Thesis for the Degree of Licentiate of Engineering

High-throughput power-efficient DSP for fiber-optic communication systems

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Abstract

Communication networks are a vital backbone of the modern society. Power dissipation of optical communication links and digital signal processing (DSP) subsystems for these links are a major concern as throughput requirements increase, and the number of deployed systems grows. We are approaching fundamental integrated-circuit scaling limits quickly, and it is thus no longer possible to assume that feature-size scaling will enable implementation of ever more complex algorithms. Therefore, approaching DSP from an implementation perspective, and designing low-power high-performance algorithms will become increasingly more important.

This thesis considers power- and energy-efficiency improvements in real-time implementation of DSP algorithms. High-throughput parallel implementations of algorithms are presented and improvements in currently-employed major power-dissipating DSP subsystems (chromatic dispersion compensation and dynamic equalization) are considered. Implementation-aware design of advanced algorithms for long-haul transmission systems is considered. This thesis also considers possible power-reduction in short-haul systems through introduction of forward error correction.

Keywords: Application Specific Integrated Circuits, Communication Systems, Digital Signal Processing, Fiber Optic Communication, Nonlinear Impairment Mitigation, Forward Error Correction

Publications

This thesis is based on the work contained in the following papers:

[A] **Christoffer Fougstedt**, Alireza Sheikh, Pontus Johannisson, and Per Larsson-Edefors. "Filter Implementation for Power-Efficient Chromatic Dispersion Compensation", *Submitted to IEEE Trans. Circuits Syst. I, Reg. Papers*,

[B] **Christoffer Fougstedt**, Pontus Johannisson, Lars Svensson, and Per Larsson-Edefors. "Dynamic Equalizer Power Dissipation Optimization", *Optical Fiber Communications Conference, OFC 2016*,

[C] **Christoffer Fougstedt**, Mikael Mazur, Lars Svensson, Henrik Eliasson, Magnus Karlsson, and Per Larsson-Edefors. "Time-Domain Digital Back Propagation: Algorithm and Finite-Precision Implementation Aspects", *Optical Fiber Communications Conference, OFC 2017*,

[D] **Christoffer Fougstedt**, Lars Svensson, Mikael Mazur, Magnus Karlsson, and Per Larsson-Edefors. "Finite-Precision Optimization of Time-Domain Digital Back Propagation by Inter-Symbol Interference Minimization", *Proceedings of 43rd European Conference and Exhibition on Optical Communications, ECOC 2017*,

[E] **Christoffer Fougstedt**, Krzysztof Szczerba and Per Larsson-Edefors. "Low-Power Low-Latency BCH Decoders for Energy-Efficient Optical Interconnects", *Journal of Lightwave Technology*, **35**, 23, 5210–5207, Dec 2017.

Related work by the author (not included in this thesis):

[F] **Christoffer Fougstedt**, Alireza Sheikh, Pontus Johannisson, Alexandre Graell i Amat, and Per Larsson-Edefors. "Power-Efficient Time-Domain Dispersion Compensation Using Optimized FIR Filter Implementation", *Signal Processing in Photonics Communications, SPPCom 2015*, SpT3D.3, Jul 2015.

[G] Alireza Sheikh, **Christoffer Fougstedt**, Alexandre Graell i Amat, Pontus Johannisson, Per Larsson-Edefors, and Magnus Karlsson. "Dispersion Compensation Filter Design Optimized for Robustness and Power Efficiency", *Signal Processing in Photonics Communications, SPPCom 2015*, SpT3D.2, Jul 2015.

[H] Krzysztof Szczerba, **Christoffer Fougstedt**, Per Larsson-Edefors, Petter Westbergh, Alexandre Graell i Amat, Lars Svensson, Magnus Karlsson, Anders Larsson, and Peter Andrekson. "Impact of Forward Error Correction on Energy Consumption of VCSEL-based Transmitters", *41st European Conference on Optical Communication, ECOC 2015*, Sep 2015.

[I] Alireza Sheikh, **Christoffer Fougstedt**, Alexandre Graell i Amat, Pontus Johannisson, Per Larsson-Edefors, and Magnus Karlsson. "Dispersion Compensation FIR Filter with Improved Robustness to Coefficient Quantization Error", *Journal of Lightwave Technology*, **34**, 22, 5110–5117, Aug 2016.

[J] Lars Lundberg, **Christoffer Fougstedt**, Per Larsson-Edefors, Peter Andrekson, and Magnus Karlsson. "Power Consumption of a Minimal-DSP Coherent Link with a Polarization Multiplexed Pilot-Tone", *42nd European Conference on Optical Communication, ECOC 2016*, Sep 2016.

Contents

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Acronyms

ADC	analog-to-digital converter
ASIC	application-specific integrated circuit
AWGN	additive white gaussian noise
BCH	Bose-Chaudhuri-Hocquenghem
BD	bounded-distance
BER	bit-error rate
CD	chromatic dispersion
CMA	constant modulus algorithm
CMOS	complimentary metal oxide semiconductor
DBP	digital back propagation
DCF	dispersion-compensating fiber
DSP	digital signal processing
EDFA	erbium-doped fiber amplifier
FD-SOI	fully-depleted silicon-on-insulator
FEC	forward error correction
FFT	fast Fourier transform
FIR	finite impulse response
HDL	hardware description language
HPC	high-performance computing
IFFT	inverse fast Fourier transform
IIR	infinite impulse response
IS	impulse response
ISI	inter-symbol interference
KES	key-equation solver
LFSR	linear-feedback shift register
LLR	log-likelihood ratio
LS-CO	least-squares constrained-optimization
LS-FB	least-squares full-band
LUT	lookup table

MD	minimum-distance
MIMO	multiple-input multiple-output
OMA	optical modulation amplitude
OOK	on-off keying
OS	overlap-save
PAM	pulse-amplitude modulation
PM	polarization multiplexed
PMD	polarization-mode dispersion
QAM	quadrature-amplitude modulation
QPSK	quadrature phase-shift keying
RRC	root-raised cosine
RS	reed-solomon
SIR	signal-to-interference ratio
SPS, SaPS	samples per symbol
SQNR	signal-to-quantization-noise ratio
SSFM	split-step Fourier method
StPS	steps per span
TD	time-domain
VCSEL	vertical-cavity surface-emitting laser
VHDL	very high speed integrated circuit hardware description language

Chapter 1

Introduction

Fiber optic communication systems are a vital backbone of the interconnected world we live in today. High-throughput intercontinental communication has effectively shrunken our world, and has resulted in a rapidly increasing demand for higher communication bandwidths. While the optical fiber channel does allow for a tremendous bandwidth, increase in bandwidth inflicts stringent requirements on digital signal processing (DSP) implementation [1]. At the same time, the fundamental limits of integrated-circuit scaling appear to be just around the corner [2], and one can no longer count on feature-size scaling to allow for implementation of more advanced algorithms. Approaching algorithm design from a joint optical and application specific integrated circuit (ASIC) implementation perspective will therefore become increasingly more important.

The development of fiber optic communication systems can be divided into several eras, in each of which which a significant breakthrough has spearheaded research and development. Important breakthroughs include, but are not limited to: the invention of the low-loss fiber [3], which enabled long-distance optical communication and sparked considerable research interest in optical communication systems; the development of communication over low-loss single-mode fiber [4]; the development of the erbium-doped fiber amplifier [5]; and one of the most recent, and important to this thesis, breakthroughs, the development of DSP-based coherent intradyne systems [6]. Intradyne systems replace the complex optical phase-locked loop with a free-running laser and DSP-based processing of the received signal, simplifying the optical hardware. The emergence of DSP-based coherent fiber-optic communication systems has enabled effective receiver-side compensation of transmission impairments [7], since coherent detection allows for linear capture of the full field information, i.e. both amplitude and phase of the received baseband signal after down-converting with a local-oscillator laser.

In this work, we differentiate between DSP-based coherent systems, mainly of interest in longer transmission distances and therefore here referred to as *long-haul*, and intensity-modulated direct detection systems, nowadays primarily of interest in shorter optical links such as datacenter interconnects and thus here referred to as *short-haul*. While the line between short-haul and long-haul is increasingly blurred with increasing interest in coherent technologies for short-distance applications [1, 8], this distinction remains useful here as these systems have very different requirements. Since transmission distance and throughput is of utmost concern for long-haul systems, the corresponding receivers are more limited in terms of power due to packing density; on the other hand, short-haul systems are energy- and latency-limited due to the sheer amount of links in a datacenter.

An important aspect of long-haul optical communication systems is the implementation of transmission impairment compensation, commonly performed using DSP techniques [9, 10], and implementation of high-throughput forward error correction (FEC) [11]. Off-line DSP is commonly employed in experiments, and many algorithms have been proposed in this context. However, real-time implementation of DSP in an ASIC poses challenges which are often not considered in algorithms derived from a purely theoretical perspective. Limitations in clock frequency and maximum power dissipation impose severe obstacles in regard to real-time ASIC implementation. Real-time DSP for optical communication systems requires extensive parallelization, pipelining, and limited-precision arithmetic in order to cope with the extreme information throughput, which will significantly impact performance.

While long-haul systems can exploit advanced DSP techniques, short-haul direct-detect systems generally use rather limited digital processing of signals due to power dissipation and latency concerns, with forward error correction applied more rarely. This thesis considers possible improvements of power and energy efficiency of digital subsystems in long-haul coherent fiber optic communication systems, and utilizing improvements to allow for more advanced digital signal processing. We also consider the possibility of adding low-complexity error correction in short-haul systems, in order to reduce over-all power dissipation.

1.1 Thesis Outline

The thesis is structured as follows. The first chapter provides a brief fundamental overview of fiber optic communication, digital signal processing, and corresponding implementation aspects, intended as a short introduction to either field. It is assumed here that the reader has fundamental knowledge of either optical communication or digital signal processing, but not necessarily both. This chapter also provides an outline to the context of the work, and presents the problem statement. The next chapter provides a summary of contributions in the following included papers.

Chapter 2

Background

Joint consideration of fiber-optic communication and ASIC implementation aspects is relatively sparsely covered in literature. This chapter provides a fundamental technical background, intended to serve as an introduction to fiber optics and to circuits and systems.This chapter also introduces the problem statement of the thesis.

2.1 The Fiber-Optic Communication Channel

The basic idea of digital optical communication can be boiled down to communicating binary data through a fiber, with light as the carrier. Traditionally, bits are encoded on the intensity of the light, i.e. a one is represented as high intensity and a zero is represented as low intensity, and directly detected using a photodiode. Modern coherent systems operate on a more advanced principle: data are carried on both phase and amplitude of a pulse, allowing for multiple bits to be transmitted using a single symbol. Phase and amplitude are commonly represented geometrically in the complex plane using a *constellation diagram* where each symbol is represented as a complex number. Constellation diagrams for on/off-keying (OOK) and quadrature phase shift keying (QPSK) are shown in Fig. 2.1.

An example of a typical frontend for a DSP-based coherent receiver is shown in Fig. 2.2. The received signal is split into X and Y polarizations, which are mixed with a local oscillator laser. The resulting in-phase and quadrature signals are detected and A/D converted for further processing in the receiver DSP chain. The local oscillator is not phase-locked to the received signal, and can also have a frequency offset

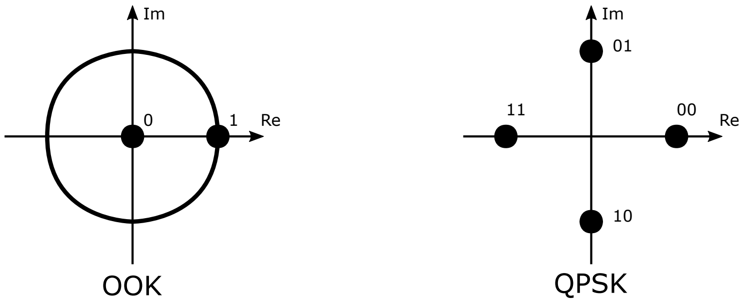

Figure 2.1: Constellation diagrams for OOK and QPSK. OOK is phase-agnostic and only dependent on the signal level, while QPSK is the opposite.

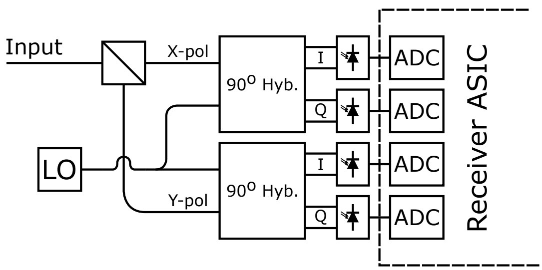

Figure 2.2: Block diagram showing a typical coherent receiver frontend.

with respect to the transmitted signal, both of which are compensated for in the receiver DSP chain.

Fig. 2.3 shows a simplified DSP-chain of a coherent receiver, in which impairments in the sampled baseband signal are compensated for, and finally demapped into bits or log-likelihood ratios (LLR) depending on whether a hard-decision or soft-decision FEC is employed. Two major blocks in terms of power dissipation is the chromatic dispersion (CD) compensation and the dynamic equalizer [9, 11]; CD compensation consists of a very long static filter while the dynamic equalizer is a moderately long filter with dynamic coefficient updating.

The fiber-optic communication channel has several peculiar properties. The refraction index of a fiber is dependent on both wavelength and signal power, and the channel is thus nonlinear. The refractive index of optical fibers varies with the state of polarization and with mechanical stress, resulting in a linear time-varying response. These effects are mainly important at long transmission distances, and this section is

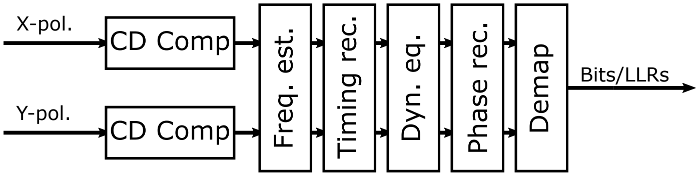

Figure 2.3: Block diagram of a coherent receiver DSP-chain.

thus primarily oriented towards channels in longer links with coherent detection.

If we neglect polarization effects, the complex envelope of the propagating signal in an optical fiber can be described using the nonlinear Schrödinger equation [12],

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})A = \left(-\frac{j\beta_2}{2}\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2}\right)A + j\gamma\,|A|^2\,A, \qquad (2.1)$$

where β_2 is the group-velocity dispersion parameter, α is the attenuation, and γ is the nonlinear parameter. This equation can be split into two parts: linear impairments, $\hat{D}$, and nonlinear impairments $\hat{N}$. Fiber-optic communication systems often operate in the pseudo-linear regime; signal input power is limited to reduce the impact of nonlinearities, and the resulting impairments can, in the case of no in-line optical dispersion compensation, be considered Gaussian-noise-like by the receiver [13]. In this case, we compensate for $\hat{D}$ using a fixed linear filter and neglect any nonlinear memory effects. Increased transmission distance and/or increased spectral efficiency can be achieved if nonlinear distortion is compensated for, instead of treated as additive noise, and nonlinear compensation algorithms, such as digital back propagation (DBP) [12] and Volterra-based nonlinear equalization [14], have therefore received significant attention recently.

So far, we have only considered single-polarization transmission and neglected polarization-dependent effects. In a practical coherent system, data are transmitted on both X and Y polarizations of the carrier wave, thus giving a doubling of the spectral efficiency in comparison to single-polarization transmission. However, polarization-mode dispersion (PMD) results in significant pulse-broadening, and the randomly varying birefringence of the fiber results in dynamic non-deterministic behavior. The received polarization-split signal thus consists of a superposition of the dispersed X- and Y-polarizations. The overall system can be modeled as a 2×2 multiple-input, multiple-output (MIMO) system. An approximation of the inverse response of the system can be written as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{11} & \mathbf{h}_{12} \\ \mathbf{h}_{21} & \mathbf{h}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \tag{2.2}$$

where $\mathbf{h}_{ij}$ is the dynamically-changing MIMO impulse response. Dynamic equalization is thus required to compensate for these time-variant effects, and to demultiplex the received signal. Paper [B] considers the well-known blind constant-modulus algorithm (CMA) [7, 15], in which the circular placement of constellation points in QPSK is exploited to estimate the impulse response error and dynamically update the estimated inverse transfer matrix of the fiber.

A major limiting factor in fiber-optic communication systems is noise. The most significant noise source in long-haul systems is amplified spontaneous noise from the in-line optical amplifiers, which ultimately limits transmission performance [16, Ch. 7], in contrast to short-haul direct-detect systems where thermal receiver noise commonly dominates [16, Ch. 4]. Noise causes erroneous decisions in the receiver and thus results in incorrectly received data. Signal-to-noise ratio may be improved by increasing the system input power, however, input power is often limited. Another option is to employ forward error correction (FEC), pioneered by R. W. Hamming [17], and C. E. Shannon who gave rise to the field of information theory [18]. The basic principle of FEC is as follows: redundant bits are added by an FEC encoder in the transmitter, the received data is then decoded, and errors are corrected. While the codes introduced by Hamming (and the later generalization, BCH codes [19, 20]) are decoded by relatively simple algebraic approaches, modern high-performance codes are more complex and most often operate using iterative approaches. Codes of interest to fiber optics include, but are not limited to: staircase codes [21], product codes [22, 23] and low-density parity-check codes [24, 25].

2.2 DSP Implementation Aspects

The immense throughput requirements in today's and future fiber-optic communication systems impose stringent requirements on both power dissipation and processing speed. Since modern fiber-optic systems operate at throughputs higher than 100 Gb/s, serial, sample-wise processing is clearly not feasible to implement. In order to cope with these require-

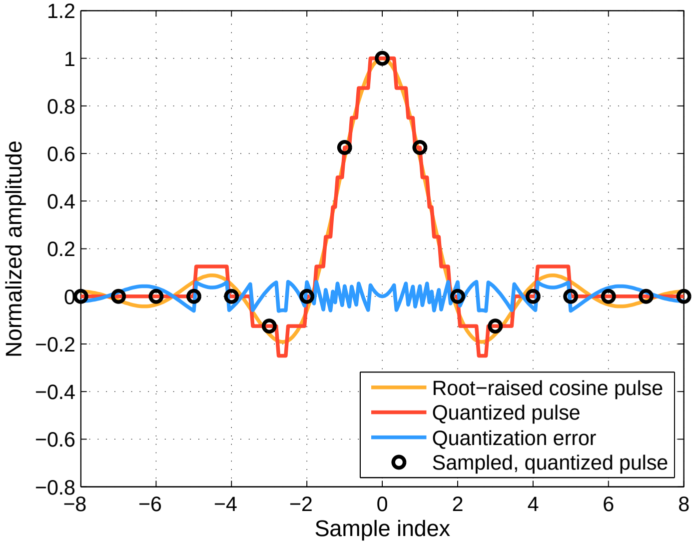

Figure 2.4: Amplitude and time discretization of a root-raised cosine pulse.

ments, highly-parallel architectures implemented with limited-resolution arithmetic are required [1]. In this section, we will discuss quantization, parallelization, and pipelining of DSP algorithms.

While the signal waveforms in a fiber are continuous in time and amplitude, the analog-to-digital converted signal is discrete in both amplitude and time. Given a band-limited signal, and a sampling frequency which fulfills the Nyquist criterion, time discretization does not result in any information loss. Amplitude quantization of the received continuous signal, on the other hand, does incur a loss of information. Fig. 2.4 illustrates amplitude and time discretization of a root-raised cosine pulse, and the resulting quantization error which may, if large in comparison to other error and noise sources, result in a bit-error rate (BER) penalty. Achieving high-order modulation format transmission without excessive BER penalty puts stringent requirements on A/D-converters, requiring very high sampling rates at moderate resolutions (6+ bits) [26].

Due to constraints in processing power, DSP algorithms for optical receivers need to be implemented using limited-resolution arithmetic. This gives rise to an additional trade-off: while increased resolution may give better performance in terms of BER, it may also contribute to a significant increase in hardware complexity and power dissipation [27].

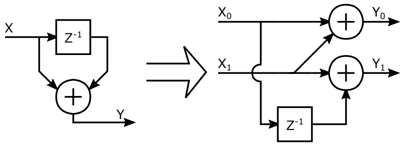

Figure 2.5: Block diagram describing parallelization of a simple moving average.

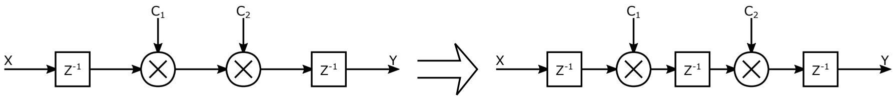

Figure 2.6: Block diagram describing pipelining of a cascade of multiplications.

It is important to differentiate between quantization of signals, and quantization of filter coefficients, when implementing filters. The former gives rise to loss of information, while the latter gives a frequency-response error. Given a static filter, frequency-response errors are known at design time and can possibly be accounted for. However, internal rounding is in many cases required to constrain signal word-lengths; each rounding step incurs a quantization error, and there is thus a trade-off between performance and power dissipation.

The maximum processing rate of DSP subsystems is limited by cycles in the dataflow graph [28], giving a hard upper limit which is referred to as the iteration bound. Given a strictly feed-forward system such as an finite impulse response (FIR) filter, parallel-processing throughput, given no latency and complexity limitations, is not limited at circuit level since feed-forward systems do not contain any loops in their corresponding dataflow graphs. Fig. 2.5 describes parallel implementation of a two-parallel two-sample moving average filter; the same principle can easily be applied to a general FIR filter.

While long critical paths clearly can affect maximum clock rate, they can also have an impact on power. Propagation delay in the implemented circuitry results in glitches, i.e. short unnecessary toggles of signals which increase power dissipation [29]. The resulting glitches may increase the power dissipation of subsequent units, due to the increase in input toggling rate. Pipelining can be used to mitigate both of these issues; by splitting paths with registers, the path-delay and possible glitch propagation may be reduced. Fig. 2.6 illustrates the pipelining principle. The datapath is split into two cycles, decreasing the overall critical timing path length. Maximum clock frequency is increased at the expense of increasing the number of registers and the cycle latency of the datapath.

While both pipelining and parallellization easily can be implemented in feed-forward algorithms such as FIR-based chromatic dispersion compensation or digital back propagation, adaptive algorithms with feedback loops pose challenges from an implementation perspective due to limitations in achievable processing rate. For example, a dynamic equalizer is commonly implemented as an FIR filter with on-the-fly updating of coefficient weights. This feedback loop limits the achievable throughput of the non-modified sample-based coefficient update. By updating the coefficients block-wise, instead of sample-wise, this requirement can be relaxed, albeit at a reduction in maximum effective update rate.

2.3 Problem Statement

The demand for bandwidth in communication systems is rapidly increasing, pushing the envelope of the achievable limits with currently employed techniques and DSP algorithms in optical communication systems [10, 30, 31]. DSP is estimated to contribute to a significant part of the overall power dissipation of current coherent links [32], and power-optimized DSP implementations and algorithms can thus significantly reduce link power dissipation. In addition, power-dissipation optimization may allow for deployment of more advanced processing and possibly a significant increase in spectral efficiency and/or transmission reach.

This thesis considers possible energy-efficiency improvement in DSP subsystems and subcomponents, and considers exploiting gained implementation knowledge to design advanced algorithms for long-haul systems. CD compensation and dynamic equalization are among the most significant causes of power dissipation in receiver ASICs [9, 11], and are estimated to be significant contributors to the overall link power dissipation [32], and are thus of focus in this work. This thesis also considers the possibility of reducing energy-dissipation by introducing more advanced processing in short-haul systems.

Chapter 3

Summary of Contributions

In this work, power dissipation in DSP for optical communication is approached from a joint algorithm-implementation design perspective. Algorithms are implemented and investigated, and results are utilized in optimizing the algorithms and in the design of novel algorithms suitable for high-throughput resolution-limited ASIC implementation.

In paper [A], implementation of CD compensation in time-domain and frequency-domain is considered. It is shown that complexity-based metrics are misleading when comparing different implementation structures. Transmission distances in which time-domain compensation is potentially more energy efficient are investigated, and shown to be in the range of the linear step-sizes most often considered in digital back propagation algorithms.

A parallel-processing CMA-based dynamic MIMO equalizer is implemented and investigated in paper [B]. It is shown that, despite similar arithmetic complexity to the FIR filtering subsystem, coefficient-update calculation is the major subsystem in terms of power dissipation. Simplification of the updating algorithm by reducing the set of samples which are averaged over in the update calculation, and removing corresponding hardware (referred to as *sample pruning*), is shown to achieve significant reduction in power dissipation, while still retaining fast polarization-tracking capability.

The design of nonlinear impairment compensation is approached with the knowledge and experience from the work included in paper [A], resulting in the Time Domain DBP algorithm presented in paper [C]. In TD-DBP, each linear step is performed in time-domain, avoiding the requirement of fixed-point fast Fourier transformation and enabling the use of effective time-domain filter techniques for the linear steps of the algorithm. It is shown that TD-DBP can achieve good performance at moderate resolutions, although coefficient-quantization induced correlated errors pose a limitation, as demonstrated by utilizing dithering to break correlations and improving performance. Simplification of the nonlinear step is also investigated, and a simple first-order Taylor expansion of the nonlinear step is shown to give sufficient performance in the considered system.

Fixed-point TD-DBP is further investigated and improved in paper [D], where effective co-optimization of filter pairs is shown to enable floating-point performance at moderate arithmetic resolutions. A novel cost metric is introduced, symbol-to-interference ratio (SIR), which is shown to correlate well with overall system performance, enabling a fast fixed-point search algorithm for effective optimization of step-pairs.

In paper [E], employment of fast, low-complexity, low-latency parallel non-iterative BCH decoder implementations is shown to enable power-dissipation reduction in vertical-cavity surface-emitting laser (VCSEL)-based optical interconnects operating with highly efficient CMOS drivers, even considering the power dissipation of encoders and decoders. While the paper considers the short-haul case, the decoders are also suitable for employment as component decoders in more advanced FEC algorithms.

In summary, this thesis approaches power dissipation reduction in optical communication links with a focus on DSP implementation aspects and algorithm design. The thesis covers improvements of currently-employed DSP subsystems, implementation-aware design of more advanced impairment compensation, and possible employment of FEC as an enabler for energy-dissipation reduction in highly-constrained short-haul links.

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