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The Importance of Digital Signal Processing in High Speed Optical Receivers
Equalization, Impairment Compensation and Performance Monitoring
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Chapter 1

Introduction

A fiber thinner than a human hair - enabling remote conversation of 500 million people - via invisible light. The brothers Grimm would have felt ashame telling such fairy tales. And yet this has become the technical reality of today's communication networks, the optical network in particular. A standard telephone or modem connection requires a digital bandwidth of 56 kbit/s = 56.000 bit/s [1]. Record experiments in the year 2008 proved transmission of a total capacity of 25.6 Tb/s = 25.600.000.000.000 bit/s [2] over a single optical fiber, the equivalent of about 500 million telephone connections. The optical fiber has a core radius of 9 μm, ten times thinner than a human hair. Light from a laser source carries the digital information at a wavelength around 1550 nm, invisible for the human eye [3].
Besides these unbelievable superlatives, the optical network is the least recognized by the average user of digital communication. The mobile phone customer is used to handle a trendy device including manyfold applications ranging from business software to fun games. A whole industry is eager to provide their customers with the latest design and the most up-to-date features. Although the technology enabling mobile communication is rarely understood by the population, the mobile phone is clearly perceived and widely accepted. The same applies for wireline or wireless local area networks (LANs) or the simple digital subscriber line (DSL) in many households. And still, all these radio and copper-wire networks would hardly work without the optical backbone network enabling high-speed world-wide digital communication.

Typically, the customer is connected to the network by electrical wireline or wireless access, e.g. a mobile phone connects to a nearby antenna that connects to the base station. However, sooner or later, the digitized information is bundled in high-speed "data pipes" that cost-effectively transport large amounts of data. Optical networks provide this back-bone network carrying the bulk of our digital communication. Besides the small amount of national and international voice communication, the internet traffic requires most of the bandwidth.
Today's internet services can be reached world-wide with practical tools like search machines, web-based email or internet shopping that simplify our daily life. Parts of our social life is shifted to online platforms for socializing, discussion or gaming. Also modern, globalized business strongly relies on fast communication, remote computing with "thin clients" or "cloud computing" and access to central servers and data-banks (data storage) [4]. Interestingly, consumer internet protocol (IP) traffic for entertainment will surpass business IP traffic driven by video applications like clip sharing and video on demand [5]. The world-wide web has become a world-wide billion dollar business. A few remote servers and computing centers allow

to provide services and applications to millions of customers anywhere, anytime, which makes this business so attractive. Throughout the last years this caused an exponential growth of IP traffic.

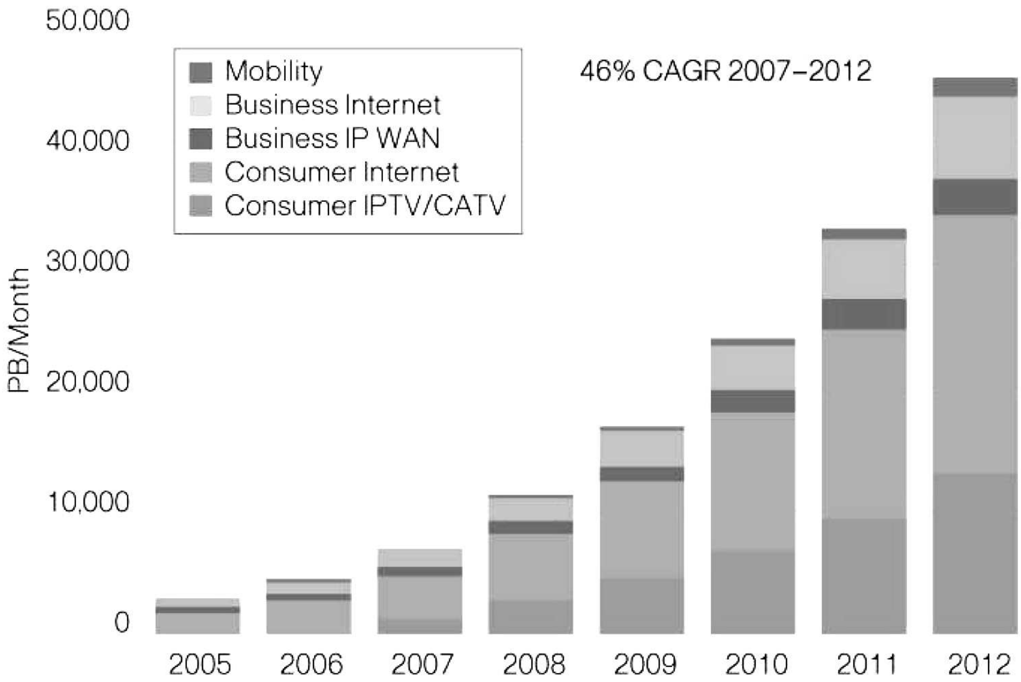

Figure 1.1: Components of consumer internet traffic growth [6].

It is clear that the exponential growth of the IP traffic requires an exponential growth of capacity in the optical back-bone network. This does not necessarily mean an exponential increase of newly installed optical transmission links. The limited bandwidth can be partly overcome by increasing the spectral efficiency with advanced higher-order modulation formats and by flexible path switching in a reconfigurable optical network. The first requires richer signal constellations and a more dense channel spacing, the second requires more robust transmission with large tolerance to optical impairments, which is contradictory to the first point. The most cost-efficient solution to this problem is to introduce digital signal processing (DSP)[1] in the transponder to improve the signal quality prior to the decision by means of equalization. While for decades, optical communication has been dominated by exploring the physics of optical effects to design optical components and devices, DSP opens up a whole new world of possibilities and challenges.

1.1 Motivation

Prerequisite to DSP at the receiver is the conversion of the optical signal into the electrical digital domain, which requires an optical front-end and fast analog/digital conversion (ADC).

[1]Throughout this thesis, the term *DSP* refers to the method of digital signal processing independent of the implementation of the DSP algorithms in a digital signal processor, a micro controller or an application specific integrated circuit (ASIC)

Secondary, the digital information has to be processed by a fast chip-set. Comparing data rates of electrical wireless and copper-wire systems in the range of 10 to 100 Mbit/s, data rates of optical systems are 1000 times higher in the range of 10 to 100 Gbit/s (in each channel). While DSP for electrical communication systems can be tested and realized by various ways on a field-programmable gate array (FPGA), by a micro controller, by a digital signal processor or by an application-specific integrated circuit (ASIC), the high data rates of optical communication systems limit implementation of comprehensive DSP to a high speed full customized ASIC with a large degree of parallelization. In this respect, DSP becomes the major bottleneck in optical communication strongly limiting the implementation complexity.
On the other hand, DSP allows to employ all algorithms and principles known from wireless and copper-wire systems to provide powerful data recovery and equalization. This enables optical path switching with adaptive channel acquisition and tracking of time varying channel distortions for equalization. It is common consensus in the optical communication industry that the benefit of DSP outweighs the drawback of the electrical bottleneck. Thus, throughout the last years, the optical communication industry has driven vendors of electronic key technologies to push their equipment closer to the physical limits of high speed electronics.

Simply speaking, an optical transmission link is a digital source transmitting information via electrical and optical channel elements to the digital sink. In principle, this allows to adapt all methods known from electrical communication to optical communication. However, especially the demodulation of the optical signal from the transmission band into the electrical base band plays an important role. It is the architecture of the *optical front-end* that defines three major classes of optical communication systems: Direct detection, differential detection and coherent detection.
While direct detection systems prove a low implementation complexity of the modulation and demodulation stage, they inherit a strongly nonlinear transfer function by the square-law characteristics of the photo diode, which requires sophisticated DSP algorithms for equalization. In addition, the phase information of the optical signal is lost. Direct detection systems are the typical representative for 10 Gbit/s transmission with intensity modulation, e.g. on/off keying (OOK). The major task of DSP is to compensate for inter-symbol-interference (ISI) induced by residual chromatic dispersion (CD) and polarization-mode dispersion (PMD). The latter also requires adaptive tracking of this time-varying channel impairment. The nonlinear channel transfer function with non-Gaussian noise statistics after square-law detection requires equalization by means of maximum-likelihood sequence estimation (MLSE) with special attention to the metrics.
Differential detection systems apply a more complex optical front-end at the receiver, which allows to transfer the optical phase information into the electrical domain. This enables phase modulation with binary and quaternary signal constellations, e.g. differential binary phase-shift keying (DBPSK) or differential quaternary phase-shift keying (DQPSK). The improvement of those modulation formats in terms of signal-to-noise ratio (SNR) makes data rates up to 40 Gbit/s feasible. Still, the nonlinear channel and the non-Gaussian signal statistics after detection require careful consideration.
Given the same data rate, from direct detection to differential detection and coherent detection the implementation complexity of the optical and electrical front-end is strongly increased. At the same time the linear transfer function of the coherent optical front-end maintains the properties of the received signal with respect to amplitude, phase and polarization and a digital

representation of the optical field becomes available in the electrical domain. This enables simple finite impulse response (FIR) filters to compensate for large values of CD and PMD, which allows uncompensated transmission over thousands of kilometers. The pre-dominant linear optical channel with Gaussian noise statistics can now be (almost) fully compensated. The powerful channel equalization by DSP suggests the use of polarization-multiplexing. Combining polarization-multiplexing with multi-level modulation bit rates of 100 Gbit/s and beyond can be enabled, while the Baud rate stays as low as 27.5 GBaud, which can be still processed electronically. In contrast to direct detection and differential detection systems, now fiber nonlinearities limit the signal quality, which require sophisticated compensation algorithms. Furthermore, processing of such large amounts of data for equalization is the main limitation for commercial applications.
The characteristics of the optical-to-electrical conversion, the optical nonlinear impairments and the limited implementation complexity for high speed processing make clear that a simple "copy and paste" of techniques and algorithms from wireless and copper-wire systems is not feasible. Instead, a careful selection of methods with adaptation to the individual requirements and conditions in optical communication is necessary. More often, "modifications" of techniques and algorithms rather look like an original new solution such that ideas from optical communication will penetrate into electrical communication systems in the future.

Reconfigurable optical networks with higher-order modulation formats and adaptive equalization imply a manyfold potential for failure. It is clear that the more hardware building blocks are included in the path of the information with several stages of analog and digital signal processing, the probability of different errors in the system increases. At the same time, the increased capacity demand makes systems more sensitive to distortions. To avoid the loss of large amounts of data due to a fatal error during transmission, it is vital to monitor the physical properties of the signal. Optical performance monitoring (OPM) analyzes short term and long term variations of the signal quality. The short-term analysis of the signal can provide information for the digital equalizer, the system margin can be estimated and possible routes for paths switching can be obtained. Furthermore, the influence of typical day-cycle temperature changes and mechanical vibrations influenced by human interaction can be analyzed. From the long-term evaluations, the influence of device aging and the quality of the optical fiber can be estimated. All together, the whole network can be analyzed for potential weaknesses or possible upgrades. Preferably, OPM does not require to interrupt the signal path and is low-cost in terms of capital and operational expenses.
Inherently, the receiver based adaptive equalizer applies monitoring of optical and electrical distortions to converge to the optimum equalization properties. Therefore, we can extract this information to analyze the signal statistics and to deduce the properties of the single channel impairments like residual chromatic dispersion, polarization-mode dispersion or noise.

1.2 Scope and Framework

The scope of this thesis is to bridge the gap between the physics of optical communication and electrical digital communication. The transmission characteristics of communication systems with analog and digital, optical and electrical components are considered. In particular, the signal properties with deterministic and statistic characteristics and their evolution throughout

the transmission line are described. In that perspective only the physical layer of the IP traffic is included. Source and channel coding are not considered. Typically, blocks for forward error correction (FEC) frame the system under observation such that the raw bit error rate (BER) that can be corrected to error-free transmission, also known as *FEC limit*, is taken as basis for performance evaluation and comparison of different systems.
For 10 Gbit/s and 40 Gbit/s the performance of several modulation formats with and without digital equalization is presented. From the signal analysis, different data recovery and equalization strategies are discussed in terms of performance and implementation complexity. Systems employing direct detection and differential detection front-ends with their strongly nonlinear receiver characteristics require maximum-likelihood sequence detection. The signal statistics for typical receiver architectures of those systems is analyzed and several realizations of the Viterbi equalizer are deduced and compared with each other. Several architectures targeting best performance and an efficient implementation have been developed by the author, in particular for receivers with optical differential detection front-end and quaternary modulation. Special consideration is given to implementation constraints of the digital equalizer and the according performance penalties.
For 100 Gbit/s only coherent detection systems with DSP for data recovery are evaluated, including timing recovery, linear distortion compensation by means of finite impulse response (FIR) filters and carrier phase recovery. As coherent detection systems typically employ polarization multiplex and a free-running local oscillator for demodulation, DSP is always required somehow to obtain a reasonable signal prior to the decision. For this class of systems, the implementation complexity becomes a critical issue. Focus is given to the equalization of all linear channel impairments like chromatic dispersion and all polarization effects. Methods for time-domain filter implementation are presented and compared including the channel acquisition during initialization of the filter transfer function. Additionally, frequency-domain filtering has been originally investigated by the author including and a robust and precise initialization of residual dispersion compensation filters.
Finally, methods for OPM from the equalizer properties of maximum-likelihood sequence detectors in direct detection systems and of FIR filters in coherent detection systems are discussed. Therefore, the author developed a method to evaluate the metrics of the Viterbi equalizer and estimate different deterministic and statistic channel parameters. Similarly, the FIR tap coefficients provide detailed information about all linear channel impairments. A systematic approach how to estimate the contributions of several combined channel impairments is the original work of the author. The reliability of the proposed channel parameter estimations is validated based on simulated data and measured data.

All simulation results are obtained from non-commercial tools developed and implemented at the “Institut für Informationstechnik” including the simulation of the optical channel and the different equalizer implementations. Captured data for off-line processing has been measured in the Nokia Siemens Networks (NSN, formerly Siemens) laboratories in cooperation with NSN and the University of Eindhoven. If not cited otherwise, the material presented is original based on the author’s research.
Wherever possible, closed form expressions are preferred. However, it should be mentioned that due to the lack of a closed form analytical channel model it is difficult to provide theoretical performance bounds, especially in case of direct and differential detection systems. Only in the limit of certain assumptions and by use of appropriate approximations optimum

solutions for equalization and data recovery can be provided. Instead, the focus of this work is to present practical methods of DSP with feasible implementation complexity for near future implementation.

1.3 Overview

This thesis is organized in three main parts, the introduction to the optical network including the optical channel and its various impairments (chapter 2), the investigation of different equalizer concepts and architectures for data recovery (chapter 3) and the evaluation of methods for OPM based on the properties of digital equalizers (chapter 4).

The first part of the thesis covers the conditions of the optical transmission system. The architecture of the optical network with its fiber transmission links is introduced (section 2.1). The most important deterministic linear and nonlinear channel distortions are described in detail (section 2.2) and an optical channel model including all individual impairments is provided (section 2.3). The section on optical transmission systems includes the generation of the signal at the transmitter, the signal properties of different modulation formats and the receiver architecture for direct detection, differential detection and coherent detection systems (section 2.4). All modulation formats are compared with each other in terms of hardware requirement and their baseline performance. Special attention is given to the noise process and the evolution of the noise statistics for different demodulation strategies performed by each receiver described in the previous section (section 2.5).

In the main part, the two equalization strategies based on MLSE (section 3.1) and linear FIR filtering (section 3.3) are investigated next to a short section on multi-symbol phase estimation (MSPE) (section 3.2).
The standard implementation of the Viterbi algorithm to realize MLSE is initially provided (section 3.1.1) followed by the performance analysis for different receiver constellations, for various modulation formats, for certain channel conditions and for selected implementation constraints (section 3.1.2). Special attention is given to equalization of differential detection systems with binary and quaternary phase-shift keying (section 3.1.3). Finally, reduced complexity implementations are proposed and the trade-off in terms of performance degradation is discussed (section 3.1.4). In a short conclusion all results are summarized and compared with each other (section 3.1.5).
The section on MLSE is followed by MSPE, a technique to recover the OSNR penalty induced by noise enhancement of the differential detection receiver (section 3.2). The concept of MSPE is briefly introduced and the potential of this method is discussed.
As coherent demodulation linearly transfers the properties of the optical field into the electrical domain, linear equalization by means of FIR filters is sufficient to compensate for the predominant linear optical channel (section 3.3). According methods for data recovery include equalization and synchronization (section 3.3.1). In order to stabilize the filter adaptation, synchronization of the sampling phase and frequency by timing recovery is necessary, as well as