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ELECTRONIC AND COMPUTER ENGINEERING

EE515 Real-Time DSP: Assignment 1

The role of Digital Signal Processing in Optical Communications Systems

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The role of Digital Signal Processing in Optical Communications Systems

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Abstract

Optical Communications systems have become more ubiquitous over the past number of years, more recently being a choice for internet data traffic for their high data transfer rates.

This review paper acts as an introduction to some of the basic concepts of optical communications systems, while also introducing some cutting-edge, state-of-the-art advances in optical communication system DSP techniques.

As an introduction, a brief description of the technology is given to provide the reader with a basic understanding of the fundamental principles behind the technology, the physics, and a generalised overview of a full optical communications system.

Advanced DSP techniques such as probabilistic shaping, coherent digital optical receiver systems, and machine learning noise removal and signal recovery techniques will be discussed in detail, aiming to give insight into the current state of advances in digital signal processing with regards to optical communication systems.

Contents

1 Introduction

Modern optical communications systems have been in use since the 1960's, with the first commercial usage in 1977 in California, where telephone traffic was transmit at a rate of 6Mbps[1]. Since this time, systems have been implemented to transmit data for applications such as telephony, cable television, and internet data.

This literature review will present a history of the usage and implementations of optical communications systems, and an overview of the applications of the technology. As an introduction to this technology, a comprehensive background will be given, explaining the physics behind optical communications systems, an overview of an optical communications system, and some of the advantages of the technology.

Following this, there is a review of the current "state of the art" within the field, as it applies to digital signal processing, and the modulation algorithms implemented. These advances in the field will be reviewed in terms of their benefits to the technology as a whole.

2 Background

In order to understand the "state of the art" within the field of optical communications systems with relation to digital signal processing, it is necessary to have a level of understanding of its background. This section will introduce the basic physics concepts, a generalised overview of a typical optical communications system, along with the advantages an optical communication system offers.

2.1 The Physics of Optical Communications

Optical communications systems utilise light, typically provided by laser diodes, or LED's, in order to transmit information along an optical fiber cable. The optics principle of total internal reflection is utilised for the purpose of transmission. When the incident angle of the light in the cable is greater than the critical angle at the "core-to-cladding interface"[1], the light will reflect back into the core. This repeats throughout the fibers core, passing the light from source to destination.

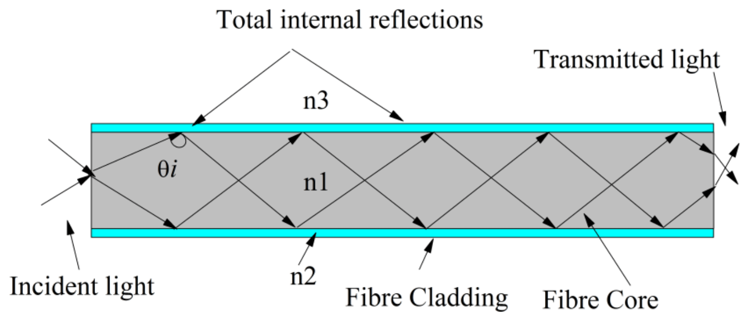

Figure 1: Total Internal Reflection within an Optical Fiber Cable[2]

Optical communications systems utilise light in the infrared spectrum to pass information along a cable. The wavelength of the light in this spectrum is in the order of thousands of micrometers (μm) in length, with frequencies in the order of hundreds of terahertz ($\approx 10^{13} Hz$). These high-frequency, low-wavelength carrier signals result in very high bandwidths, and very high data transfer rates[3].

The directionality of laser light within these systems allows for greater efficiency, as energy is not required for the filtering or correction of divergent beams[3].

2.2 Optical Communications System Overview

Optical communications systems are typically composed of the components listed in Figure 2, that is a light source, an information source, an encoder and modulator, optics at both the transmitting and receiving side, a transmission medium, a detector, and a receiver.

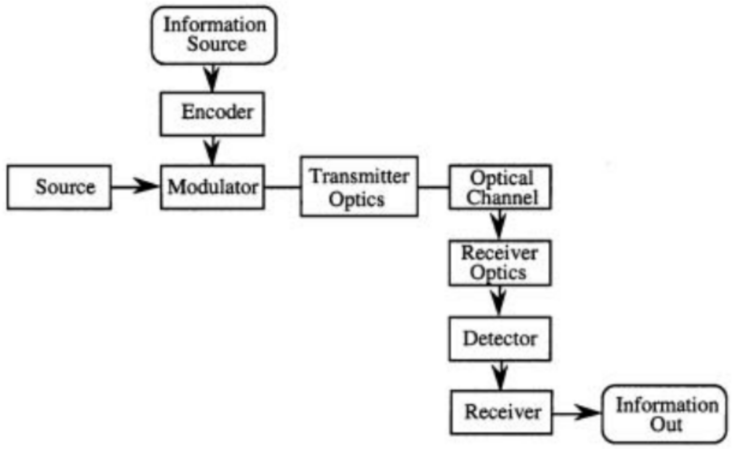

Figure 2: Generalised Block Diagram of an Optical Communications System [3]

As previously discussed, the light source used is typically an LED or a laser diode (LD). Laser diodes offer advantages in modulation speed, power and spatial coherence[1].

At the transmission side, the incoming source must be modulated with the data signal. The modulation techniques used, and the most recent advances in these techniques will be discussed within this review paper.

At the receiving side, a photodiode converts the incoming light signal to an electrical signal. This is typically followed by multiple amplification stages, and can also include circuitry for decoding the signal, or error detection[1].

2.3 Optical Communications System Advantages

There are many advantages to using optical communications systems over traditional communications systems using, for example, copper wire. Optical communications systems allow for greater resistance to interference and signal attenuation, which can cause problems in traditional systems.

2.3.1 Interference

Interference can be present in traditional data transmissions through a phenomenon known as "Crosstalk" which occurs when signals within different channels of a system have an adverse, interfering effect on one another[4]. While this is an issue within the traditional data communications systems, limiting the amount of lines which can be run in close proximity, it poses no such issues within optical communication systems (provided there is adequate cladding in place[3]).

Optical data transmission is relatively resistant to interference, both in terms of Electromagnetic, and Radio-Frequency interference, thus making them more suitable than metal based, traditional transmission systems in situations where there is high likelihood of these types of interference[1].

2.3.2 Attenuation

Attenuation in optical systems is much less of an issue than in its metal based counterpart. This is due to attenuation being mainly caused by absorption and scattering within the transmission medium[1]. Within glass cable, this attenuation is extremely low, however, with plastic core cable, it can be higher, due to impurities within the material[1].

Attenuation within traditional systems is higher due to the "skin effect" which increases attenuation at higher frequencies[5]. Due to this effect, systems utilising copper wire require repeaters at approximately 2-5km intervals, compared to a distance of approximately 50km in fiber optic cabling[3][6].

3 Current State-of-the-Art

3.1 Modulation Techniques

Currently there is a body of work being produced within the area of modulation techniques for optical communications systems. One such technique, showing promise in increasing spectral efficiency[7], while simultaneously achieving lower optical signal to noise ratios (OSNR), and higher transmissions distances[8], is Probabilistic Shaping.

3.1.1 Probabilistic Shaping

Probabilistic shaping is a technique utilised for increasing spectral efficiency within an optical communications system. Symbols are transmit via probabilistic shaping by using non-uniform probabilities (outcomes have unequal probabilities of occurring). Constellation points are distributed, using these non-uniform probabilities, along the complex plane, in contrast to simpler square quadrature amplitude modulation (QAM) constellation points, which are on a square grid. When implemented alongside QAM this technique has been demonstrated experimentally to give greatly increased sensitivity[7][8].

Shaping allows for sensitivity gains of up to 0.8dB within optical communications systems utilising 16QAM and 64QAM. In order to implement the shaping within the system, the following probability mass function was applied:

$$P_x(x_i) = \frac{1}{\sum_{k=1}^{M} e^{-vx_k^2}} e^{-} vx_i^2 \quad [7] \tag{1}$$

In testing for mismatched SNR, the variation of SNR of 11dB was shown to not require any modifications to the input distribution[7]. This study concluded that due to the robustness, sensitivity, and transmission distance improvements gained from using shaping, that probabilistic shaping is "highly suitable for a practical application in optical communications systems".

The benefits attributed to probabilistic shaping were also found in a study on spectral efficiency in a 400Gb/s optical communications system, which found that with probabilistic shaping alongside 64QAM, a 50% "reach" improvement was achieved over system in which probabilistic shaping was not implemented[8].

This study compares the efficiencies of a "PS" (Probabilistic Shaping) system, versus that of a hybrid-QAM system. Hybrid QAM utilises multiple, time-interleaved QAM's in order to improve the performance of regular QAM's. The Maxwell-Boltzmann distribution shown below was used for the distribution of the PS constellation points.

$$P_x(x_i) = \frac{\exp(-\nu(Re(x_i)^2 + Im(x_i)^2))}{\sum_{k=1}^{M} \exp(-\nu(Re(x_k)^2 + Im(x_k)^2))} \quad [8] \tag{2}$$

The experimental setup used, as shown in Figure 3, shows the utilisation of DSP techniques for the pre-transmission processing of the signal. The input data is initially mapped to PS-64QAM symbols. These are then passed through a pre-distortion (using look-up-tables) and pre-equalization stage. This pre-equalization stage is composed of a 21-tap constant modulus algorithm (CMA) Finite-Impulse-Response (FIR) filter[8].

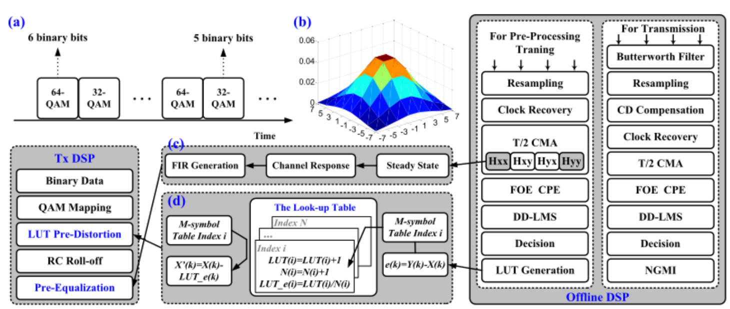

Figure 3: Experimental Setup as in [8]

Due to the lower optical signal to noise ratio (OSNR) achieved using probabilistic shaping, a transmission rate of 400Gb/s was achieved over a transmission distance of 3,600km, a 50% increase over the maximum transmission distance achieved when using a hybrid-QAM system[8].

3.2 Coherent Detection and DSP

With the increased usage of coherent detection within optical communications systems, it has become necessary for DSP techniques to be implemented in order to correct for transmissions errors due to the high data rates. DSP algorithms have allowed for higher order modulation techniques than those which were previously utilised (as discussed within the section on probabilistic shaping). These algorithms can also allow for lower overhead within the systems, as they can be used to mitigate the effects of, for example, chromatic dispersion, allowing for the removal of dedicated optical dispersion compensation units from the signal chain of the receiver[9].

3.2.1 DSP Algorithms

DSP algorithms allow for the mitigation or compensation of several "impairments" associated with coherent optical communication transmissions. These include chromatic dispersion and polarization mode dispersion. By reducing complexity in these systems, higher data rates can be achieved[10].

The receiver system described in Figure 4 shows two fixed equalizers, four "butterfly-configured" adaptive equalizers, and two phase recovery units.

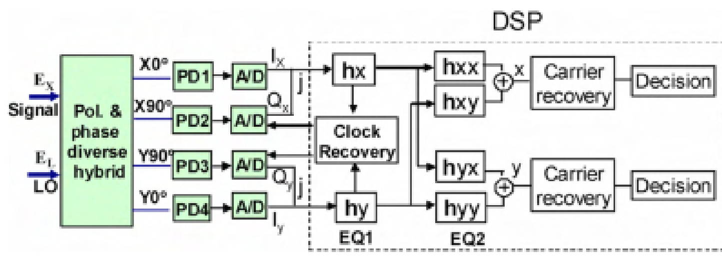

Figure 4: Generalised Digital Coherent Receiver[10]

In order to compensate for chromatic dispersion, Fast Fourier Transform based frequency-domain equalization can be used. Using this technique, the symbol rate increases on a log scale, allowing for much lower complexity when compared with a standard time-domain or frequency domain FIR filter. As such, within this study, FFT-FDE based fixed equalizers are utilised.

Polarization-mode dispersion compensation is achieved using the four adaptive equalizers. For this purpose, a T/2 spaced time-domain FIR filter filter is used. This offers the best possible performance, however, if complexity is a concern, a viable alternative is to use a 2T/3 FIR filter. Using a constant modulus algorithm (CMA), the filter coefficients can be chosen[10].

The Viterbi-Viterbi (or Mth-power) method is used for the phase recovery units. The incoming signal is raised to the M^{th} power in order to remove data modulation, and to attain the frequency offset between the transmit signal and the local oscillator. Removing the frequency offset gives the frequency recovered signal, to which the process is repeated in order to estimate the phase noise, given by taking an average over multiple adjacent symbols[10].

Similar experiments have shown that the digital filtering described in [10], utilised in a coherent detection receiver system can achieve high data transmission rates[11].

3.3 Machine Learning Techniques

Recent studies have demonstrated the benefits of machine learning techniques in coherent optical receiver systems[12][13]. These techniques have been shown to give possible gain increases of approximately 2dB[12], or can be used for signal recovery[13].

3.4 ML for 16-QAM Demodulation

Machine learning techniques show promise as a replacement for the aforementioned DSP techniques for the purpose of low complexity, high performance coherent optical receiver systems.

A K-Nearest Neighbours (KNN) classification can be used for the purposes of removing noise from a signal. Using components of each symbol of the 16-QAM output as features, and the groups of symbols as the classes, a model can be trained .

Fuzzy c-Means clustering, a version of the k-Means algorithm, calculates the probability that an incoming signal belongs to a cluster. This, when combined with the KNN algorithm, has been shown through simulation to give better performance than any of the previously discussed, more traditional DSP techniques[12].

3.5 Neural Networks

Neural networks have recently proposed as an alternative to traditional DSP systems for low resolution analog to digital converters. This is due to the high power consumption of high performance DSP systems within optical communication receivers. A recent study has shown that a one-bit vertical resolution ADC, when combined with a neural network, can recover a complex modulated signal[13].

The purpose of this approach is to implement a binarized coherent optical receiver to better utilise lower power ADC's. The binarized neural network can allow for bitwise operations to be performed, rather than arithmetic operations, which reduces overall memory usage[13].

The proposed solution in this study successfully (in simulation) reconstructed a complex modulated signal in both a 50Gb/s SP-QPSK and 100Gb/s PDM-QPSK system. The neural network allows for the use of lower cost ADCs, while the reduction in memory usage and calculation complexity allows for an increase in performance[13].

4 Conclusions

It is clear that there has been much work done on modulation techniques, signal recovery, and coherent detection within the last number of years. These techniques have allowed for benefits such as offsetting noise introduced in transmission, reducing system complexity, increasing transmission distances, and increase in performance.

While newer machine learning techniques are promising increased performance, on lower cost, lower power ADC's, there is still work being done on increasing performance to the greatest extent possible using more traditional DSP techniques, as with probabilistic shaping.

The aim of all of the techniques mentioned is to increase data rates and throughput within optical communications systems in an effort to increase their usage and ubiquity in worldwide communication systems.

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