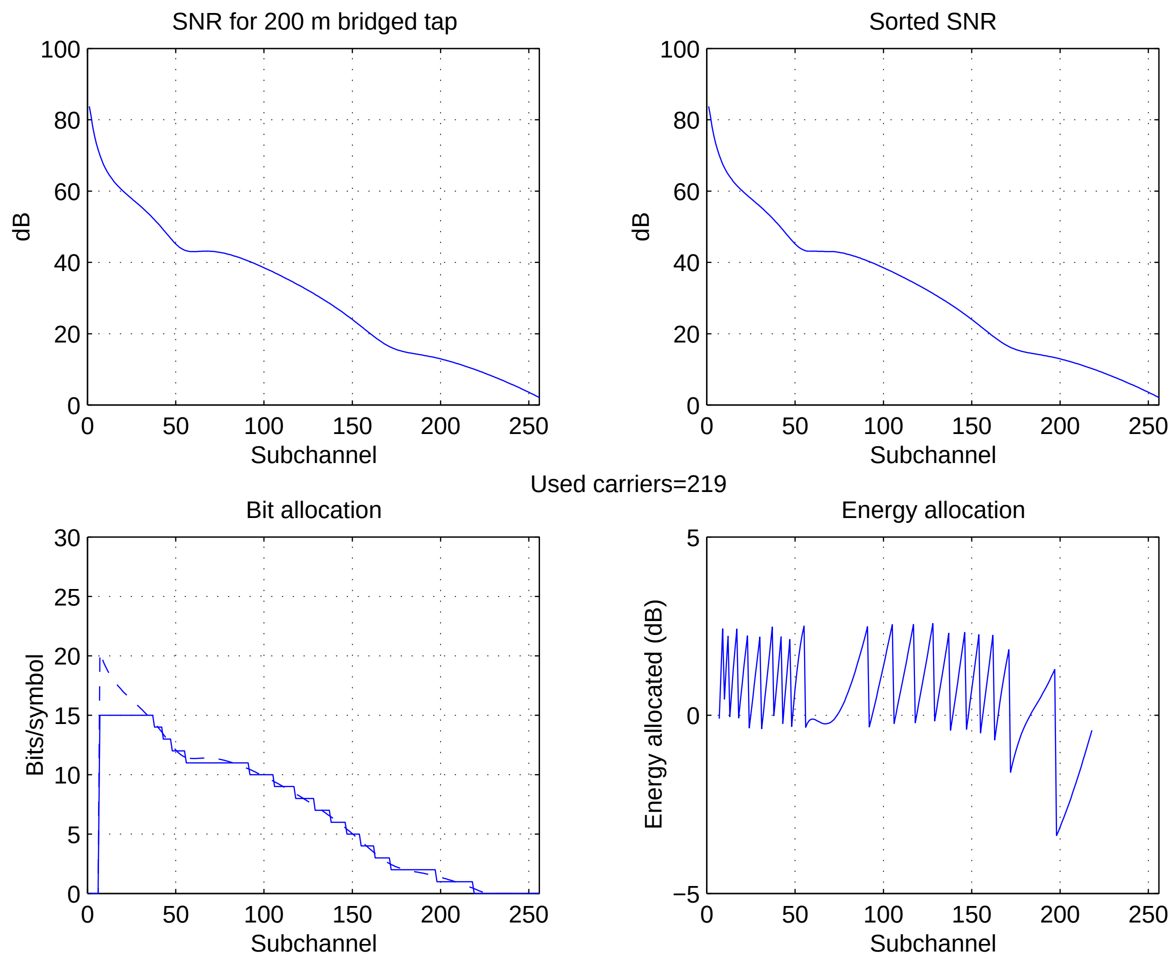

Figure 4.7: Demonstration of RALA for a 0.4 mm twisted-pair bridged tap with a length of 200 m

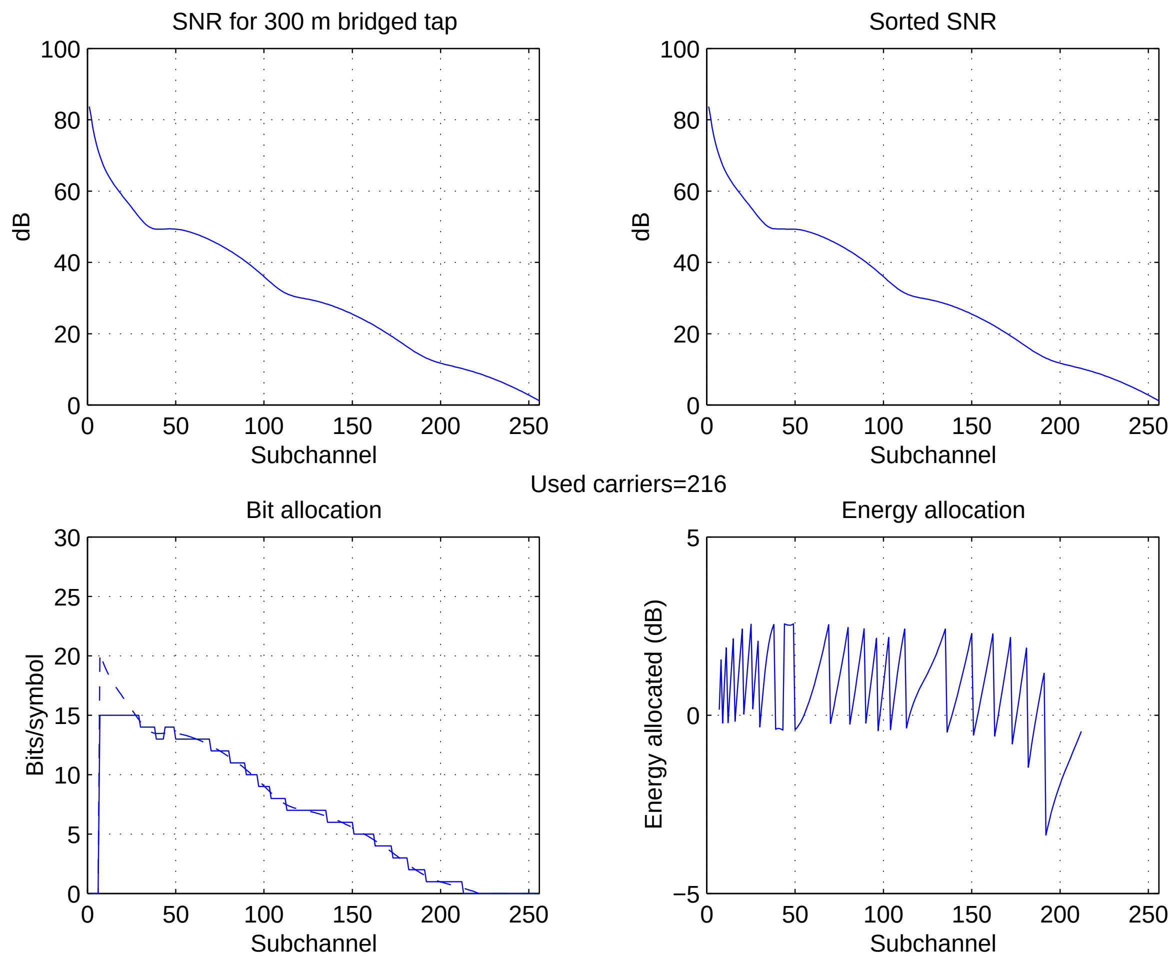

Figure 4.8: Demonstration of RALA for a 0.4 mm twisted-pair bridged tap with a length of 300 m

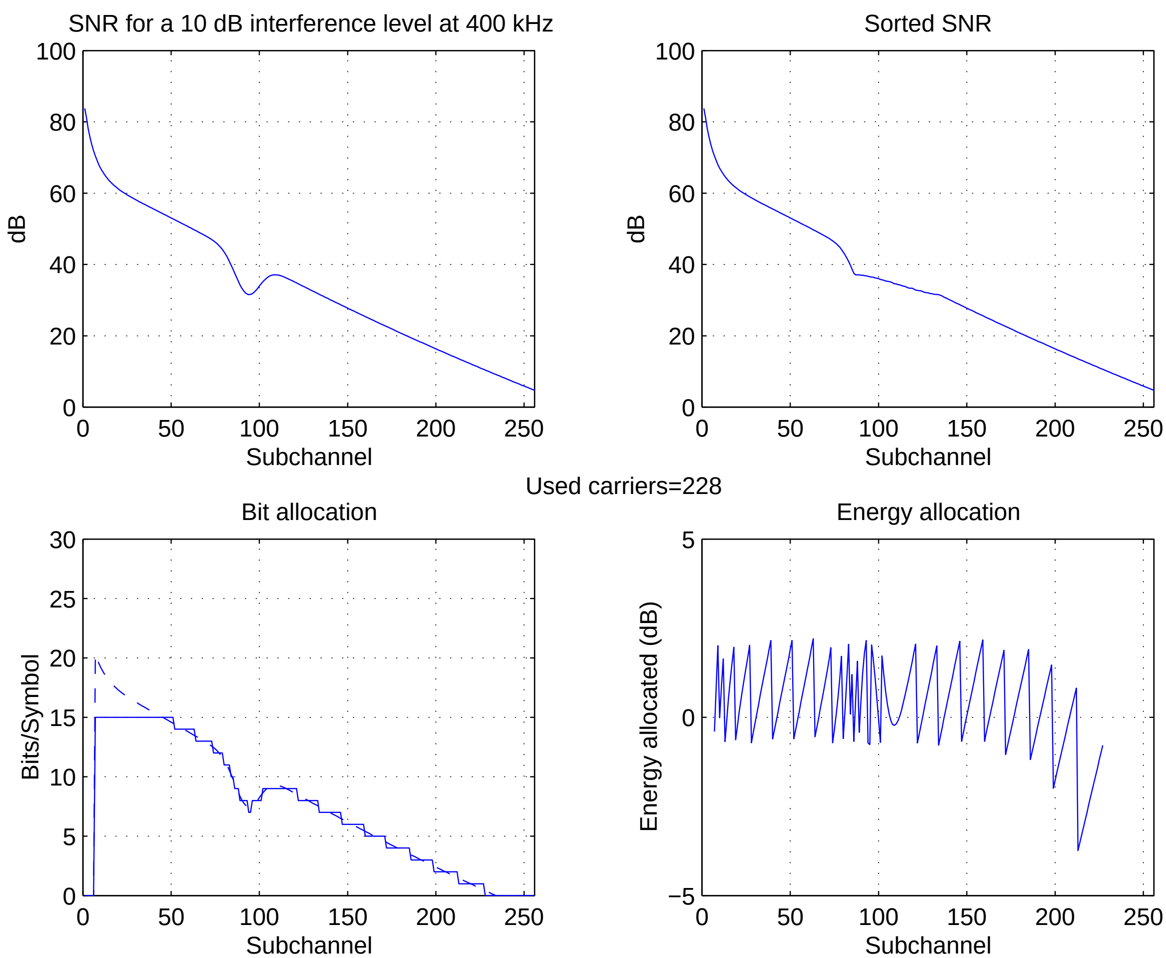

Figure 4.9: Demonstration of RALA for a 10 dB interference level at 400 kHz

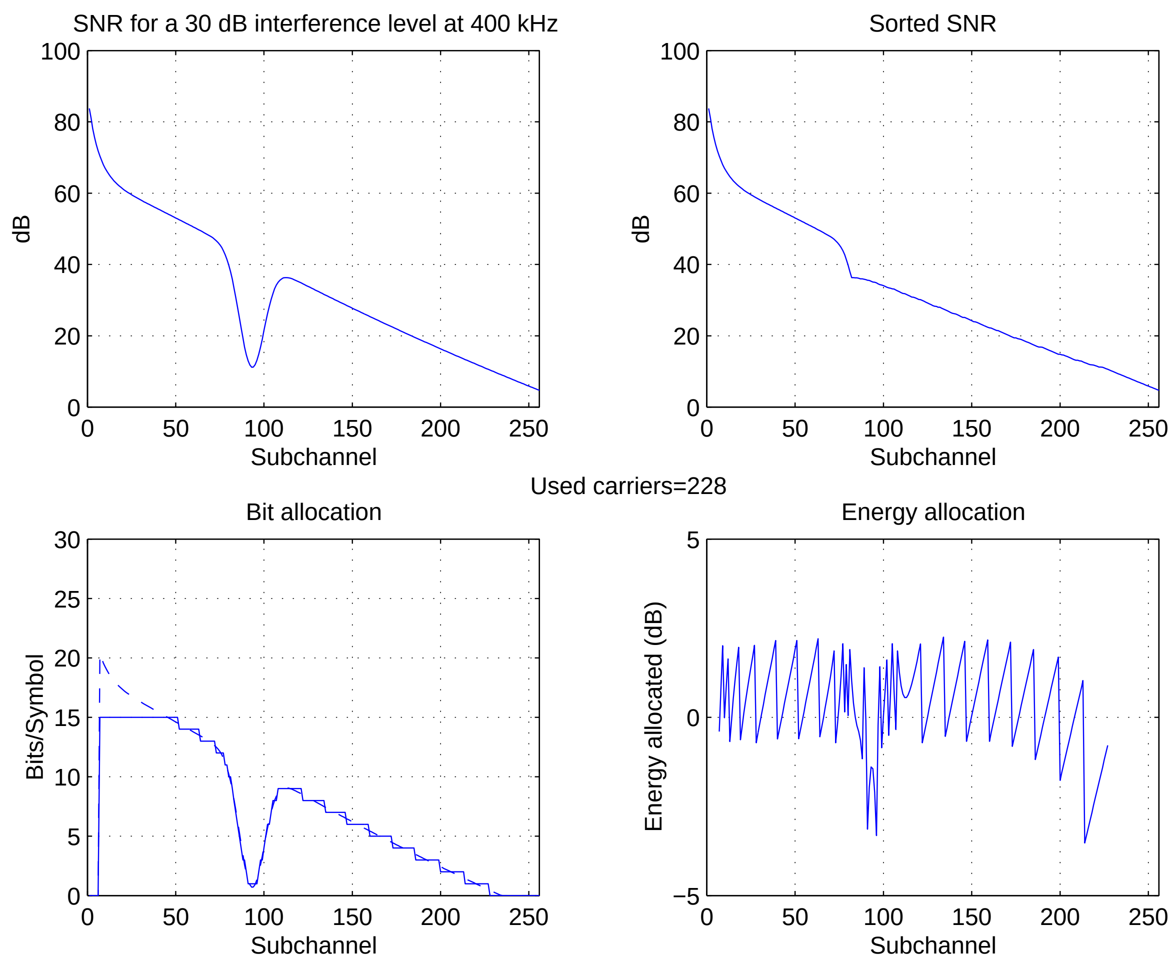

Figure 4.10: Demonstration of RALA for a 30 dB interference level at 400 kHz

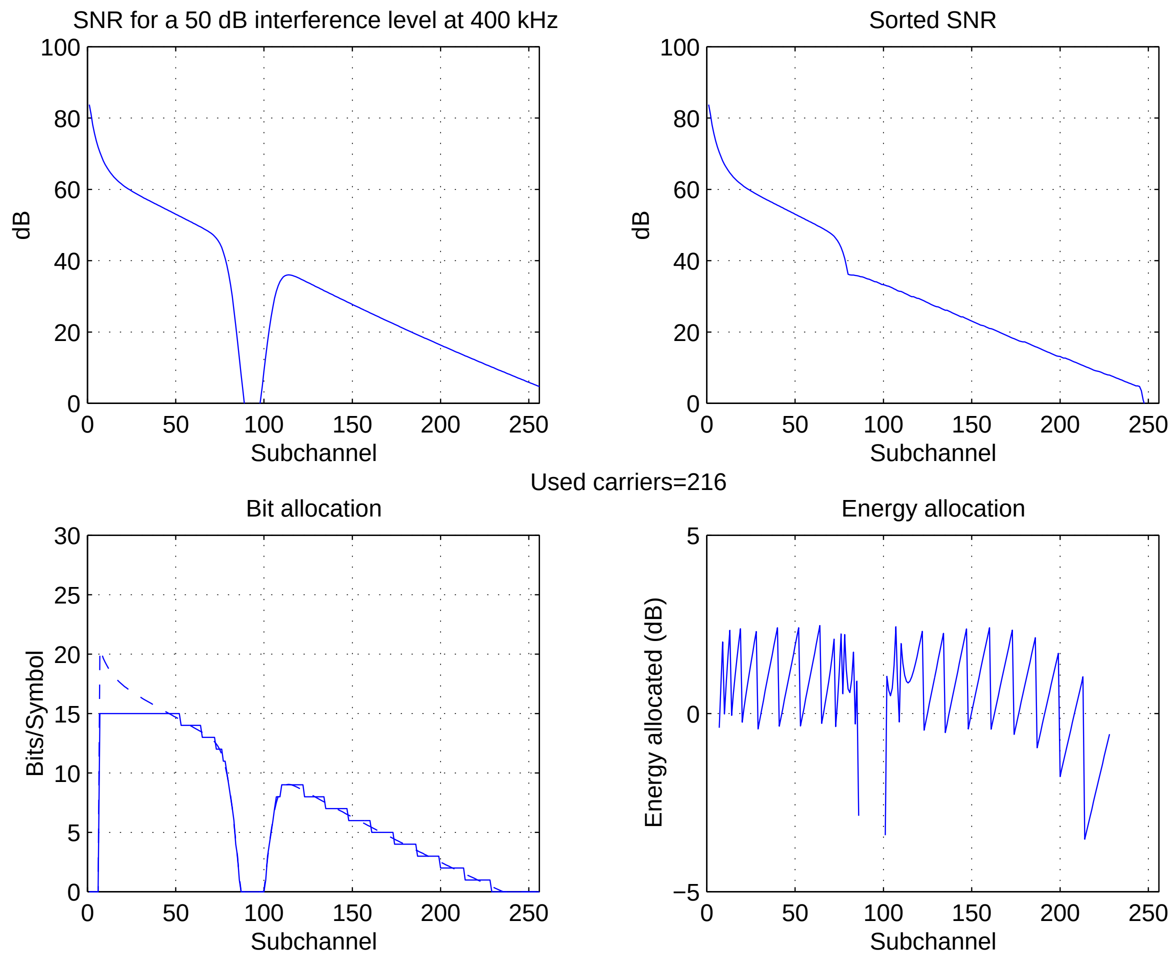

Figure 4.11: Demonstration of RALA for a 50 dB interference level at 400 kHz

For a 50 dB interference level (Figure 4.11), the algorithm allocates no bits and no energy around subchannel #93. The gap can be seen in Figure 4.11(c) and (d).

CHAPTER FIVE

IMPLEMENTATION AND SIMULATION

5.1 Chapter Overview

The purpose of this chapter is to provide a description of the implementation and simulation of the formulas and algorithms of Chapter 3 and 4, in order to derive the results provided in the following chapter (Chapter 6).

5.2 Basic description

As already mentioned, the purpose of this dissertation is threefold. The first is to combine some of the related research to simulate a generic exchange (especially multi-pair cables). The second is a computational study to determine the ADSL downstream data rate (ADSL downstream capacity) for a specific pair as a function of other services within the cable, specifically within the same binder group. The third is a computational study to determine the maximum reach for ADSL (given a required downstream data rate) as a function of other services within the same binder group. Specifically, the effects of ISDN (Basic Rate DSL), HDSL, E1 and other ADSL services will be pursued.

5.3 Block diagrams

Block diagrams for the simulation program are shown in Figure 5.1 to 5.5.

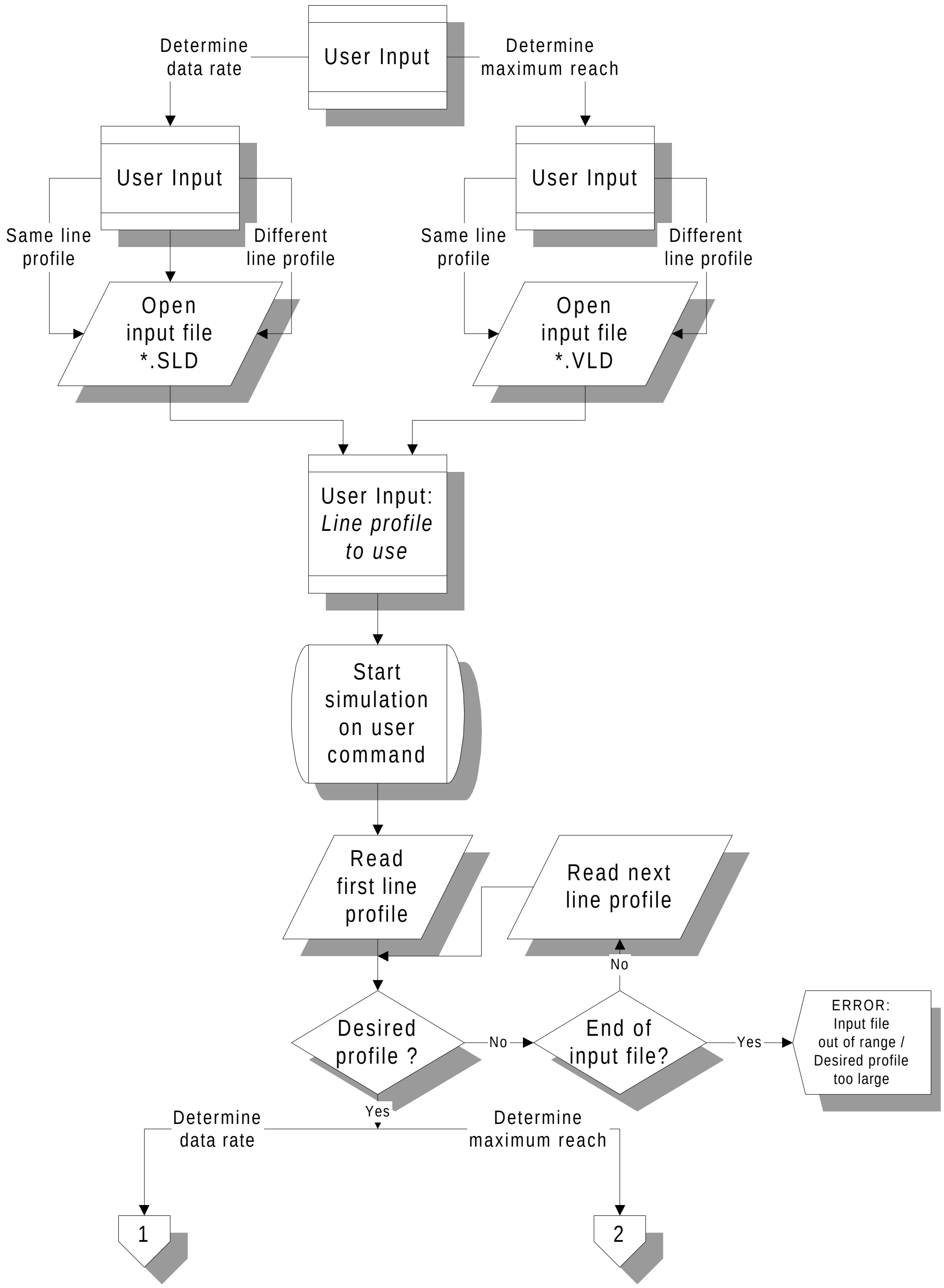

Figure 5.1: User input

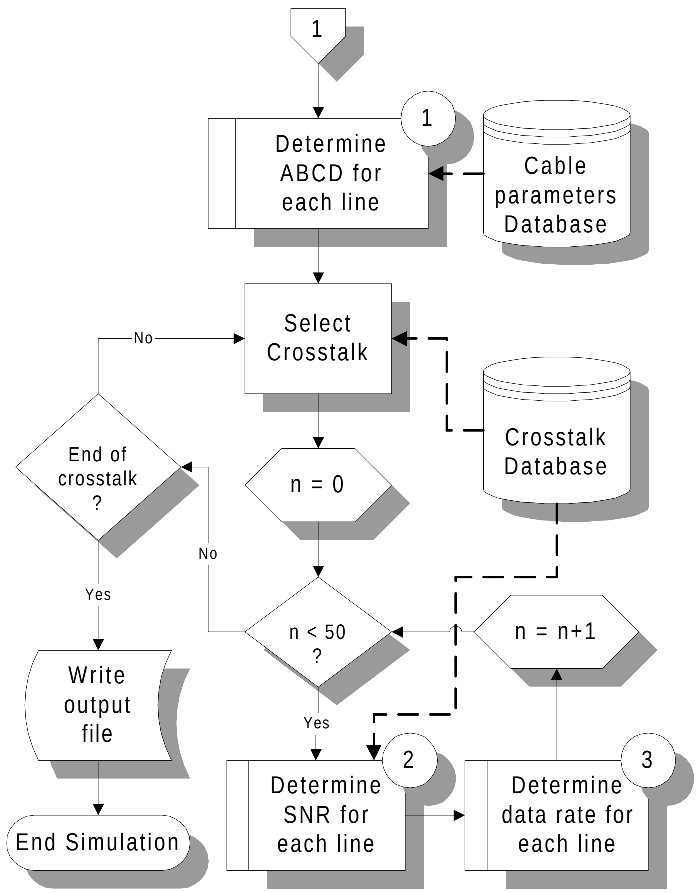

Figure 5.2: Determination of ADSL capacity

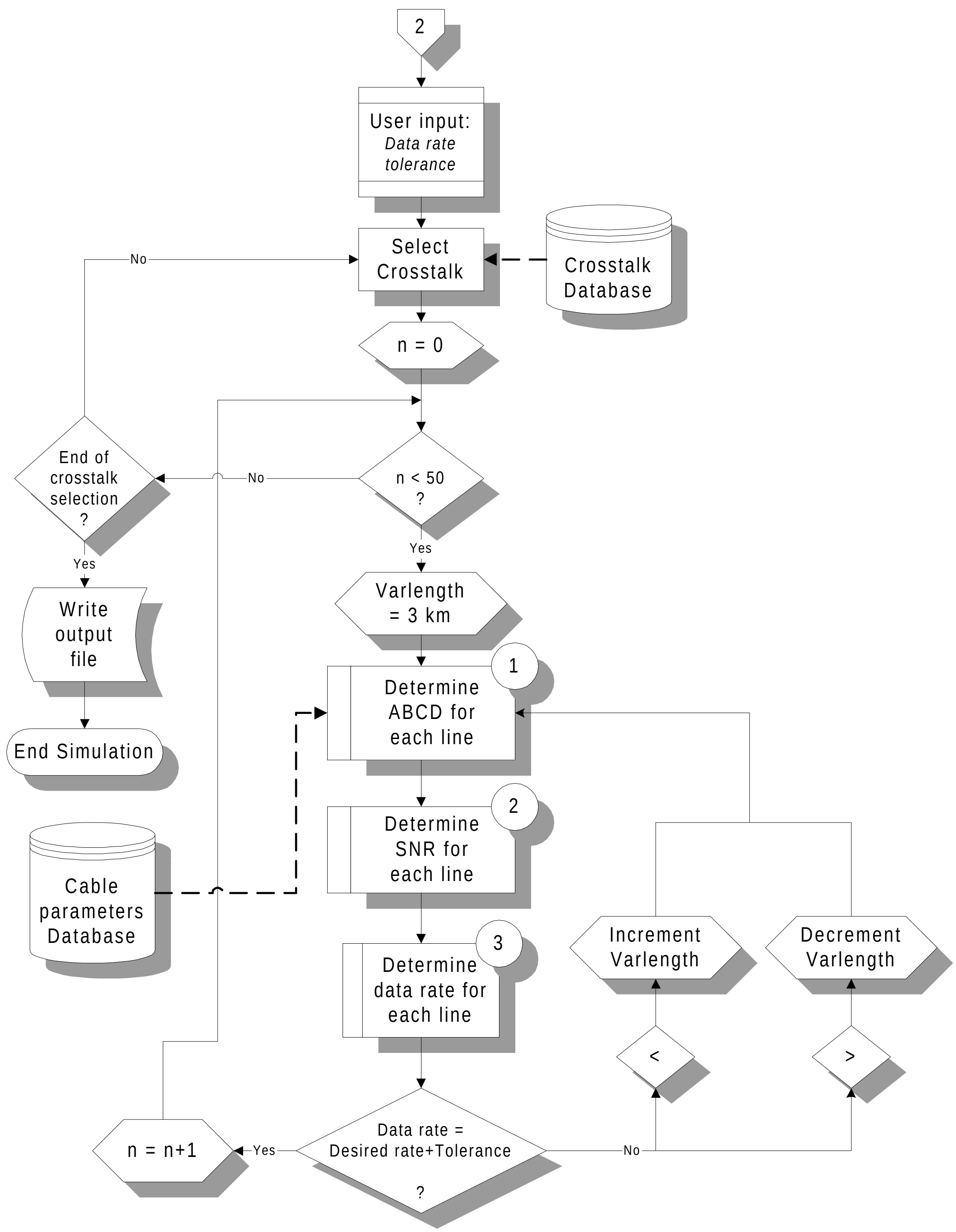

Figure 5.3: Determination of maximum reach

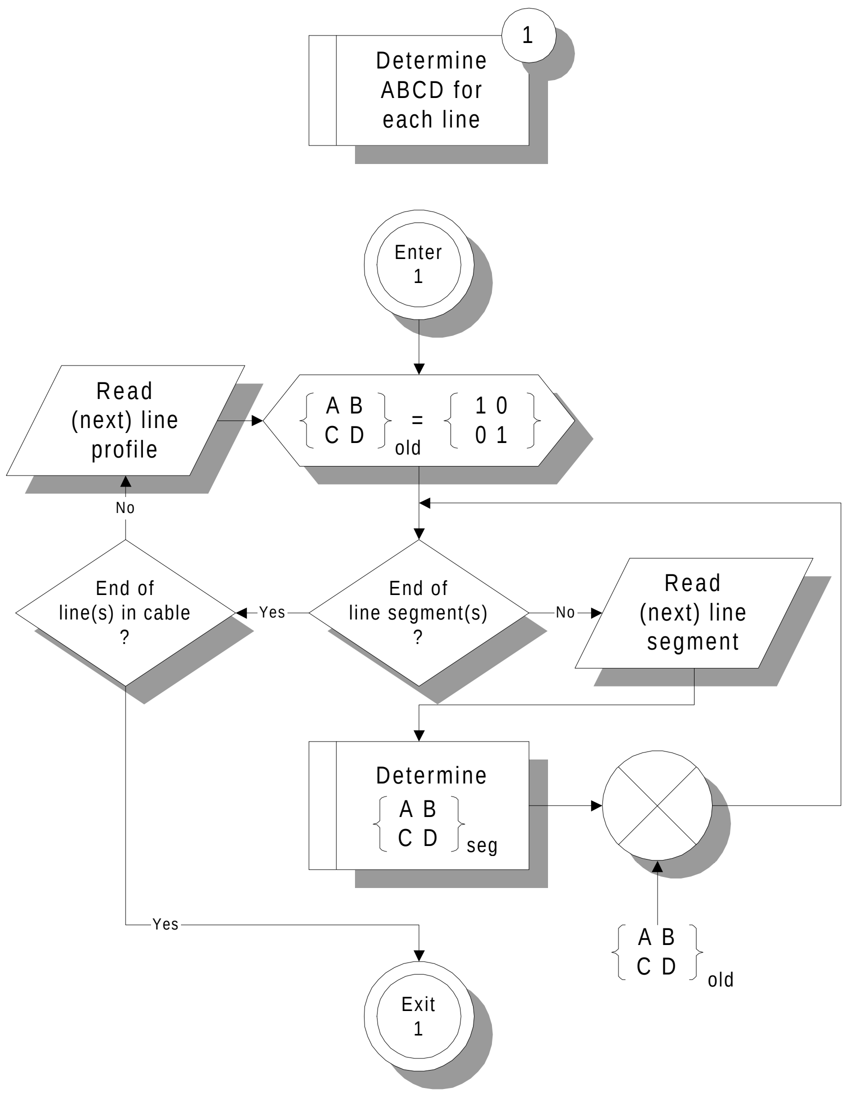

Figure 5.4: Multiplying ABCD matrixes

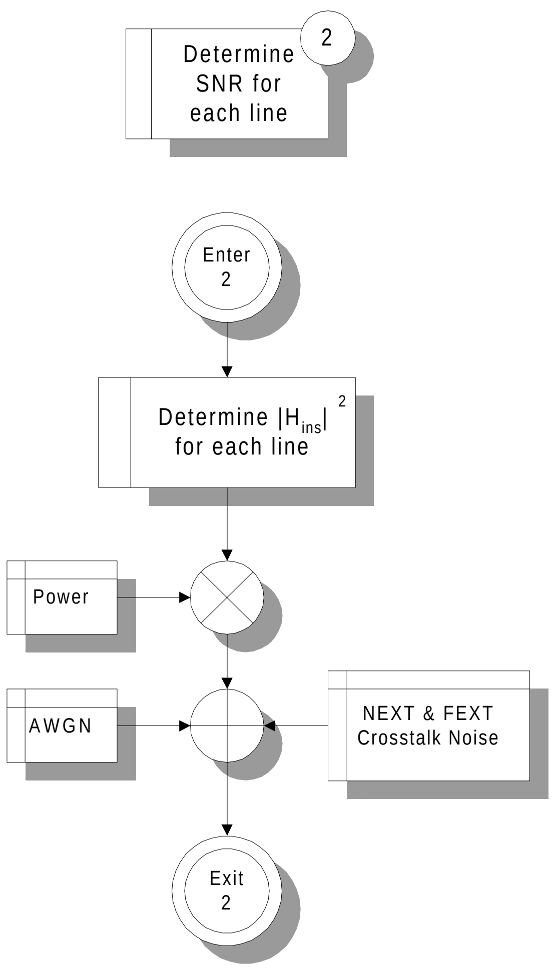

Figure 5.5: Determination of SNR / data rate for each subchannel

As shown in Figure 5.1, the simulation program uses pre-defined input files to obtain information about the topology of the cable. To determine ADSL downstream capacity, all line segments for a specific line are fixed, thus specified by a *Simulation Line Data* (SLD) file. In order to determine the maximum reach for the lines, a variable length is required, thus a *Variable Line Data* (VLD) file is used.

To determine ADSL performance, the simulation program simply cycles through all crosstalkers as well as the number of each crosstalker. On the other hand, to determine the maximum reach, the variable length of the line should be iteratively changed, until the desired data rate is reached. The crosstalkers are pre-defined and stored in a Crosstalk Database, used to determine the crosstalk noise.

The SNR is determined as [13, 18]:

$$\begin{aligned} SNR_{dBm}(f) &= 10 \cdot log_{10}\left(\frac{P_{Tx} \cdot \mid H_{ins}(f) \mid^2}{Noise_{AWGN+NEXT+FEXT}}\right) \\ &= 10 \cdot log_{10}(P_{Tx} \cdot \mid H_{ins}(f) \mid^2) \\ &\quad -AWGN_{dBm/Hz} - NEXT_{dBm/Hz}(f) - FEXT_{dBm/Hz}(f) \end{aligned} \tag{5.1}$$

where P_{Tx} is the transmitter power [mW], $NEXT_{dBm/Hz}$ and $FEXT_{dBm/Hz}$ is the sum of the NEXT(FEXT) noise PSDs of the disturbers for each line.

5.4 Specifications

The following general specifications were used:

- AWGN = -140 dBm/Hz
- Total ADSL downstream transmitter power = 110 mW (-40 dBm/Hz)
- 100Ω source and termination impedances
- ADSL self-NEXT when using ECH spectral allocation
- no ADSL self-NEXT when using FDM spectral allocation

- ADSL FEXT for either ECH or FDM spectral allocation
- NEXT and FEXT models as specified in ANSI T1.413-1998 standard [Annex H of [19]]
- 0.4 and 0.5 mm wire gauges with model parameters as specified in Table 3.1.

When determining ADSL downstream data rate, the following specifications also apply:

- Line with no bridged taps or gauge changes, with a total length of 5.5 km, or
- Line with maximum allowable bridged tap length (762 m), no gauge changes and a total length of 5.5 km.

When determining the maximum reach for ADSL, the following specifications also apply:

- Required downstream data rates of 2.048, 6.144 and 8.192 Mbps;
- Line with no bridged taps or gauge changes, or
- Line with remote side bridged tap of maximum allowable length (762 m) and no gauge changes.

The downstream rates where chosen because of E1 rates being used in South Africa and European countries (E1 = 2.048 Mbps, 3·E1 = 6.144 Mbps, 4·E1 = 8.192 Mbps). The chosen wire gauges are typically used in practice.

CHAPTER SIX

RESULTS

6.1 Chapter Overview

This chapter provides the results of the simulation program as specified in Chapter 5. A discussion of the results are also provided.

6.2 ADSL downstream capacity

Figure 6.1 to 6.8 show the ADSL downstream data rate vs. the number of interferers, when different interferers are placed in the same cable binder as the ADSL line for which the capacity is determined. When referring to *capacity*, reference is made to the downstream data rate. The following general observations can be made:

- ADSL interferers have little effect on the capacity of the ADSL line under consideration when FDM spectral allocation is used. This can be explained by the fact that the upstream and downstream spectrum are located next to each other, eliminating NEXT interference. However, the slight decrease in the data rate, as the number of interferers increase, is due to FEXT interference within the cable.

- The capacity decreases as the number of interferers increase. The $(\cdot)^{0.6}$-factor of the NEXT model (Equation (3.27)) is mainly responsible for this phenomena.

- When using ECH spectral allocation, the introduction of any interferer provides a great decrease in the capacity (from maximum). For the case of 0.4 mm wire (fig. 6.1) the overall effect is greater than for 0.5 mm wire (fig. 6.3).

- When more than one interferer is present in the cable, the decrease in the capacity is small between consecutive points, compared to the decrease from zero to one interferer. When considering the NEXT PSD graphs in Chapter 3 (fig. 3.13 to 3.17), it is evident that two or more interferers do not have such a big relative impact on the total noise of the system, when compared to the introduction of any one interferer.

- 0.5 mm wire provides better capacity than 0.4 mm wire. 0.5 mm wire has a lower loop resistance than 0.4 mm wire, as can be seen from Figure 3.1, providing a lower insertion loss and correspondingly a higher throughput.

- The capacity more than doubles when using 0.5 mm wire (fig. 6.3, 6.4) as compared to 0.4 mm wire (fig. 6.1, 6.2).

- The introduction of a bridged tap of maximum allowable length has the general effect of decreasing the downstream data rate (fig. 6.5 to 6.8 compared to fig. 6.1 to 6.4). This is mainly due to the introduction of an echo signal in the local loop, reducing the main signal's amplitude. This corresponds to an increase in insertion loss, lowering the effective throughput of the system.

- When considering the power spectral densities of the different interferers, the interferers may be ordered in the following descending order (in terms of obtainable performance): ADSL, ISDN, HDSL - adjacent binder, HDSL, E1 - adjacent binder and lastly E1. In some cases a worse case interferer may perform better than a ”better case” interferer. This usually depends on the particular part of the frequency spectrum being used. An example is the E1 interferer with ADSL ECH spectral allocation over 0.4 mm wire (fig. 6.1), when compared to the rest of the scenarios (fig. 6.2 to 6.4).

- When using FDM spectral allocation (fig. 6.2, 6.4), the presence of one or more E1 interferer(s) literally cripples the ADSL system. E1 has a strong PSD over the whole ADSL band when compared with other services, mainly because of the AMI modulation being used.

- When considering multiple types of interferers within the same cable, the performance can at best be equal to, or be worse than the worst interferer for the particular case. For example: Consider 30 ADSL, 10 ISDN, 2 HDSL and 3 E1 interferers, all in the same binder group. Suppose we use 0.4 mm wire with ECH modulation over a 5.5 km line with no bridged tap (fig. 6.1). The data rate will be located below 540 Kbps (2 HDSL interferers).

When comparing Figure 6.1 and Figure 6.3, the following observations may be made:

- When using 0.4 mm wire (fig. 6.1), ADSL performance is nearly the same for ISDN and E1 (adjacent binder) interferers, as well as for HDSL (adjacent binder) and E1 interferers.

- When using 0.5 mm wire (fig. 6.3), ADSL performance is nearly the same for ADSL and ISDN interferers, as well as for HDSL and E1 (adjacent binder). This suggests that the use of only ADSL, or a combination of ADSL and ISDN, will have little influence on the capacity for a certain number of interferers.

- When using 0.5 mm wire, the presence of HDSL (adjacent binder) interferers provides acceptable performance, with ADSL capacity dropping about 600 Kbps. For all other cases (HDSL, E1 and E1 (adj)) ADSL capacity is more than halved.

When comparing Figure 6.2 and Figure 6.4, the following observations may be made:

- When using 0.4 mm wire (fig. 6.2), the presence of other interferers (except ADSL) has unacceptable implications on the capacity of ADSL.

- When using 0.5 mm wire (fig. 6.4), the presence of ISDN and HDSL (adj) interferers may be tolerated.

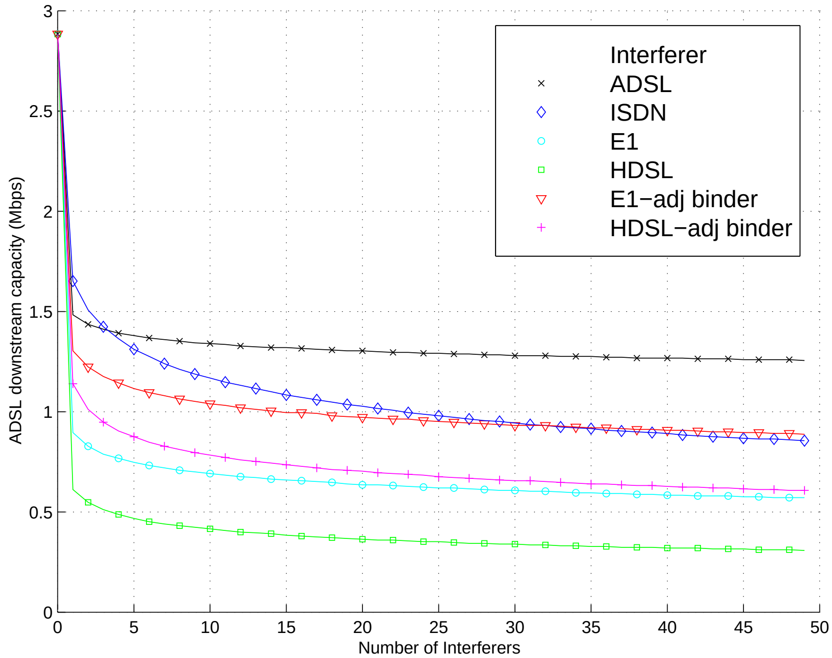

Figure 6.1: ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with no bridged tap, using ECH allocation

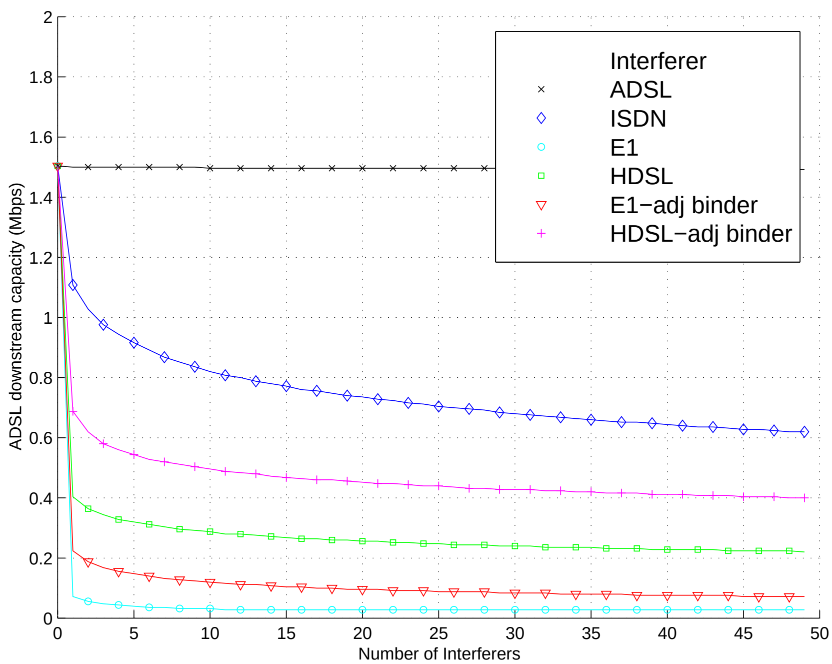

Figure 6.2: ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with no bridged tap, using FDM allocation

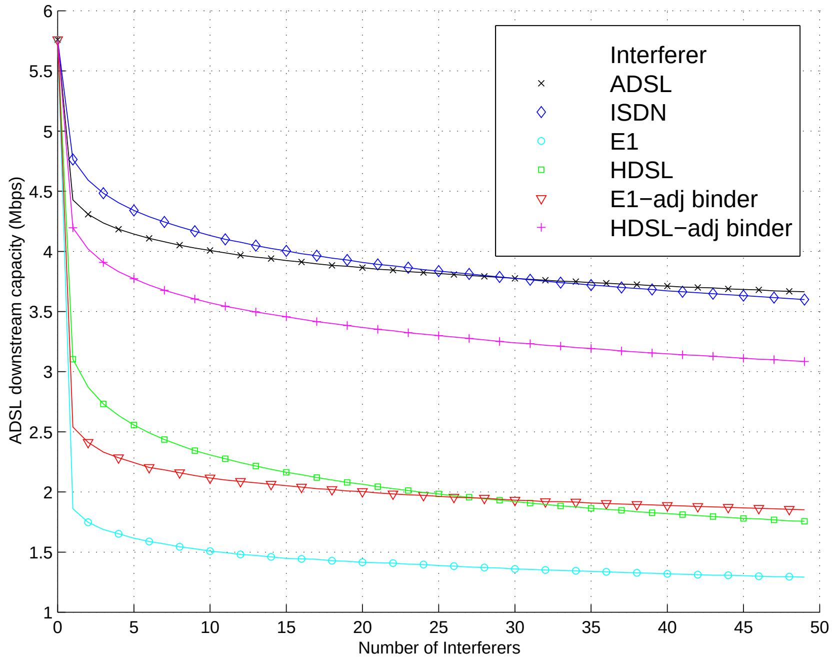

Figure 6.3: ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with no bridged tap, using ECH allocation

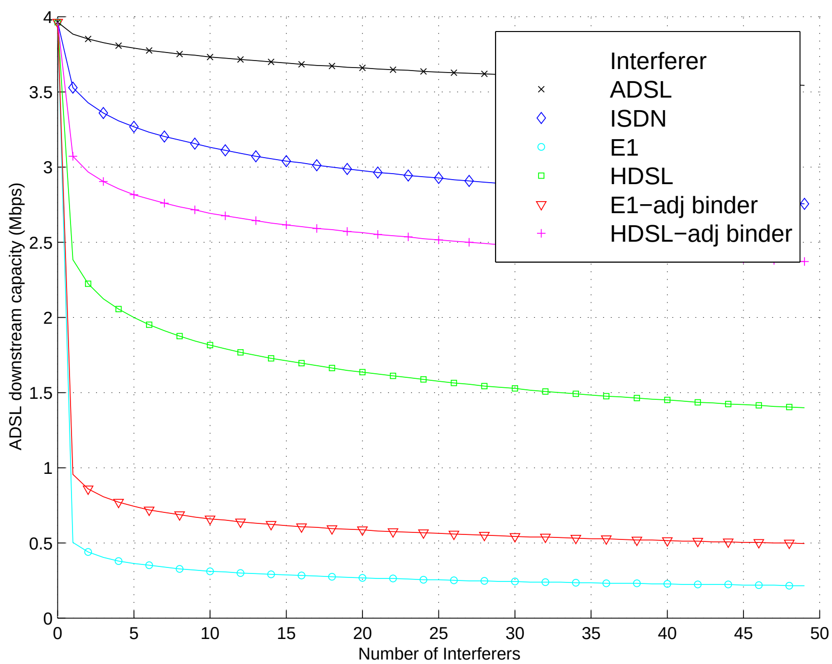

Figure 6.4: ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with no bridged tap, using FDM allocation

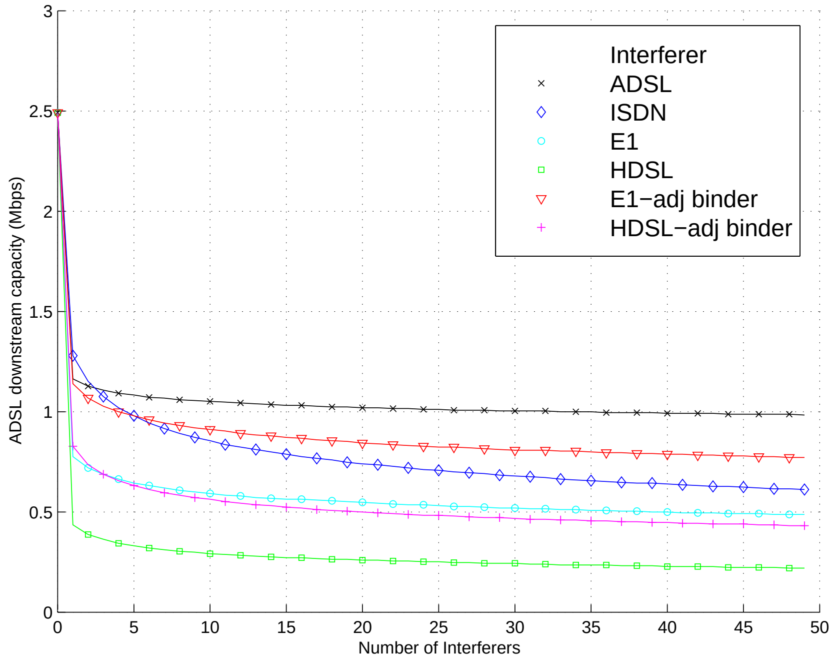

Figure 6.5: ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with maximum length bridged tap, using ECH allocation

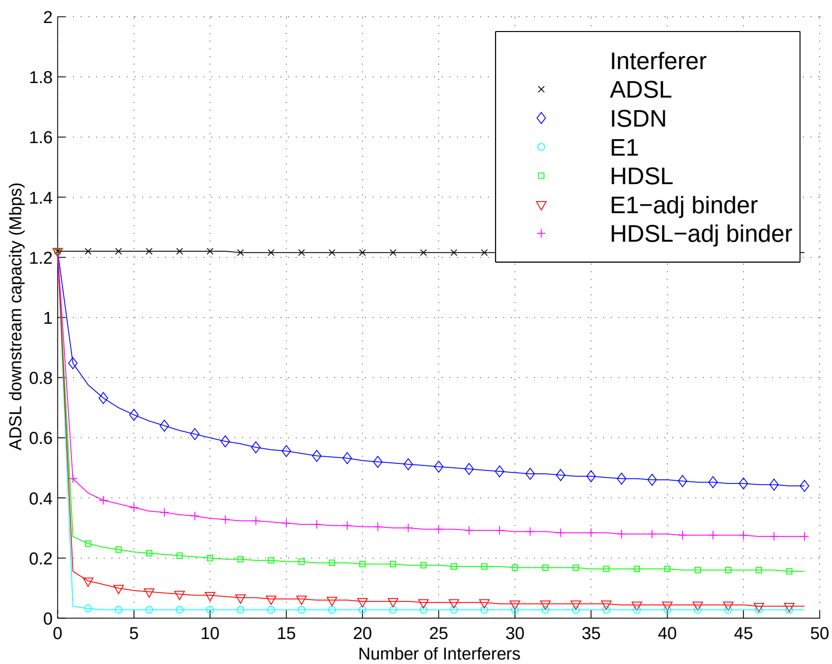

Figure 6.6: ADSL downstream data rate vs. the number of Interferers for 0.4 mm wire with maximum length bridged tap, using FDM allocation

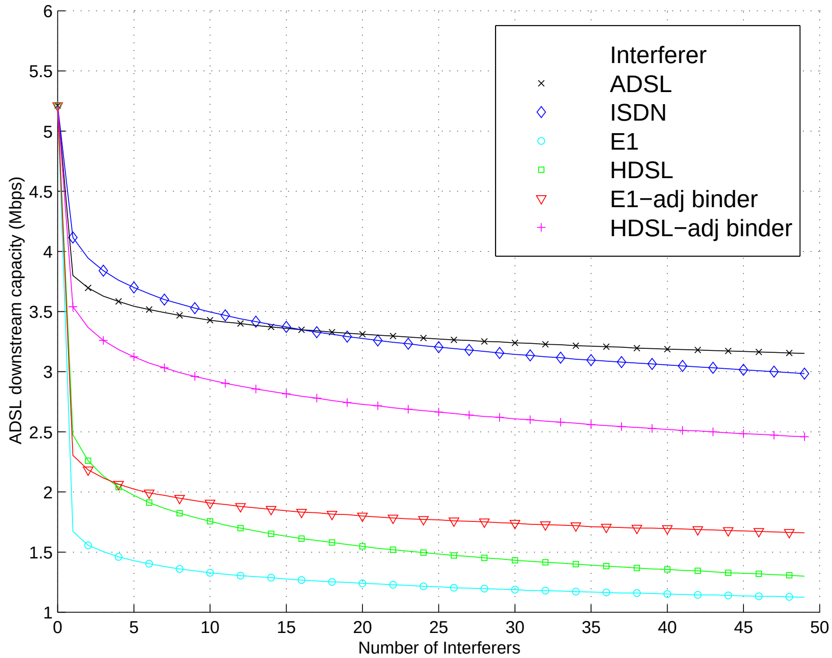

Figure 6.7: ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with maximum length bridged tap, using ECH allocation

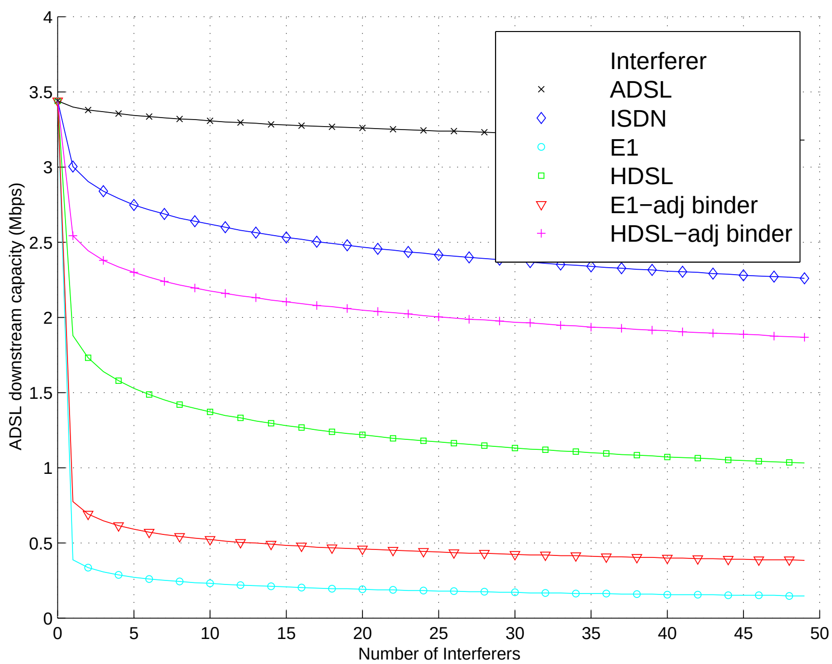

Figure 6.8: ADSL downstream data rate vs. the number of Interferers for 0.5 mm wire with maximum length bridged tap, using FDM allocation

6.3 ADSL maximum reach

The previous section determined the maximum data rate for a fixed length of local loop. This method is used for the case of determining the data rate for existing local loops. It will be hard or very costly to change the length or gauge of the line. DLC technology can be implemented if the data rate determined for the specific line is too low.

This section determines the maximum length of copper wire permitted to deliver a specific data rate to a customer. Once again, the maximum length is a function of the worst case interferer present in the cable. Let's first consider the case of providing 2.048 Mbps.

6.3.1 2.048 Mbps downstream data rate

Figure 6.9 to Figure 6.16 show the maximum ADSL reach possible for a supported data rate of 2.048 Mbps with various scenarios. The following general observations can be made:

- When only ADSL with FDM spectral allocation are used (fig. 6.10 and 6.12), maximum reach is achieved, independent of the number of ADSL interferers present.
- The use of 0.5 mm wire over 0.4 mm wire gives an additional reach of about 1.5 km.
- E1 and E1 (adj) decreases the reach possible by more than 1 km for ECH (fig. 6.9 and 6.11) and by more than 2 km for FDM (fig. 6.10 and 6.12).

When comparing Figure 6.9 and Figure 6.11, the following observations are made:

- The use of only ADSL, or a combination of ADSL and ISDN, has little effect on the reach possible for a certain number of interferers.
- When using 0.5 mm wire (fig 6.11), HDSL and E1 (adj) provides approximately the same reach for the same number of interferers.
- HDSL technology is preferred over E1 technology when present in the same cable as ADSL.

When comparing Figure 6.10 and Figure 6.12, the following observations are made:

- HDSL technology is strongly recommended over E1 when using FDM spectral allocation, due to reach increase of about 2 km when compared with E1.

When a bridged tap of maximum allowable length is added, there is an overall decrease in reach of about 250 m (fig. 6.9 to 6.12 compared to fig. 6.13 to 6.16).

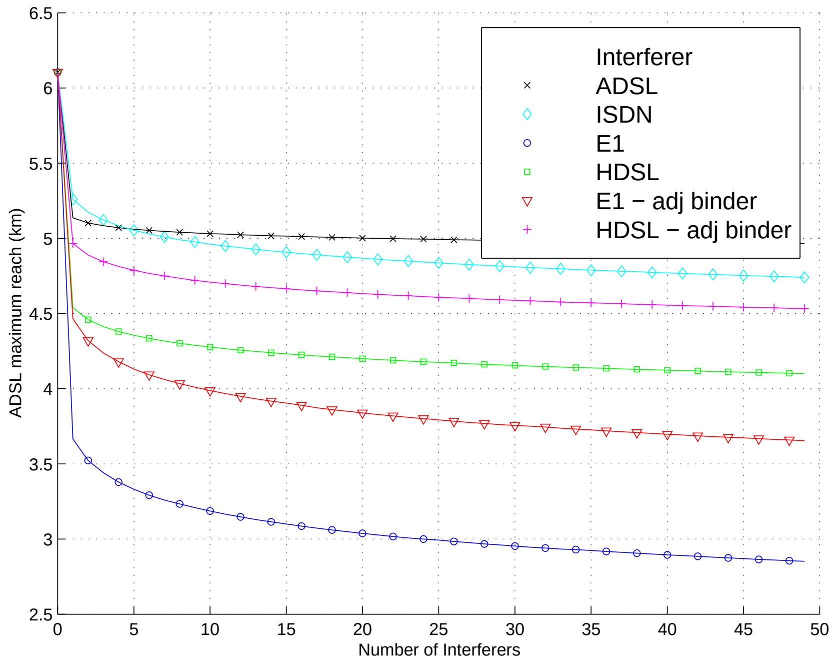

Figure 6.9: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with no bridged tap, using ECH allocation

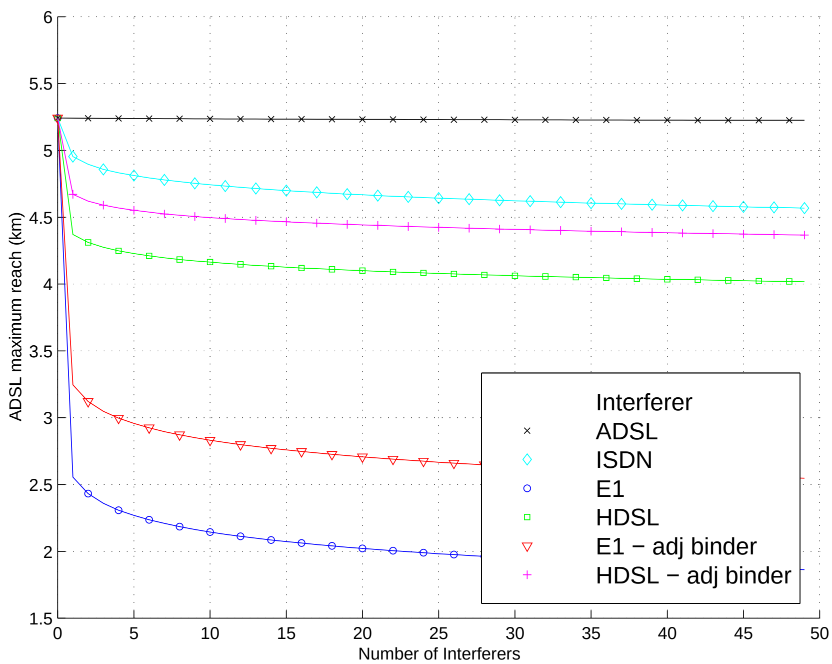

Figure 6.10: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with no bridged tap, using FDM allocation

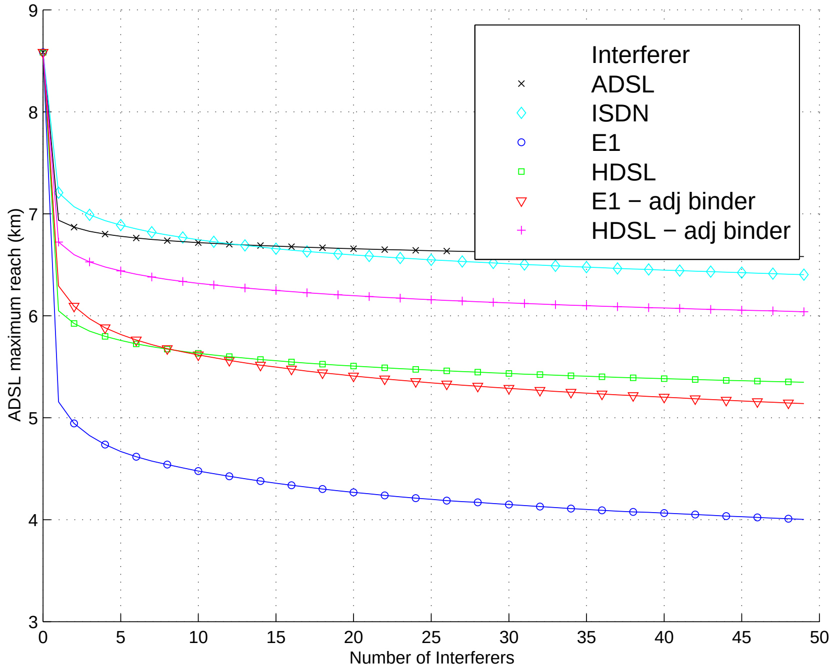

Figure 6.11: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with no bridged tap, using ECH allocation

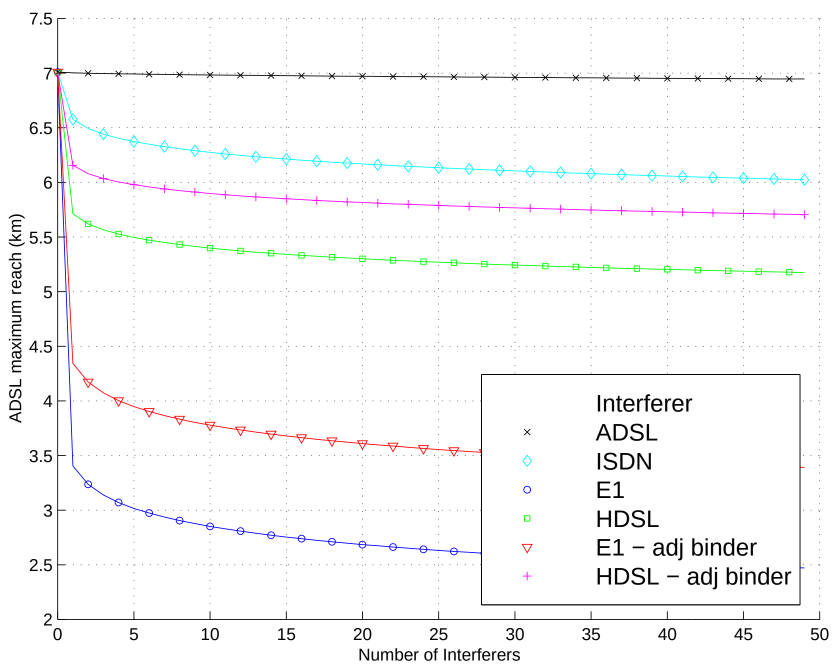

Figure 6.12: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with no bridged tap, using FDM allocation

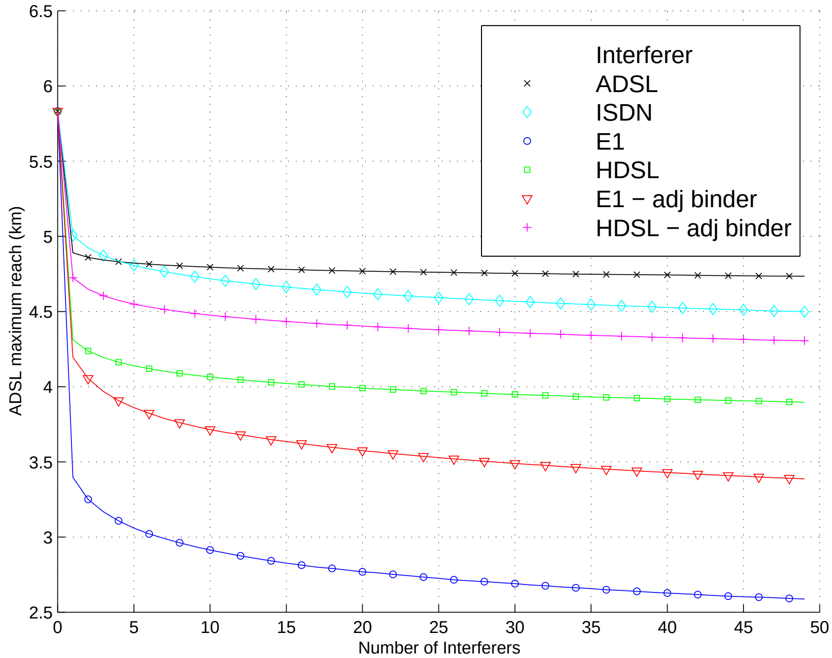

Figure 6.13: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with maximum length bridged tap, using ECH allocation

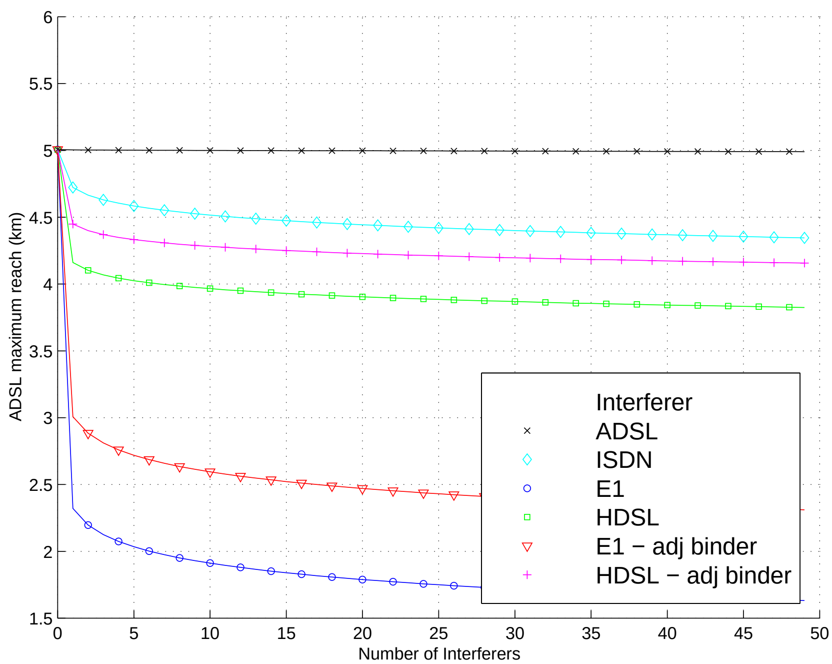

Figure 6.14: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.4 mm wire with maximum length bridged tap, using FDM allocation

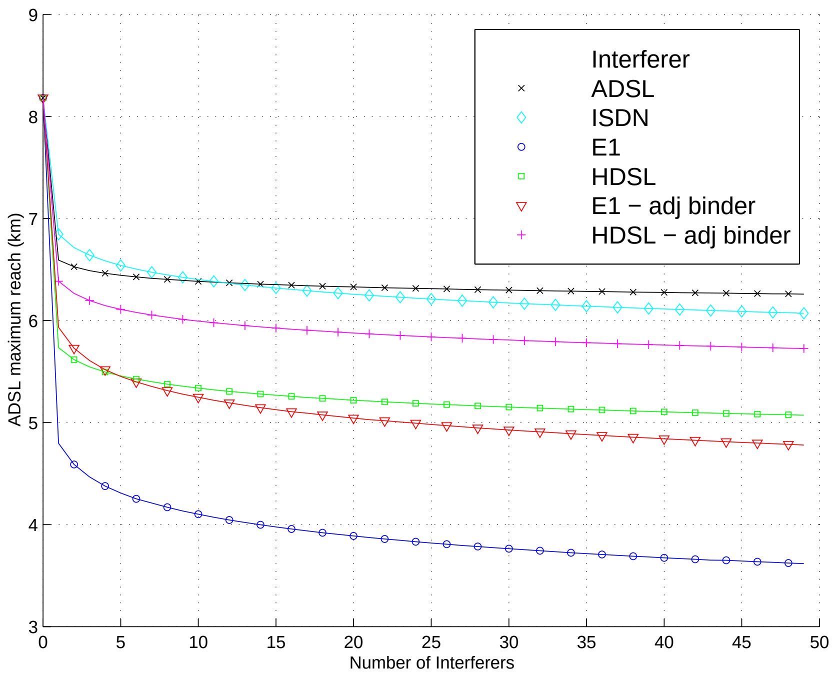

Figure 6.15: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with maximum length bridged tap, using ECH allocation

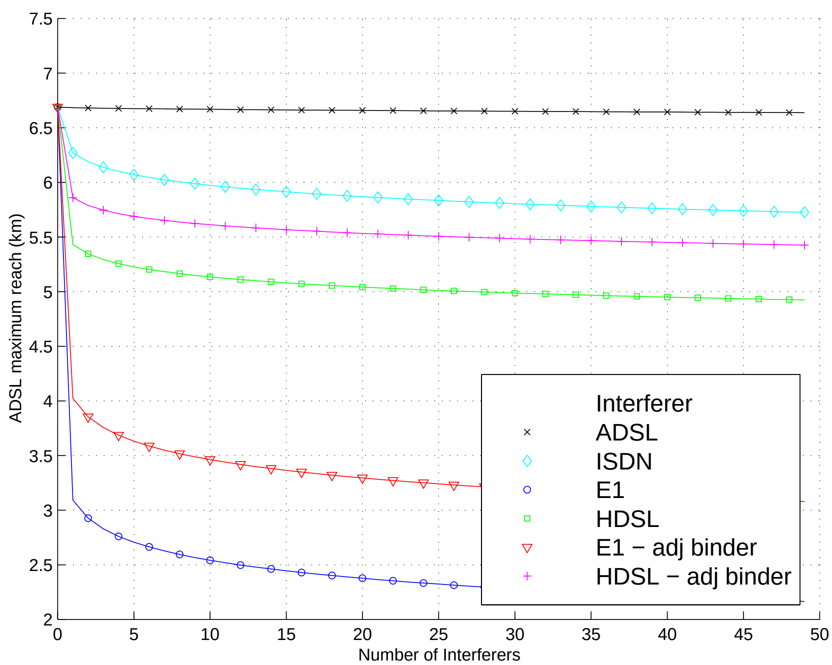

Figure 6.16: ADSL maximum reach vs. the number of Interferers for 2.048 Mbps over 0.5 mm wire with maximum length bridged tap, using FDM allocation

6.3.2 6.144 Mbps downstream data rate

Figure 6.17 to Figure 6.24 show the maximum ADSL reach possible for a supported data rate of 6.144 Mbps. The following general observations can be made:

- The reach obtainable in the presence of ADSL, ISDN, HDSL or HDSL (adj) interferers is close to each other, with a deviation of about 500 m between minimum and maximum.
- Once again, it is strongly recommended not to use E1 technology in the same cable as ADSL. Reach is reduced dramatically when E1 technology is introduced.
- The use of any combination of ADSL, ISDN and/or HDSL (adj) provides approximately the same reach for a certain number of interferers.
- On average, the use of ECH has no distinct advantage over the use of FDM.
- The use of 0.5 mm wire over 0.4 mm wire provides an increase in reach of about 1 km.

The introduction of a bridged tap of maximum allowable length leads to an overall decrease in reach of about 200 m (fig. 6.17 to 6.20 compared to fig. 6.21 to 6.24).

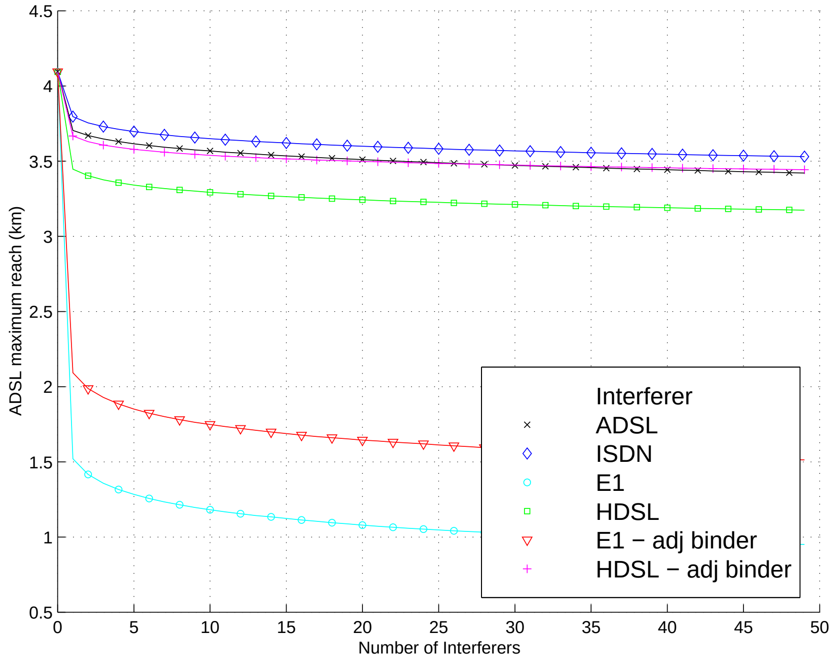

Figure 6.17: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire with no bridged tap, using ECH allocation

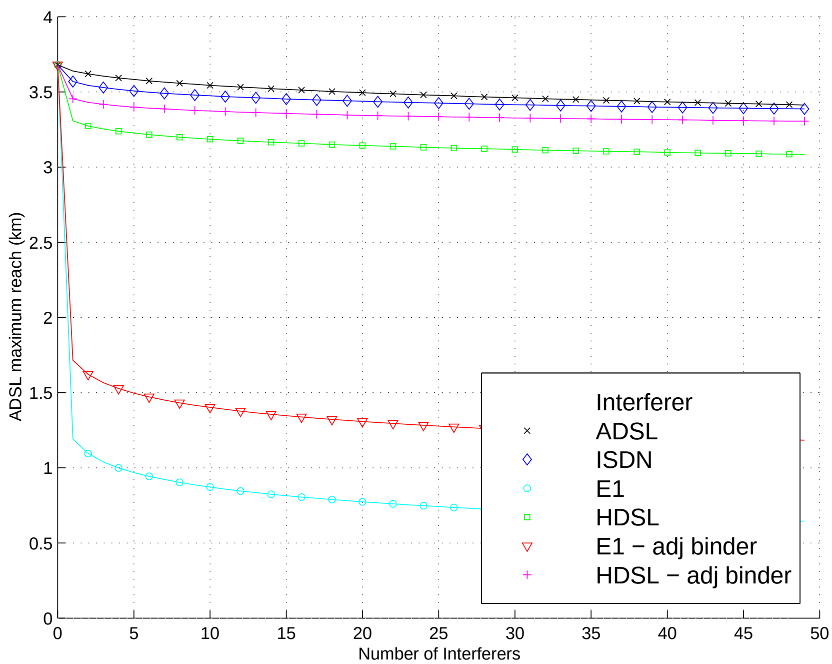

Figure 6.18: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire with no bridged tap, using FDM allocation

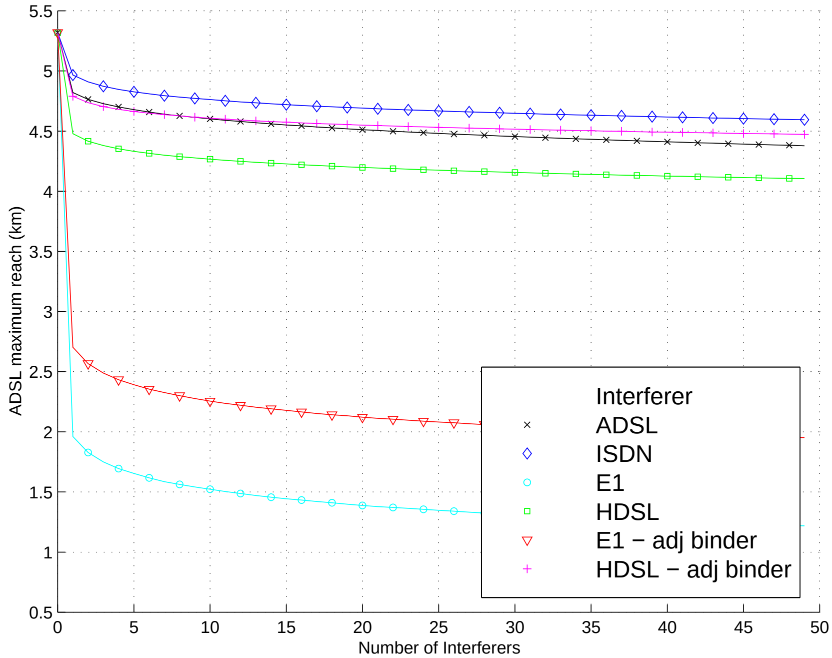

Figure 6.19: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire with no bridged tap, using ECH allocation

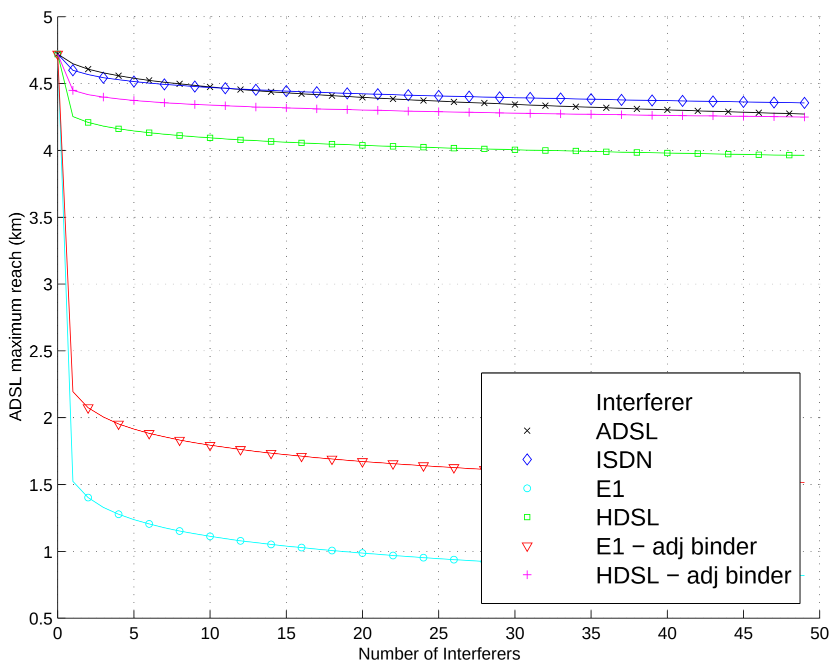

Figure 6.20: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire with no bridged tap, using FDM allocation

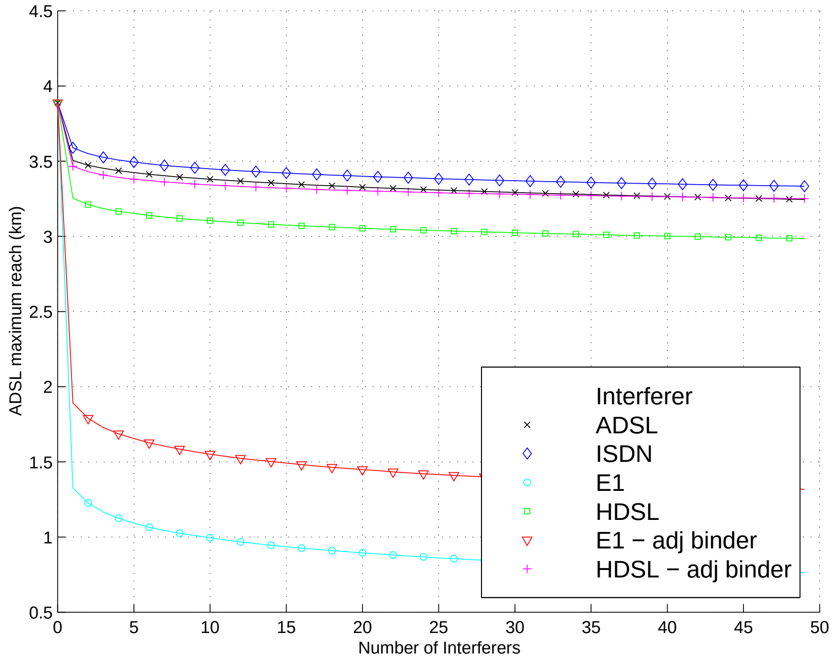

Figure 6.21: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire maximum length bridged tap, using ECH allocation

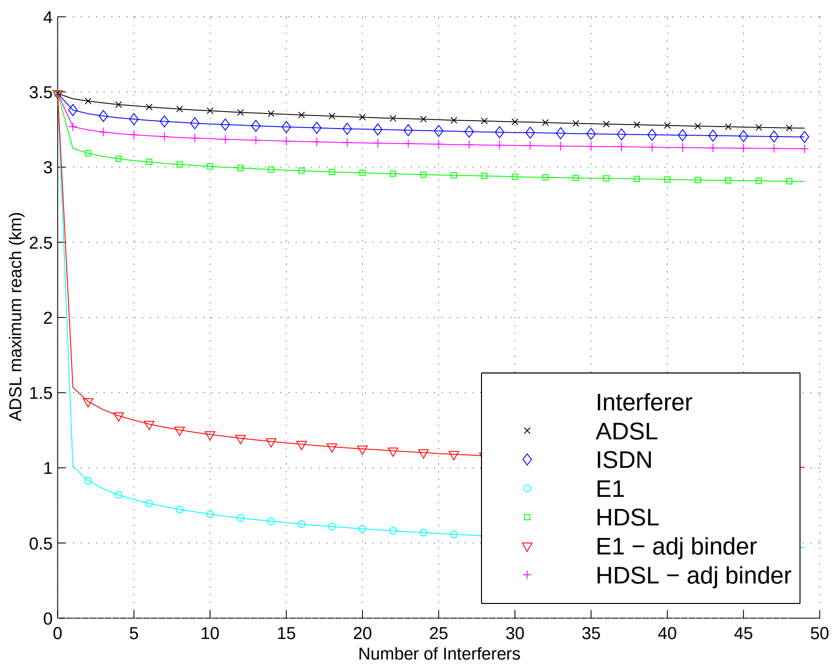

Figure 6.22: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.4 mm wire maximum length bridged tap, using FDM allocation

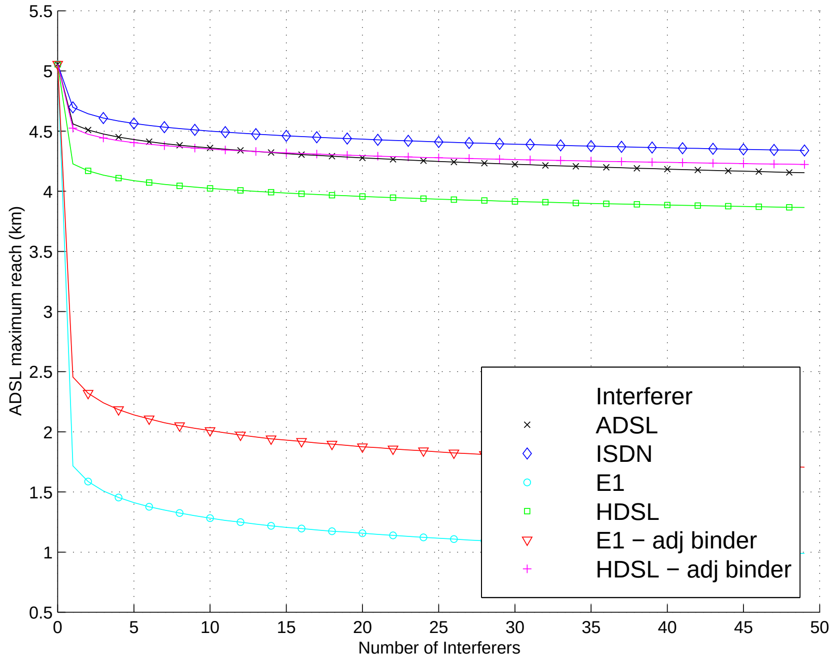

Figure 6.23: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire maximum length bridged tap, using ECH allocation

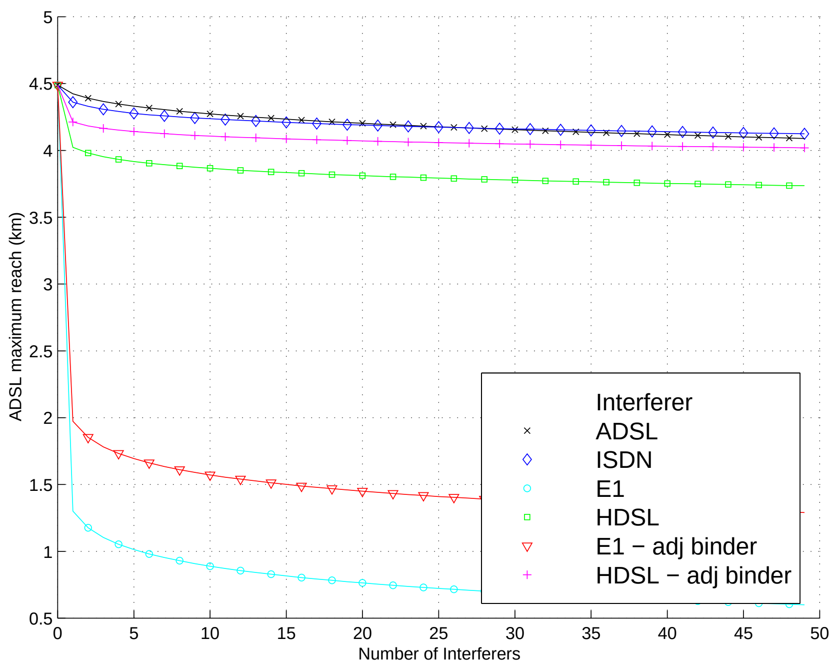

Figure 6.24: ADSL maximum reach vs. the number of Interferers for 6.144 Mbps over 0.5 mm wire maximum length bridged tap, using FDM allocation

6.3.3 8.192 Mbps downstream data rate

Figure 6.25 to Figure 6.32 show the maximum ADSL reach possible for a supported data rate of 8.192 Mbps. The following general observations can be made:

- The reach obtainable in the presence of ADSL, ISDN, HDSL or HDSL (adj) interferers is close to each other, with a deviation of about 500 m between minimum and maximum.
- The use of any combination of ADSL, ISDN and/or HDSL (adj) provides approximately the same reach for a certain number of interferers.
- Once again, it is strongly recommended not to use E1 technology in the same cable as ADSL. Reach is reduced dramatically when E1 technology is introduced.
- On average, the use of ECH has no distinct advantage over the use of FDM.
- The use of 0.5 mm wire over 0.4 mm wire provides an increase in reach of about 800 m for ECH and 300 m for FDM.
- With 35 or more ADSL interferers present, reach is worse than HDSL when using 0.5 mm wire and ECH spectral allocation (fig. 6.27).
- With 25 or more ADSL interferers present, reach is worse than HDSL when using 0.5 mm wire and FDM spectral allocation (fig. 6.28).

When a bridged tap of maximum allowable length is added, there is an overall decrease in reach of about 150 m (fig. 6.25 to 6.28 compared to fig. 6.29 to 6.32).

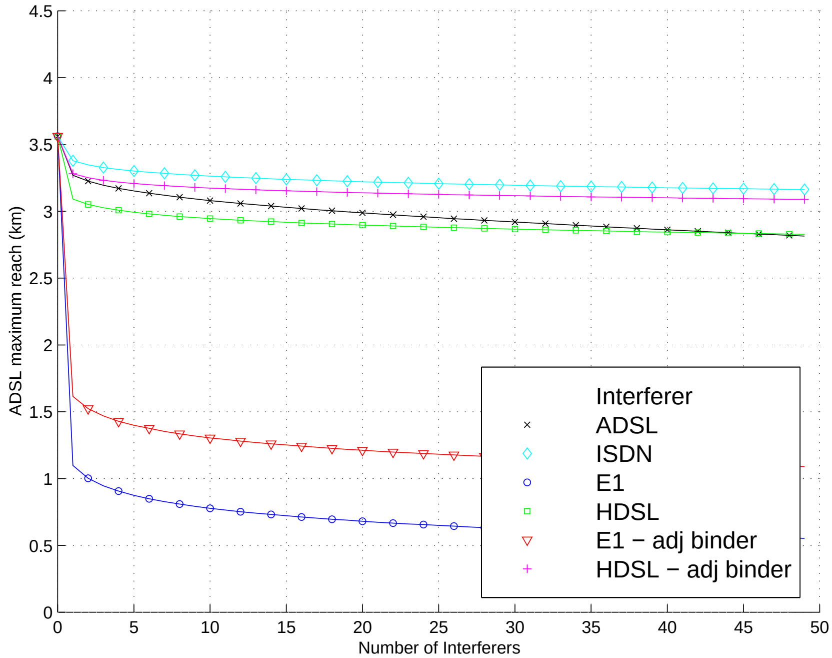

Figure 6.25: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with no bridged tap, using ECH allocation

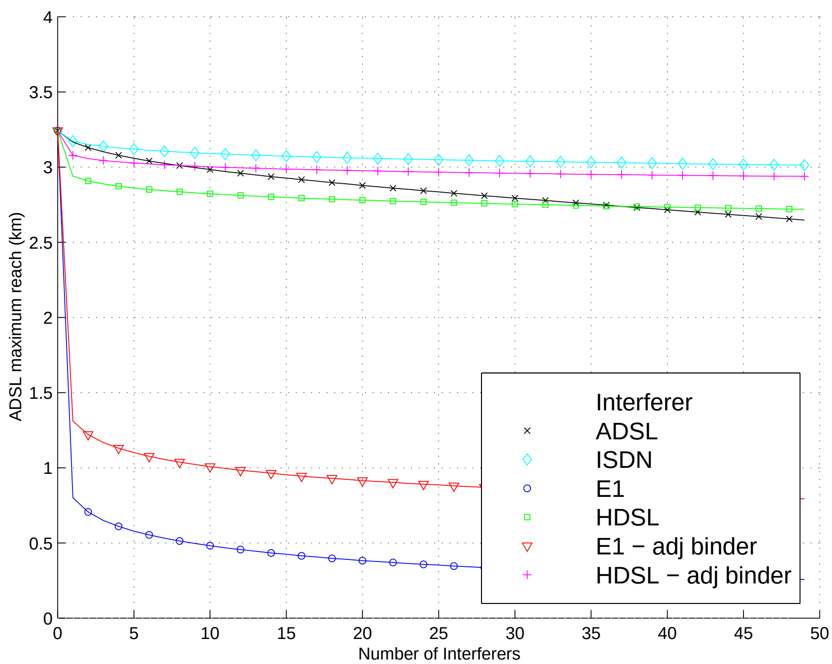

Figure 6.26: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with no bridged tap, using FDM allocation

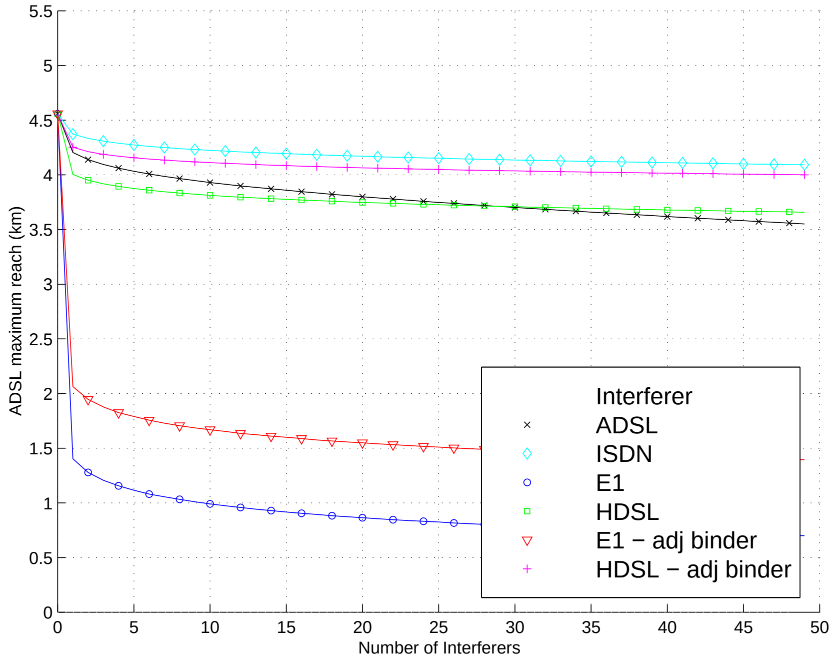

Figure 6.27: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with no bridged tap, using ECH allocation

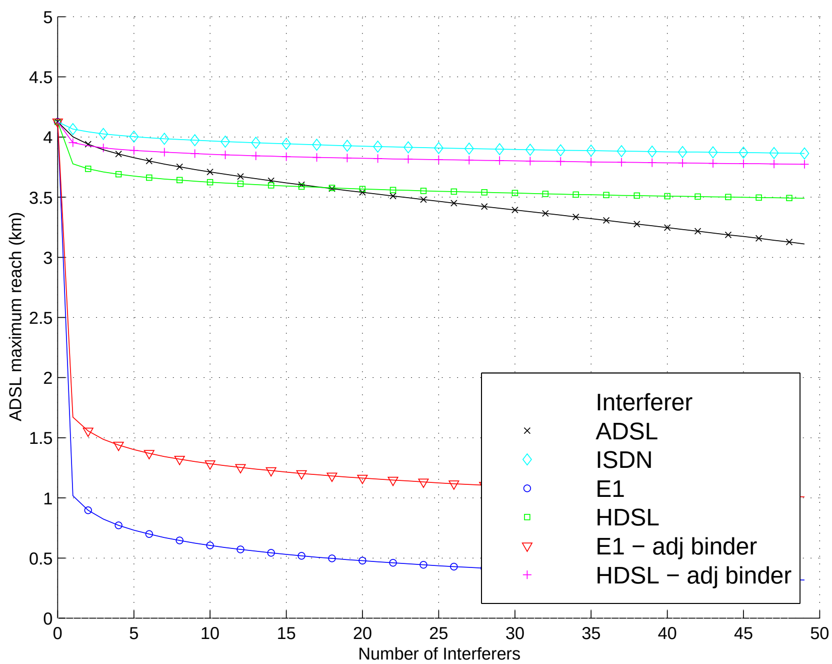

Figure 6.28: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with no bridged tap, using FDM allocation

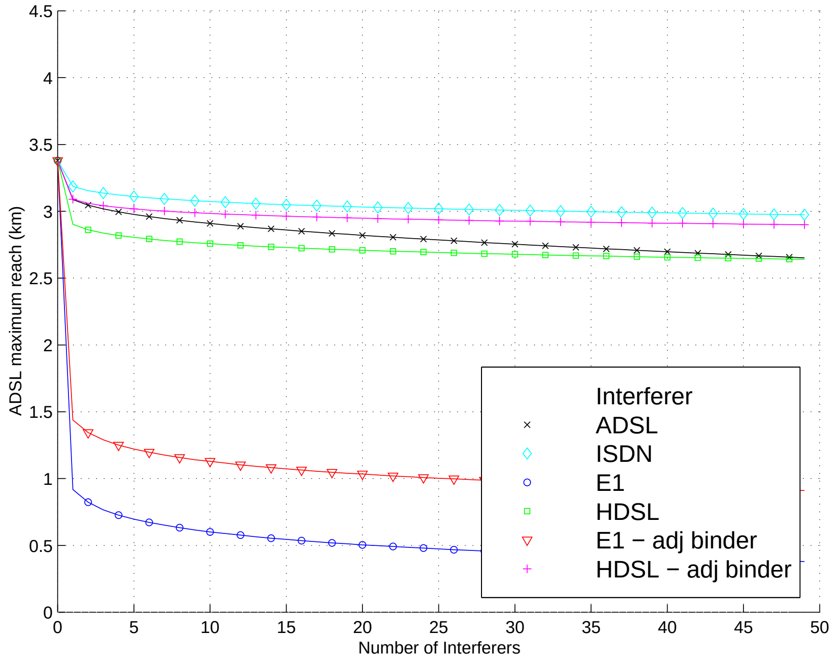

Figure 6.29: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with maximum length bridged tap, using ECH allocation

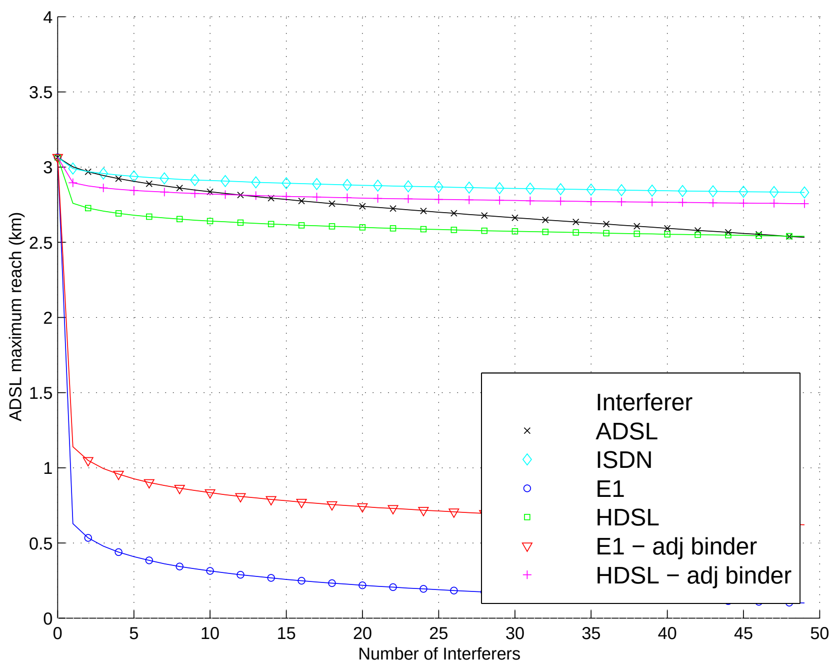

Figure 6.30: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.4 mm wire with maximum length bridged tap, using FDM allocation

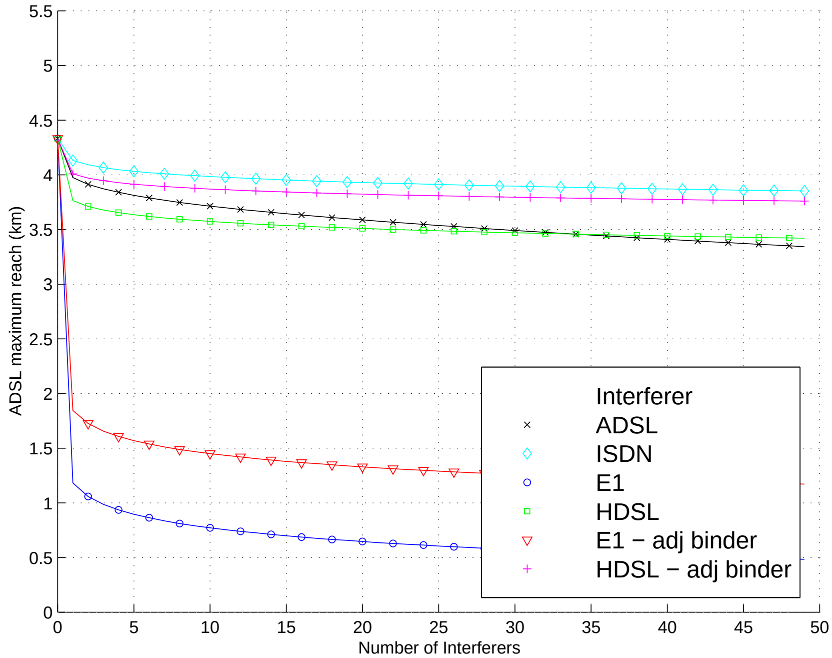

Figure 6.31: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with maximum length bridged tap, using ECH allocation

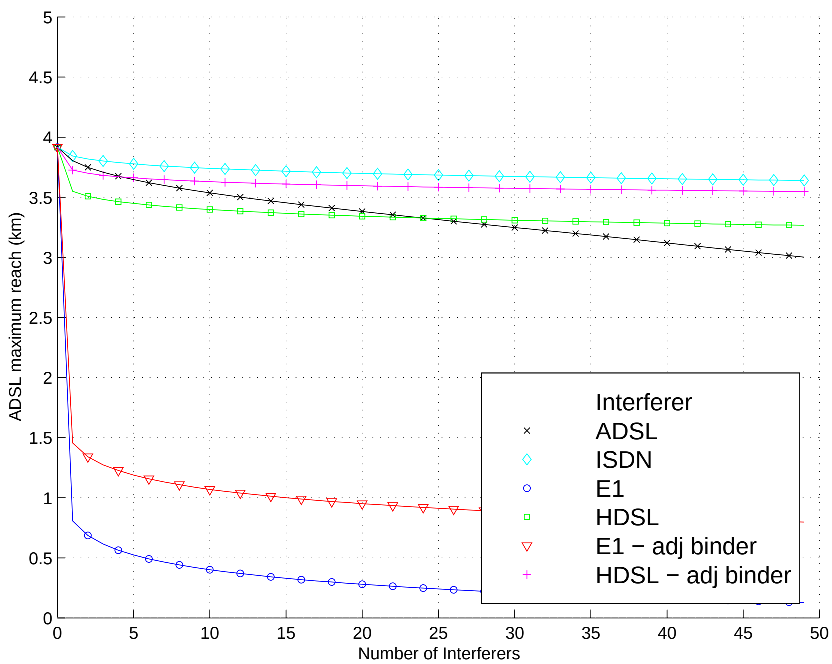

Figure 6.32: ADSL maximum reach vs. the number of Interferers for 8.192 Mbps over 0.5 mm wire with maximum length bridged tap, using FDM allocation

CHAPTER SEVEN

CONCLUSION

This dissertation aimed to determine ADSL capacity in a generic exchange environment, including AWGN and other services, consisting of other ADSLs, ISDN, HDSL and E1.

First, ADSL downstream capacity (data rate) was determined as a function of the number of each interferer, separately present within the same cable as ADSL. A fixed length cable with a certain topology for each line was used. Secondly, ADSL capacity (maximum reach) was also determined, but for a specified data rate of either 2.048, 6.144 or 8.192 Mbps.

Standardized models were used, as described in Chapter 3. This included the primary parameter models and the power spectral densities of ISDN, HDSL, E1, upstream ADSL and downstream ADSL. The near-end crosstalk and far-end crosstalk models were also discussed, as well as other impairments found in the network. Also, a bit loading algorithm developed by Campello [1], was corrected and used to optimize the allocation of bits/symbol/subchannel, subject to a fixed energy constraint, as described in Chapter 4. The implementation into a simulation program and specifications used, were described in Chapter 5.

From the results presented in Chapter 6, the following conclusions may be drawn:

- Use the largest wire gauge possible.
- When only ADSL is present, use FDM spectral allocation.
- When other services are also present, ECH spectral allocation delivers marginally better capacity. Because ECH requires additional signal processing, FDM is usually chosen to limit complexity. However, the additional reach possible is sacrificed.
- It is not recommended to use E1 within the same cable as ADSL. Rather place E1 in separate cables, which are properly shielded.
- HDSL is preferred over E1 when considering using binder groups adjacent to ADSL.
- When having a combination of interferers, the actual capacity obtained will be located at, or below the capacity determined for the worst case interferer.
- When using only ADSL:
    - 2.048 Mbps may be supported over 0.4 mm gauge lines up to about 5.2 km, and over 0.5 mm gauge lines up to about 7.0 km.
    - 6.144 Mbps may be supported over 0.4 mm gauge lines up to about 3.5 km, and over 0.5 mm gauge lines up to about 4.5 km.
    - 8.192 Mbps may be supported over 0.4 mm gauge lines up to about 3.0 km, and over 0.5 mm gauge lines up to about 4.0 km.
- When ISDN services are also mixed with ADSL:
    - 2.048 Mbps may be supported over 0.4 mm gauge lines up to about 4.7 km, and over 0.5 mm gauge lines up to about 6.4 km.
    - Reach is dependent on the number of ADSL services when supporting 6.144 Mbps
    - Reach is also dependent on the number of ADSL services when supporting 8.192 Mbps

As the required data rate increases, the power spectral density of the service being considered becomes more important, as well as the number of each interferer present.

From the graphs obtained in Chapter 6, the number of customers which could be supported, can be determined by obtaining the number of interferers allowed for a specific scenario. Note that the result obtained is the number of customers/binder group.

The aims of this dissertation were achieved, resulting in the Downstream data rate and Maximum reach, versus the number of interferers, for each interferer seperately, as shown by the graphs in Chapter 6.

A number of topics warrant further investigation:

- Complex mathematical expression to determine capacity. From the graphs obtained, a complex mathematical equation may be derived to obtain actual capacity possible. It should be a function of the type of interferer(s) present, the number of each interferer and the data rate required.
- Determination of capacity when using *Synchronized DMT* (SDMT) for use in *Very-high-bit-rate DSL* (VDSL): The total bandwidth is increased to 30 MHz with a subchannel bandwidth of 43.125 kHz. Line lengths are limited to 1 km. The same type of capacity graphs may be determined.
- ADSL deployment optimization using the OPNET simulation package.

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