1

Introduction

Digital communications have gained immense importance in the last two decades. This development was supported by the invention of mobile communications, but it was especially boosted by the enormous expansion of the Internet. Applications like video-streaming, file sharing, telecommuting or video-conferencing awakened the desire for increasing data rates, resulting in a hundred-fold increase from some hundred kbit/s to around several ten Mbit/s in the last twenty years. Today, the necessity of sufficiently high data rates is as present as ever. With High Definition Television (HDTV) gaining momentum and the tendency to use cloud services and connect everything in the Internet of Things customers still long for reliable and suitable connections.

Basically, there are three different options to bring broadband services to the customers. Fully fiber-based networks would be the technically most advanced solution providing the highest available data rates. But optical equipment and trenching of cables is extremely costly, making it economically non-profitable for telecommunication companies.

As a second option, Long Term Evolution (LTE) can be considered as an alternative to fiber for provision of broadband services. Thanks to achievable data rates and comparably low cost of installation, this is definitely true for undeveloped and sparsely populated areas. In urban areas however, where lots of customers share the available bandwidth, mobile services can easily come at the expense of reliability and connection quality.

The third very valuable option is Digital Subscriber Line (DSL) [GDJ06, SSCS03, SCS99]. Digital subscriber line technology offers wireline broadband services by enabling digital communications over the existing telephone infrastructure. The telephone lines were originally designed for voice communications at frequencies of up to some kHz providing limited data rate. DSL simply widens the occupied transmission bandwidth, resulting in an enormous gain in performance. In addition, DSL has the great advantage of profiting from the copper telephone network, which is widely expanded and contains several hundred million loop plants. By occupying that existing infrastructure it has lower implementation cost than fiber and due to the fact that each user occupies a single copper line it can provide highly reliable services.

Since the development in the late 1980's, DSL has seen many improvements. In the first fifteen years High Data Rate Digital Subscriber Line (HDSL), Symmetric Digital Subscriber Line (SDSL) and Asymmetric Digital Subscriber Line (ADSL) were designed and operated in the market. Starting with HDSL and its extension SDSL, symmetric services with data rates of some Mbit/s were provided to the customers first on two twisted-pairs and then also on one twisted-pair. In the late 90's, the more consumer-oriented ADSL was introduced triggered by the Internet boom. With higher Downstream (DS) than Upstream (US) rates, it perfectly meets the Internet users' requirement for asymmetrical service as they normally download more than they upload. ADSL is able to provide DS rates of nearly 10 Mbit/s and a tenth of that in US. An evolutionary step followed in the mid 2000's with the invention of Very High Speed Digital Subscriber Line (VDSL). By then, fibers attached the network core to the Central Office (CO) and DSL services connected the CO to the customer premises, which resulted in loop lengths of some kilometers. With VDSL, the fiber was coming closer to the customer. Fibers were laid to the end of the street where an Optical Network Unit (ONU) was installed. As a result, VDSL only runs on the twisted-pair connection between the ONU and the customer premises and loop lengths were reduced. The shortened cable lengths allowed occupancy of much higher frequencies and enabled an increase in data rate to some tens of Mbit/s. The successor of VDSL, Very High Speed Digital Subscriber Line 2 (VDSL2), still operates on the last mile between customer premises and fiber-network core, but at an even higher bandwidth.

Modern DSL communication systems like VDSL and VDSL2 use the frequency band up to several ten MHz on each copper cable to offer much higher data rates than achievable with the voice bands. Unfortunately, the twisted pairs of the different users are bundled within large cable binders typically containing 20 to 100 individual pairs. Due to the high frequencies and non-perfect insulation of the twisted pairs there is significant electromagnetic coupling among nearby lines. This leads to severe interferences between the different users transmitting within a binder, resulting in two different kinds of Crosstalk (XT): Near-End Crosstalk (NEXT) and Far-End Crosstalk (FEXT). Near-end crosstalk occurs when transmit signals of one stream direction disturb the received signals of the other stream direction. It can be easily avoided by the use of duplexing methods. Far-end crosstalk results when the transmit signals of the same stream direction interfere. It can be up to 20 dB larger than the background noise and is the major performance limiter between adjacent lines in a cable binder. Because of that it is very reasonable and highly effective to mitigate the far-end crosstalk interferences.

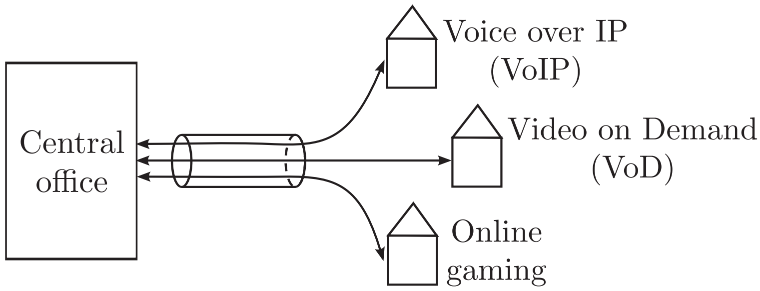

Figure 1.1: Multimedia applications in DSL access networks

Principally, the negative impact of FEXT can be minimized in two ways. Far-end crosstalk can either be eliminated by crosstalk cancellation or reduced by spectrum management [Rua14, Cen04, Yu02]. Digital subscriber line systems are multicarrier systems, where the bandwidth is split into a large number of narrowband transmission channels. They apply Discrete Multi-Tone Transmission (DMT), a technique which is identical to Orthogonal Frequency Division Multiplexing (OFDM) [Roh11]. Spectrum management exploits this fact by reasonably shaping the transmit spectra on the different lines. By adapting the transmit power on the subchannels of all lines in the binder, less mutual interferences are produced. The crosstalk influence is decreased but can never be completely avoided. In addition, spectrum management is not advantageous in every transmission scenario.

Crosstalk cancellation tackles the problem with FEXT by signal processing. For that purpose, DSL systems are modeled as multi-user systems where every user in the binder is considered as a transmitter and also as a recipient of the signals of all other lines. When full Channel State Information (CSI) of both direct and crosstalk channels is known with adequate precision and accuracy, crosstalk cancellation and precoding techniques are able to completely remove the interferences from the other lines. Especially methods based on Zero-Forcing (ZF) are known for eliminating FEXT in a near-optimum way. However, crosstalk elimination procedures might also need an unbearable amount of computational complexity to achieve crosstalk-free transmission for large binder sizes. Generally, only limited computational resources are available and FEXT can only be partially removed.

Nowadays, DSL systems have to be able to support an always increasing amount of high-rate applications. At the same time, they face services with highly differing data rates and as a result users with highly varying data rate demands (see Fig. 1.1). If DSL users want to stably run several high-rate applications in parallel, they will need guarantees on their achievable data rates. Partial crosstalk cancellation procedures could be a solution, but existing algorithms select the canceled crosstalkers by focusing on capacity maximization and do not take into account the data rate demands the customers really have. This makes service providers either not being able to give data rate guarantees to their customers or spending more computational complexity than actually needed for target achievement on a binder.

In the following two important problems of DSL systems are addressed: Firstly, the issue of estimating the crosstalk channels for crosstalk cancellation and precoding is discussed as system performance strongly depends on the quality of channel estimation. Both US and DS channels need to be initially estimated with sufficiently high accuracy. To always maintain the full performance of the DSL system the precoder and canceler coefficients need an update over time as the DSL channel can vary slowly due to temperature and humidity changes. Channel estimation and update procedures are introduced which combine the good performance of pilot-based estimation techniques with low pilot and signaling overhead.

Secondly, another goal is to find crosstalk mitigation methods which satisfy the need of setting and supporting data rate requirements in DSL access networks at a limited amount of computational complexity available for a binder. In a first step, novel successive selection algorithms for partial crosstalk cancellation and precoding are found, which are able to adapt the users' data rates to the desired values. In a second step, the successive selection methods are combined with spectrum management techniques to support high data rate targets with a low amount of computational complexity more efficiently.

The structure of the thesis is given as follows: In Chapter 2, DSL systems are considered in a single-user environment. The chapter gives an overview of techniques and methods applied on a single twisted-pair and describes the transmission channel of a single line.

Chapter 3 extends the description of DSL systems to the multi-user environment, where crosstalk is not modeled as noise, but as an interference channel. Properties of multi-user up- and downstream transmission at the presence of crosstalk are explained and the considered crosstalk channel model is presented.

The crosstalk cancellation techniques which are the basis for all proposed methods, are introduced in Chapter 4. Upstream full crosstalk cancellation and downstream full precoding completely eliminate crosstalk. Partial crosstalk cancellation and partial crosstalk precoding do not remove the influence of crosstalk in total, but just reduce it. Only the interferences of a set of selected crosstalkers are eliminated.

Spectrum management is explained in Chapter 5. For proper understanding, the spectrum management problem and existing solutions to it are presented.

The contributions and results of this thesis are given in Chapter 6 and especially in Chapter 7. Chapter 6 explains the proposals for crosstalk channel estimation and crosstalk channel update and gives performance results. Chapter 7 addresses the problem of data rate constraints in DSL access networks and limited computational resources for crosstalk cancellation procedures. Two methods are presented, which allow users in a cable binder to obtain their data rate targets with a limited computational complexity. The first method uses partial crosstalk cancellation and precoding and selects the set of eliminated crosstalkers based on their data rate targets. The second proposal extends the first method by combining it with spectrum management. For both procedures performance results are given. All contributions and their corresponding results are summarized in the conclusion in Chapter 8.

II

Digital Subscriber Line Transmission

2.1 Basics

The DSL technology allows the transport of high-bit rate digital information over conventional old copper telephone lines. Essentially, a digital subscriber line is the analog twisted-wire pair connection between the CO and the customer premises (see Fig. 2.1), also referred to as the local loop.

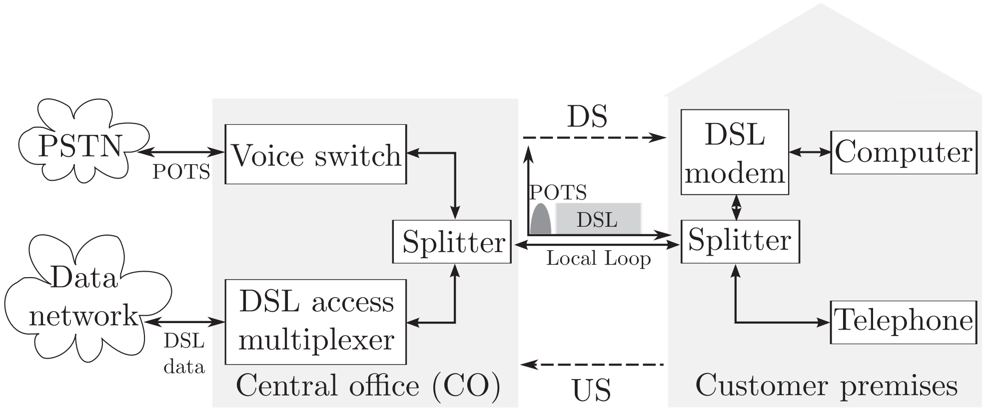

Figure 2.1: DSL reference model for a single-line situation

A DSL transmission can be either established in the US direction, i. e. from the customer premises to the CO, or in the reverse DS direction, since all DSL services provide both streaming ways. As the initial use of the twisted pairs was the analog telephony, the local loop carries both the signal of the Plain Old Telephone Service (POTS) and the DSL data signal, where POTS occupies the baseband from 200 Hz to 4 kHz and DSL uses frequencies up to 30 MHz in the copper line. To separate the telephone signal from the DSL service, DSL filters (splitters) are needed on both sides of the loop. At the customer premises, the voice signal is directed to the telephone after the splitter. At the CO, a voice switch directs the voice signal into the Public Switched Telephone Network (PSTN). To process the DSL signal, modems are required on both ends of the copper line. On the side of the customer