Transmission limitations of 2R reshaping repeaters and applications of high-speed wavelength conversion in optical networking

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Abstract

Since the inception of optical networking, a goal has been to create an all-optical network. The rapid breakthrough for wavelength-division multiplexing (WDM) in point-to-point links has brought this prospect considerably closer. However, at the same time questions regarding the scalability of the all-optical network remain. This thesis deals mainly with different aspects on the scalability of optoelectronic repeaters in optical transport networks. It also deals with applications of high-speed wavelength converters in all-optical networking.

Optoelectronic repeaters can have a use in optical networks, complementing or replacing all-optical solutions. The main application can be seen in optical switching nodes to perform wavelength conversion and other functions made possible by the use of integrated electronics such as monitoring, switching, and regeneration.

It is shown that linear (1R) as well as reshaping (2R) optoelectronic repeaters can extend the standard dispersion limit in optical transmission by use of RZ (the 1R case) and NRZ (the 2R case) modulation. A drawback of 1R repeaters is the rapid accumulation of noise, which to some extent can be limited by use of reshaping in the 2R repeater. However, while the noise is efficiently suppressed in the amplitude domain, a timing noise called jitter is generated, and will accumulate in the network. A model for jitter accumulation in 2R repeaters is developed, showing that jitter accumulation follows roughly the same law as amplitude noise in 1R repeaters. This model is adapted to different problems and shows how noise, crosstalk, and patterns-dependent effects cause jitter which limits the scalability of a network. Many of the general results also apply to a broader class of reshaping all-optical wavelength converters based on optical gating, which are also limited by jitter accumulation.

In ultra-high-speed optical networking using optical time-division multiplexing, the capacity of a single wavelength channel is pushed to its extreme. This technology can be used in single-channel systems or in conjunction with WDM to increase the capacity further. Wavelength converters supporting these speeds can be of great importance in such networks. In addition to the basic wavelength conversion functionality, it is experimentally shown how a 40-Gb/s wavelength converter based on cross-phase modulation in an optical fiber together with a fast tunable laser can be used as a switching element in an optical packet switch. This wavelength converter also features simple header erasure by passively filtering out a 2.5-Gb/s NRZ header from a 40-Gb/s RZ payload. Basic operating characteristics of the wavelength converter are also investigated experimentally showing power requirements and possible wavelength conversion spans. Simulation with 2-ps pulses show that this wavelength converter is probably scalable to 160 Gb/s.
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Stockholm 2000
List of papers

The thesis is based on the following papers, which will be referred to by their letters in bold face:


J. P. Öhlén, B.-E. Olsson, D. J. Blumenthal, “All-optical header erasure and penalty-free rewriting in a fiber-based high-speed wavelength converter”, accepted for publication in IEEE Photon. Techn. Lett..

The following papers are related to the work in this thesis, but not included:


## List of acronyms

<table>
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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>1R</td>
<td>Reamplification</td>
</tr>
<tr>
<td>2R</td>
<td>Reamplification, Reshaping</td>
</tr>
<tr>
<td>3R</td>
<td>Reamplification, Reshaping, Retiming</td>
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<tr>
<td>AC</td>
<td>Alternate Current</td>
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<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
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<td>Continuous Wave</td>
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<td>BER</td>
<td>Bit-Error Rate</td>
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<td>EDFA</td>
<td>Erbium-Doped Fiber Amplifier</td>
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<tr>
<td>EOP</td>
<td>Eye-Opening Penalty</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>HEC</td>
<td>Horizontal Eye Closure</td>
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<tr>
<td>NRZ</td>
<td>Non Return to Zero</td>
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<td>OEO</td>
<td>optoelectronic repeater (O/E-E/O converter)</td>
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<tr>
<td>OTDM</td>
<td>Optical Time-Division Multiplexing</td>
</tr>
<tr>
<td>PMD</td>
<td>Polarization-Mode Dispersion</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RZ</td>
<td>Return to Zero</td>
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<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
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<td>Time-Division Multiplexing</td>
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<tr>
<td>XGM</td>
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Chapter 1

Introduction

In the last five years, there has been a tremendous growth in the area of information technology. It is often referred to as exponential, explosive, and other superlatives when people try to describe the evolution in a single sentence. Indeed, many say it is a revolution. Although technology can only provide the means for the evolution we are seeing, it has already started to affect the way people communicate and live their lives.

In the communications area, fiber-optics is gaining importance as the only technology that can offer the large capacities that are required in the core networks. The last couple of years has seen some dramatic changes, but the area of fiber optics has been around for some 30 years. The basic technology was there, and one could foresee communication systems with capacities several orders of magnitude larger than what was in use at that time. In the early 80’s the research efforts started to take off, but at that time there was no need for the huge capacities which were made possible. Different applications were thought to be the future driving force for bandwidth — video telephony, high-resolution digital television, and video on demand. In the end, however, the Internet turned out to be what made a massive deployment of fiber-optic technology happen.

1.1 Background

The evolution of fiber-optic communication [1] is to a large extent based on three technological breakthroughs: the low-loss optical fiber, the semiconductor laser, and more recently the erbium-doped fiber amplifier. The basic principle used in the optical fiber, guiding of light, was shown in the 1840’s using water jets and glass rods. In the following years the technique was used for illumination, and in early ideas for television systems. In 1927, Clarence W. Hansell filed a patent on a new device for picture transmission, which included glass fiber, which is often cited as the birth of fiber-optics. In the meantime telephone systems were built and microwave transmission systems were developed for transmission of analog and digital data. It took almost 50 years since then until the glass fiber became
Chapter 1. Introduction

practical for information transmission. For a long time, the loss of optical fibers was too large and it was generally thought that they were not well suited for communication over long distances. However, C. K. Kao did not dismiss fibers so easily, and based on physical considerations he argued that optical fibers could have losses lower than 20 dB/km, making them suitable for communication [2].

In 1970 Kapron, Keck and Maurer at Corning Glass Works were able to reduce the loss in the optical fiber to 20 dB/km at 633 nm [3], and later to 4 dB/km. With the use of longer wavelengths, where the optical fiber has inherently lower loss, attenuation of 0.5 dB/km at 1.2 μm and 0.2 dB/km at 1.55 μm were shown by NTT in 1976 and 1978 respectively. This is the standard values for loss in optical fibers today, and are limited by fundamental properties of the glass itself. In parallel with the development of the optical fiber, the first semiconductor lasers were made, providing a compact and practical light source for fiber-optic communication. Schawlow and Townes came up with the principle of the laser in 1958 [4]. The first semiconductor lasers made in 1962 [5], [6] and room-temperature continuous-wave (CW) operation was achieved in 1970. These early lasers had a life time of less than an hour, but the technology evolved quickly to make these lasers very reliable. The combination of the low-loss optical fiber and the semiconductor laser as a compact and reliable light source was widely accepted as superior for high-capacity communications.

There are different wavelength regions, or windows that are of interest for communication. The most important of these windows are situated around 850 nm, 1300 nm, and 1550 nm, due to the properties of the optical fiber and the available light sources. Depending on the application there are different requirements, leading to the use of different components and different wavelengths. Many systems for local-area networks and interconnects use light-emitting diodes generating light over a broad wavelength range with fairly low output power. However, high-capacity optical communication requires higher optical power and light at a single wavelength to avoid signal distortion. The first lasers emitted light at many wavelengths (optical frequencies), but soon a variety of single-frequency semiconductor laser were developed [7]. With an optical spectrum a few MHz wide it is also possible to combine several optical signals at different wavelengths (wavelength channels) in a single optical fiber by use of wavelength-division multiplexing (WDM). At the end of the fiber the different wavelength channels can be filtered out and sent to different receivers.

In spite of the very low loss in the optical fiber, the optical signal needs to be amplified regularly. The earlier systems utilized electronic regenerators which recovered the digital bit stream and retransmitted the signal [8], but in the 80’s different optical amplifiers very studied. The combination of WDM and an optical amplifier which could amplify all wavelength channels at once would be quite powerful and significantly lower the system cost and complexity. The erbium-doped fiber amplifier (EDFA) from the late 80's [9] was the first one that become practical. It has been a driving force for WDM and has a wide-spread use in installed systems today. It operates at a wavelength of 1.55 μm and has a bandwidth of roughly 10–20 THz depending on the application. The amplifier
1.2. Optical networking

With the technological advances that were made mainly in transmission, the idea of an all-optical network emerged in the late 80’s. Optical switches interconnected with fibers would form an optical ether to which various equipment could be connected. To compensate for the loss, the signal would be amplified in the optical domain. The resulting network would be completely transparent and by setting the switches properly it would be possible to “see” the receiver from the transmitter. Once built its capacity could be upgraded simply by exchanging the terminal equipment.

In the late 1980’s several optical networking projects were started, aiming at realistic testbeds which would show the feasibility of an optical network. This has been a world-wide effort, with several projects in North America, Europe and...
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While fiber optics has been quite successful for transmission, all-optical networking turned out to be more difficult. At the time of its conception, the performance of the building blocks was simply not good enough and it is only today that the technology is reaching the point where optical networking could be feasible \[17\]–\[19\]. Still, some basic problems remain. A transparent optical system is by its nature analog, which means that any degradations that the signal suffers, will accumulate along the signal path. The increased complexity in a full-scale optical network with optical switches will make these problems more pronounced, and it is now widely recognized that some kind of regeneration is necessary in an optical network.

Today simpler optical networks are built, which typically have a limited number of nodes and very simple functionality compared to the electronic systems where most of the switching is done. In spite of the simple functionality, such a network is still a large step from a transmission link connecting electronic switching nodes. With the increased transmission capacity the problem of switching is growing. Even if it is unlikely that optics would replace electronics in this area, much could be gained if optics could take responsibility for some of the switching burden.

1.3 Scope of this thesis

This thesis is focused on high-capacity transport networks with their high bit rates and sometimes large geographic areas they cover. These networks are usually shared between thousands of users and carry large volumes of traffic. Performance and reliability have been the prime concerns and the high cost of the systems is shared among its users. Different technologies were investigated to overcome the emerging problems with all-optical networking. One approach that could be feasible was to use integrated optoelectronic repeater (OEO) to perform functions in an optical network. A receiver, a simple electronic circuit, and a transmitter would be integrated on a single chip with an optical input and an optical output. Such a device would only be able to handle a single channel, making demultiplexing necessary in a WDM system. At nodes where the channels are demultiplexed, the optoelectronic repeater could perform different functions within the optical network, and would potentially have a low cost. These functions could e.g. be wavelength conversion, reshaping, switching, power equalization, monitoring, and control of the network. Some of these functions, wavelength conversion, reshaping and power equalization, can also be made with optics, but the integrated optoelectronic repeater it potentially more flexible and has a potential for higher degree of integration.

The following chapter introduces some basic concepts and building blocks of importance to the work in this thesis. Chapter 3–4 forms a basis for the work in paper A–G and is concerned with dispersion, noise and crosstalk limitations in optical networks. Specifically the properties of nonlinear reshaping have been
investigated. Such a functionality provides a simple type of regeneration and could be implemented fairly easily in an electronic circuit.

The second part of the work in this thesis is concerned with high-speed optical systems. If an optical system can support bit rates much higher than what is possible with electronics, they can be attractive in spite of a lower degree of integration and functionality. This is a moving target as both electronics and optics are evolving, but today I think high-speed optical systems should support at least 40 Gb/s and have the prospect of much higher bit rates. Chapter 5 describes some fundamentals of high-speed optical time-division multiplexing. It also introduces the work of paper H–J where a high-speed wavelength converter is investigated and used to demonstrate some basic functionalities needed in an optical packet switch.
Chapter 2

Basic elements of optical communication

Some basic concepts and building blocks of importance for the understanding of this thesis will now be introduced. For a comprehensive introduction to fiber optics and communications one should turn to some of the available text books [20]–[26]. A simple fiber-optic transmission system using wavelength-division multiplexing (WDM) is first described. Then basic concepts of optical networking and signal regeneration are introduced.

2.1 A simple fiber-optic link

In the systems we consider, binary digital information, ONEs and ZEROs, is transmitted by turning a light source on and off, which if called on/off keying. The light is an electro-magnetic wave which is described by the electric field amplitude, usually represented with the complex electric field as

\[ E(t) = E(t)e^{-i\omega t} \]  

(2.1)

where \( E \) is the electric field envelope and \( \omega \) the angular frequency of the light carrier. The complex electric field \( \mathcal{E} \) can be normalized so that the optical power is simply given by \( |E|^2 \), which we will assume here. The electric field has a direction and can be decomposed into two perpendicular components, or polarizations. In many cases it is sufficient to consider one of these, which is made here. To send information on an optical signal a semiconductor laser is modulated, either directly by turning the driving current to the laser on and off, or externally by using an external modulator to turn the light from a continuous-wave (CW) laser on and off. The different modulation methods are illustrated
in figure 2.1. The power of the signal from the transmitter, $P_{tx}$, can be written as

$$P_{tx}(t) = P_1 \cdot \sum_{k=-\infty}^{+\infty} \alpha_k g(t - kT) \tag{2.2}$$

where $\alpha_k = 1/0$ represents ONE/ZERO symbols. If $B$ is the bit rate, $T = 1/B$ is the length of the time slot assigned to each symbol, the bit slot. $P_1$ is the peak output power and $g(t)$ is the used pulse shape. The peak value of $g(t)$ is 1 somewhere within the bit slot $0 < t < T$, and is 0 when $t$ is well outside of the bit slot. Depending on the shape of the pulse $g(t)$ the output signal shape will be different. If consecutive ONEs result in a constant output power, we talk about non-return-to-zero (NRZ) modulation. For this case, $g(t)$ could be a square pulse of length $T$, but there are many other pulse shapes resulting in an NRZ signal. If the pulses $g(t)$ are significantly shorter than $T$ the output power would return to zero between two ONEs, which is called return-to-zero (RZ) modulation.

In a WDM system, there are several transmitters at different, but closely spaced frequencies or wavelengths. The different optical signals (wavelength channels) are combined with a multiplexer and then coupled into a single-mode optical fiber. To compensate for the loss that the signal suffers on its way, one or several optical amplifiers are used to amplify the signal. At the receiving end of the link, the wavelength channels have to be separated by a WDM demultiplexer, which has one output port for each wavelength channel. Each channel is then detected by a square-law detector, a photo diode, that gives an output signal that is proportional to the received optical power ($P_{rx}$) given by the square of the input electric field envelope ($E_{rx}$),

$$s_{rx} = R \cdot P_{rx} = R \cdot |E_{rx}|^2 \tag{2.3}$$
where \( R \) is the responsivity of the detector. The detector also acts as a low-pass filter that integrates the signal energy. In theory the 3-dB bandwidth of the detector has to be at least \( 0.5B \), but in practice somewhat more is required, \( 0.75B \) is a typical value. In the receiver, there is a clock-recovery circuit which acquires the correct timing of the input signal. Then a decision circuit compares the filtered signal to a threshold value at time given by the clock-recovery circuit and determines if it is a ONE or a ZERO. In the system, noise from optical amplifiers and the receiver will cause bit errors, i.e. a transmitted ZERO is mistaken for a ONE at the receiver due to noise or other impairments. The bit-error rate (BER) is the probability of a bit error, and the most important figure of merit in digital communication systems. For this kind of optical systems one requires \( \text{BER} = 10^{-9} \) or lower. The lowest optical power at a receiver for which it is possible to reach this BER is called the sensitivity of the receiver. Due to signal degradation a higher input power is often required, and it is common to describe this using the penalty concept. To define the penalty the studied system is compared to a reference system, and the difference in required optical power at the receiver is called the penalty of the system. When penalty is used one has to pay careful attention to how it is defined in each case as it is often used in somewhat different contexts.

### 2.2 An optical network

While the fiber-optic link described above provides communication between two nodes, one usually needs communication between many different nodes. If there would be a dedicated link between each pair of nodes in a network, the number of links would grow as the square of the number of nodes in the network. This is not very practical, and therefore the nodes are usually connected in a complicated network that is divided into several network layers [26]. To send information between two entities in a network, e.g. two telephones or a browser and a web server, the information starts at the highest network layer and is sent to the layer below. Each layer communicates with the layer directly above and below within a node, and with the same layer at another node in the network. In this way different information sources are combined and switched, almost exclusively in the electronic domain and at the lowest layer in the network, the nodes are connected with fiber-optic links. In an optical network, optical technology takes responsibility for some of the switching, and is not limited to the lowest network layer [27]–[30].

In the simple optical network outlined in figure 2.2, node A wants to transmit data to node B and establishes a semipermanent connection, a circuit. To do this a wavelength channel is allocated between node A and B. To reach node B the signal can go through node X and Y on its way. Traditionally, the signal is taken out of the optical domain at X and Y, switched completely in the electronic domain using different communication protocols, and finally transmitted again in the optical domain. Another way to do this is by the use of an optical switch, with
several input fibers, each carrying several wavelength channels. Each wavelength channel on the input is then switched independently to the desired output fiber. In such a system, node A transmits the signal on a wavelength \(\lambda_1\), destined for node B. On the link between A and X, there are other wavelength channels present, and at X the node switches the wavelength channel \(\lambda_1\) to the fiber going to node Y, and node Y switches the signal to node B. When the signal arrives at node B it is taken out of the optical domain and processed electronically. The links between the different nodes usually carry several wavelength channels with different destinations.

At the input to node Y, there can be two channels on different input fibers, but with the same wavelength, that are destined to node B. Switching both channels directly to B is not possible as they cannot have the same wavelength if they are transmitted in the same fiber. Such a situation is called wavelength blocking. One way to solve this is by the use of a wavelength converter, which can convert a signal on one wavelength to another wavelength that is not occupied on the desired output fiber. Wavelength converters can be realized in many ways \[31\], \[32\]. It is quite common to use “optical gating”, where one optical signal controls another optical signal at a different wavelength. Such a wavelength converter can be realized with semiconductor optical amplifiers (SOAs) by utilizing cross-gain (XGM) modulation \[33\], \[34\], or cross-phase modulation (XPM) \[35\]–\[38\] in an interferometer. A solution based on an optoelectronic repeater \[39\], \[40\] is quite similar in functionality, but with a different implementation. The optical signal is detected and then retransmitted directly, without further processing. Other wavelength conversion techniques such the one used in papers I–J are based on nonlinear processes in optical fibers \[41\]–\[45\], semiconductors \[46\], or nonlinear optical materials.

One can also notice that in the example of figure 2.2, one of the signals at node Y intended for node B could be sent over node Z, thereby avoiding the wavelength blocking situation. The benefit of wavelength conversion has drawn
2.3 Different levels of regeneration

In both a transmission link and in an optical network, the signal will be degraded when it arrives at its final destination. If the degradation is too large, there will be errors when the bits are detected at the final destination. Because a fiber-optic system is analog, the degradation of the BER can be quite rapid once a critical point is reached. After this critical point it is not possible to recover the transmitted information. If many nodes or a long distance are passed on the way, this can happen before the final destination. In that case the signal needs to be regenerated, before it can be transmitted further.

There are different levels of regeneration which are usually divided into three categories, illustrated in figure 2.3. A 1R repeater simply amplifies the incoming optical signal, and can be an optical amplifier or a linear optoelectronic repeater. In such a regenerator, signal degradations except for loss will remain, and accumulate in the network. The next level of regeneration is 2R (reamplification+reshaping), where the signal levels are restored by nonlinear reshaping of the optical signal. This approach will clean up an eye that is partially degraded much attention [47]–[49], and large improvements have been found also when a limited number of wavelength converters are used in the network nodes [50], [51]. The benefit depends on the network topology and is still in discussion. However, the use of wavelength converters makes it easier to select a path through the network, because wavelength channels can be allocated at each node independently. If no wavelength converters are used, the whole network has to be taken into account for the allocation of wavelengths, making it a more difficult task.

![Figure 2.3. Illustration of the different level of regeneration, 1R–2R–3R. On transmission, the optical signal is attenuated in the fiber. A 1R regenerator amplifies the signal, but the signal distortion remains. A 2R regenerator amplifies the signal and restores the signal levels to their original levels. In the process amplitude noise is removed, and jitter (timing noise) is introduced. The 3R regenerator amplifies the signal and restores both the signal levels and position of the edges, thus removing both amplitude noise and jitter.](image-url)
by e.g. amplitude noise or dispersion. However, a 2R repeater suffers from a timing noise called jitter which will limit the performance as the signal propagates in the network. The 3R (reamplification+reshaping+retiming) repeater restores both the signal levels and the signal timing. Due to this, a very large number of 3R regenerators can be cascaded without severe signal degradation. These classifications are not complete, and there are a somewhat fuzzy boundary, especially between 1R and 2R where a repeater could be linear in terms of the optical power, but not in terms of the complex electric field.

In a network there can be a mixture of all these different types of regenerators. The use of 1R and 2R regenerators is mainly motivated by their lower cost. However, for both types the signal will be degraded along its path. At some point the signal needs to be regenerated with a 3R regenerator, which will transmit a clean signal. The use of only “regeneration” usually refers to 3R regeneration.
Chapter 3

Intersymbol interference in optoelectronic repeaters

In an optical communication system, distortion of the signal shape is one of the things that will limit the maximum transmission distance and the highest possible bit rate. The digital information is usually encoded with on/off keying, where digital ONE and ZERO symbols are represented by turning the light source on and off. Each bit in the digital bit stream has a bit slot of duration $T = 1/B$ if $B$ is the bit rate. Intersymbol interference means that the energy of a symbol is spread outside its bit slot and will interfere with its neighbors. At the receiver it will then be harder to distinguish between a ONE and a ZERO, and a higher input power will be needed. The signal can also be completely corrupted making correct detection impossible. In an optical communication system, different parts of the optical signal will have different delays which is called dispersion. This is one origin of the intersymbol interference and will limit the transmission distance and the bit rate in an optical network.

3.1 Dispersion in optical communication systems

There are several types of dispersion that can affect an optical communication system [20]-[22],[52],[53]. In short-distance or low-speed systems using multi-mode fibers and multi-frequency sources, the signal is divided into different modes. This is the cause of modal dispersion which is the most important limitation for such systems. In high-capacity systems, the use of single-mode optical fibers and single-frequency lasers eliminate modal dispersion, but there are other types of dispersion that can degrade such systems. Due to imperfections in the optical fiber or other components the two polarizations of an optical signal will have slightly different speeds, which is the source of polarization-mode dispersion (PMD). This might be a severe limitation in systems with bit rates
Chapter 3. Intersymbol interference in optoelectronic repeaters

Figure 3.1. A single-mode semiconductor laser has a narrow spectrum. When the light is modulated, the spectrum broadens to roughly the same spectral width as the modulating signal. The insets illustrate the optical frequency spectrum of the light before and after modulation.

Beyond 10 Gb/s, because the amount of PMD will change randomly with time and a linear compensation scheme would need active control. However, the most visible dispersion effect in an optical fiber is the so-called group-velocity dispersion. An optical signal is composed of different frequencies which will have slightly different speeds in the fiber. In the following “dispersion” alone refers to group-velocity dispersion unless otherwise stated.

When an optical signal is modulated its optical spectrum will broaden from a single frequency to a frequency spectrum given by the bandwidth of the modulated signal as illustrated in figure 3.1. Upon propagation through the optical fiber, the different frequencies will experience different delays depending on their frequency. A 10-Gb/s NRZ signal will have an optical 3-dB bandwidth around 10 GHz or 0.08 nm. Standard single-mode optical fiber has a dispersion of 17 ps/nm·km at 1.55 μm. From this it is possible to calculate the delay difference between light at two slightly different wavelengths. If the frequencies within the 3-dB bandwidth of 10 GHz have delay differences larger than a bit slot, or 100 ps for a 10 Gb/s signal, there should be a significant distortion. Carrying through such a calculation for standard single-mode fiber and a 10 Gb/s signal, one would expect signal distortion starting at a transmission distance of 74 km, not very far from more accurate analyses which often arrive at around 60 km. In general, the maximum distance in km is approximately given by

\[ L < \frac{10^5}{D \cdot B^2} \]  

(3.1)

if \( D \) is given in ps/nm·km and \( B \) in Gb/s.

There are several methods to overcome the limit set by dispersion [20], [21], [52]–[55], [57]–[53] and it is possible to transmit 10 Gb/s over distances of 200 000 km [60]. In the earlier days of fiber optics, dispersion was less a problem, due to the lower bit rates used and the absence of optical amplifiers. Instead electronic 3R regenerators were used to regenerate the signal before its amplitude was too low to allow error-free regeneration. When the fiber amplifier extended the possible transmission distance and the higher bit rates pushed the dispersion limit closer, there was a great need for dispersion compensating techniques.

Today there are both fibers with lower dispersion that can be used in place of the standard single-mode fiber [54], as well as dispersion compensating fibers...
3.2 Simulation methods and figures of merit

with a negative dispersion value which are cascaded with standard fiber to produce a low net dispersion [55]. Fiber Bragg gratings [57] can have properties similar to dispersion-compensating fiber and may potentially give compact low-loss compensation. Due to the nonlinear properties of the optical fiber it is also possible to have solitons [21], [22], [58], [59], e.g. pulses where the fiber nonlinearity will balance the effect of dispersion and produce pulses that are not affected by dispersive pulse broadening. There are also dispersion-managed solitons [60], [61] which are not true solitons, but have similar properties. With the dispersion compensation methods available today, solitons have their main application in high-speed optical time-division multiplexed (OTDM) systems. Finally, there are analog electronic dispersion compensation methods [62] as well as digital in the form of a full-scale 3R repeater which also removes the noise that has been accumulated along the signal path.

3.2 Simulation methods and figures of merit

For simple estimates it is possible to use simple analytical approaches like the one used in the previous section or calculations based on Gaussian pulses that can include the effect of chirp [20]–[22]. In order to make more accurate estimates it is necessary to rely on numerical calculations. The propagation of an optical signal in a single-mode fiber can be calculated by solving the nonlinear Schrödinger equation [20], [22]

$$\frac{\partial E(t, z)}{\partial z} + \frac{\alpha}{2} E(t, z) + i \frac{\beta_2}{2} \frac{\partial^2 E(t, z)}{\partial t^2} = i \gamma |E(t, z)|^2 E(t, z).$$  (3.2)

This equation is sufficient for most purposes and takes first order dispersion and fiber nonlinearities into account. In this equation, $t$ is the time in a frame that travels along with the signal in the fiber at the group velocity. $E(t, z)$ is the complex electric field envelope that depends on time as well as the distance in the fiber, $z$. The loss in the fiber is $\alpha$ and $\beta_2$ is proportional to the dispersion parameter $D$ and given by

$$\beta_2 = \frac{\lambda^2}{2\pi c} \cdot D. \quad (3.3)$$

The parameter $\gamma$ is the nonlinear coefficient and is calculated as

$$\gamma = \frac{2\pi n_{NL}}{\lambda A_{eff}}. \quad (3.4)$$

where $n_{NL}$ is the nonlinear refractive index of the fiber and $A_{eff}$ is the effective area of the fiber.

With eq. (3.2) it is possible to calculate how the signal changes upon propagation in the fiber, taking nonlinear effects like self-phase modulation, cross-phase modulation, and four-wave mixing into account. At the receiver the eye diagram is used to determine the signal quality by use of different figures of merit. In
Chapter 3. Intersymbol interference in optoelectronic repeaters

Figure 3.2. To characterize an optical communication system, different figures of merit or eye masks are used. Here we use the following figures of merit. The eye-opening penalty is defined as $\text{EOP} = 10 \cdot \frac{\log(a/b)}{b}$, where $b$ is the difference between the ideal ONE and ZERO levels, and $a$ the maximum vertical eye opening. The horizontal eye closure (HEC) is the ratio between the maximum width of the eye and the length of a bit slot, $\text{HEC} = c/d$.

3.3 Cascading of optoelectronic repeaters

When an optoelectronic repeater is used, the amount of intersymbol interference is given by the interaction between dispersion in the fiber and the properties of the optoelectronic repeater. To some extent the behavior of some types of wavelength converters using optical gating is similar in the sense that the optical phase is not conserved when a new light source is used, as mentioned in section 2.2. In contrast to fiber-based components, active semiconductor devices including the optoelectronic devices considered here generally have a limited signal bandwidth, and would act as filters. It is well known that if several identical
3.3. Cascading of optoelectronic repeaters

When an optical pulse is transmitted, the optical frequency can change between different parts of the pulse, which is called chirp. Depending on the sign of this chirp, a pulse can initially be compressed and then broadened, or broadened directly. A transmitter can be designed to have a chirp giving pulse compression. Figure 3.3 shows a chirp-free pulse, a pulse with the “right” chirp and a pulse width the “wrong” chirp. If the pulses are initially compressed upon transmission they can be detected when the pulses are still shorter than the transmitted pulses. They will then be slightly broadened by the electrical filter in the OEO, and return to their initial pulse width before they are transmitted again. By choosing the proper chirp the transmitted pulse shape will stabilize, which is illustrated in figure 3.3. The use of this scheme for transmission of digital data would clearly extend the dispersion limited transmission distance. However, it requires return-to-zero (RZ) modulation, whereas most systems use NRZ modulation today.

To support transmission of NRZ data one can introduce 2R reshaping in the
Chapter 3. Intersymbol interference in optoelectronic repeaters

Figure 3.4. A 10 Gb/s signal (a) is passed three times through a 4th order Bessel filter (b) and a 4th order Butterworth filter (c), both with a 3-dB bandwidth of 7.5 GHz.

OEO. In such a system, it is possible to extend the limits set by dispersion for NRZ modulation. The eye diagram would be partially closed by dispersion and electrical filtering, but can be re-opened by a reshaping repeater as shown in figure 2.3. In broadband digital communication systems, the frequency response of the components needs to fulfill two important requirements. The bandwidth needs to be at least as large as the signal bandwidth. For 10 Gb/s NRZ data, a bandwidth of 5 GHz is needed in theory but in practice 7.5 GHz is often required. Equally important is the phase response which gives the group delay. This is similar to group-velocity dispersion in an optical fiber and describes the delay that different frequencies will experience when passing a component. If the difference in group delay within the signal frequency spectrum is too large, this will result in severe signal distortion. Figure 3.4 illustrates the difference between two filters of the same bandwidth. The original 10 Gb/s signal shown in figure 3.4a is passed three times through a 4th-order Bessel filter (figure 3.4b) and a 4th-order Butterworth filter (figure 3.4c), both with a 3-dB bandwidth of 7.5 GHz. The Bessel filter has a very low difference in group delay and shows very small horizontal distortion. The Butterworth filter has a very flat amplitude response, sacrificing the group delay. Due to this, it has a somewhat oscillating behavior and a horizontal eye closure originating from the displacements of the signal edges. When the signals are passed through a reshaping element in a 2R repeater, they would be reshaped to restore the signal levels. In both cases the vertical eye closure would also be gone and the oscillations in the Butterworth case would be gone. However, for the Butterworth case the displacement of the edges would remain and introduce a significant horizontal eye closure for the eye in figure 3.4c. This kind of degradation cannot be compensated for by other means than retiming by a 3R regenerator.

Depending on the frequency response both for the amplitude and the phase, the performance of 2R optoelectronic repeaters can be vastly different. In an idealized system it is fairly easy to have a very low distortion and a good signal shape even after more than 100 repeaters. Such a system was studied by simulation in paper C and even in the presence of fairly large amounts of dispersion many repeaters could be passed before the signal was degraded. In practice it can be hard to achieve this performance as most real components are not very ideal.
3.4 Sources of degradation: tails and filters

In electronic systems, the degradations can depend on the used bit pattern. Such a pattern dependence can be introduced by a long tail in the impulse response that extends well beyond the end of a bit slot, as shown in Figure 3.5. The “head” of the impulse response is the desired high-frequency part, whereas the “tail” introduces a memory effect, causing the amplitude in one bit slot to depend on the previous bits. If the tail is very long, but still with a finite area, the contribution of the previous bits would be averaged out, and would not degrade the system. If the tail is sufficiently short, the contribution from the previous bits in a random signal would be similar to noise although it can be calculated once the bit sequence is known. Paper G considers how such amplitude variations from a parasitic tail with a small area are transformed into timing jitter. This jitter will be pattern-dependent and could degrade systems with cascaded 2R repeaters, even if the effect is hard to see for a single repeater. The model is then applied to data from a loop experiment in paper G, and also used to model the experimental results of [64].

To analyze this effect, we will now consider a NRZ signal at the input to a filter with an impulse response $h(t)$ consisting of a desired head $h_1(t)$ and a...
parasitic tail $h_2(t)$. The impulse response is illustrated in figure 3.5 and written as $h(t) = h_1(t) + h_2(t)$. The signal at the input to the filter can be written as

$$s(t) = \sum_{k=-\infty}^{+\infty} \alpha_k g_{in}(t-k),$$  \hspace{1cm} (3.5)$$

where $g_{in}(t)$ is the input pulse form and $\alpha_k = \pm 1$ represents ONE or ZERO symbols which are random in a random bit stream. For simplicity, the time will be normalized to the duration of a bit slot. The output from the filter, $p(t)$, can then be calculated using a convolution:

$$p(t) = \int_{0}^{\infty} h(t')s(t-t')dt' = h_1(t) \otimes s(t) + h_2(t) \otimes s(t).$$  \hspace{1cm} (3.6)$$

To simplify the calculation we will use a head shorter than the bit slot ($T_1 < 1$) and an area of 1. The tail is rectangular and has a length $T_2$ and an area of $\epsilon$. In the time range $0 < t < 1$ the signal $p(t)$ at the filter output can be calculated as

$$p(t) \approx \sum_{k=0}^{+\infty} \alpha_k (h_1(t) \otimes g_{in}(t-k)) + \sum_{k=0}^{+\infty} \alpha_k (h_2(t) \otimes g_{in}(t-k))$$

$$= \sum_{k=0}^{+\infty} \alpha_k g_{out}(t-k) + \frac{\epsilon}{T_2} \sum_{k=1}^{T_2} \alpha_k.$$

Here, $g_{out}(t) = h_1(t) \otimes g_{in}(t)$ is the output pulse form. The first term of this expression is the desired part originating from the head whereas the second term stems from the parasitic tail and will cause a pattern-dependent signal amplitude after the filter. This can appear as noise and statistical properties of this term can be calculated. If the bits are totally random and independent with equal probability of ONE and ZERO, the variance of the last term can be written as

$$\sigma^2 = \left( \frac{\epsilon}{T_2} \right)^2 \sum_{k=1}^{T_2} E[\alpha_k^2] = \frac{\epsilon^2}{T_2}.$$  \hspace{1cm} (3.8)$$

This noise-like term would cause an increased BER in the receiver, and gives a penalty depending on its amplitude. In paper G the effect is considered in conjunction with a 2R repeater where the pattern-dependent amplitude fluctuation that is transformed into pattern-dependent jitter by the reshaping function. This leads to an increased BER at the final receiver, even with fairly low amounts of amplitude fluctuations.

Long tails in the impulse response are also present when AC coupling is used. In an AC-coupled device, the DC component of the signal (the average signal amplitude) is removed, making the average amplitude of the input signal
equal to zero independent of the input signal levels. To accomplish this, a large capacitor is put in series with the signal at the input and output of the device. This greatly simplifies the design of high-speed systems and electronic devices. For an AC-coupled case, the impulse response will have a long negative tail with an area equal to the area of the head. In order to apply the equations above, one would replace $\epsilon$ with $-1$, but otherwise they would remain the same. One can see that $\sigma_{\alpha}$ goes to zero as $T_2$ increases, which is reasonable. For the square tail used here, the relation between the lower cut-off frequency and $T_2$ is $f_{low} = 0.44/T_2$, and this can give a measure of the distortion resulting from the AC coupling. Keeping in mind that the expressions use normalized times and frequencies, one can find that 0.1 dB penalty from AC coupling in a 10-Gb/s system requires an lower cut-off frequency of 6 MHz for signals with random and independent bits having equal probability of ONE and ZERO. In reality the signals that are encountered are not completely random and lower values can be required. However, it is also possible to use line codes which change the bit pattern to have a more equal distribution of ONEs and ZEROs, independent on the input bit pattern. The requirements on the lower cut-off frequency can then be significantly relaxed.
Chapter 4

Noise and Jitter

In an optical communication system noise from components in the signal path will limit the performance, even if the degradations from dispersion have been compensated for and undesired nonlinearities are kept under control. Noise will be added mainly in optical amplifiers and in the receiver, but also other types of active components can add noise. Because the system is analog the noise powers will add up, and eventually degrade the signal when the signal power is too low compared to the noise power.

At the receiver, a signal corrupted by noise can be written as

\[ s_{rx}(t) = s_{in}(t) + n(t) \]  

(4.1)

where \( s_{in} \) is the input signal without noise and \( n(t) \) is the noise that has been added to the signal. The detected signal is then low-pass filtered by an integrating filter described by the impulse response \( h(t) \), mainly to remove noise at high-frequencies where no signal energy is present. The filtered output

\[ D(t) = h(t) \otimes [s_{in}(t) + n(t)] = S(t) + \Delta s(t) \]  

(4.2)

is then fed to the decision circuit where \( D(t) \) is used as a decision variable. The decision circuit looks at the value of \( D(t) \) in the middle of the bit slot, and then

\[ \text{Detector} \rightarrow [s_{in}(t) + n(t)] \rightarrow \text{Filter} \rightarrow S(t) + \Delta s(t) \rightarrow \text{Decision} \]

**Figure 4.1.** In the receiver both the signal \( s_{in}(t) \) and the noise \( n(t) \) will be detected. A receiver filter filters out high-frequency noise and then a decision is made to recover the digital bit stream. The insets show the eye diagram before and after the noise filter, and the probability distribution of the decision variable around the ONE and ZERO levels.
compares it with a threshold to decide whether it is a ONE or a ZERO. The whole process is illustrated in figure 4.1. The noise $\Delta s(t)$ will be Gaussian for practical purposes and has a variance of $\sigma^2_t$. If the filtered signal $S(t)$ has a peak-to-peak amplitude of $A$, one usually defines the signal-to-noise ratio as:

$$\text{SNR}_0 = \frac{(A/2)^2}{\sigma^2_s}.$$  \hspace{1cm} (4.3)

When noise is added to the signal, there is a small possibility that the decision variable falls below the threshold when a ONE has been transmitted. The receiver will then detect a ZERO, and a bit error has occurred. To find the error probability, or the bit-error rate, the fractions of the distribution functions that are on the wrong side of the threshold are integrated. If ONES and ZEROs are equally probable and the noise is signal independent, i.e. the noise variance is equal for both ONES and ZEROs, the threshold will be in the middle of the signal levels and the BER can conveniently be calculated as [21]

$$\text{BER} = \frac{1}{\sigma_s\sqrt{2\pi}} \int_{-A/2}^{A/2} \exp \left( -\frac{x^2}{2\sigma^2_s} \right) dx = \frac{1}{2} \text{erfc} \left( \frac{A/2}{\sigma_s\sqrt{2}} \right) = Q \left( \sqrt{\text{SNR}_0} \right).$$  \hspace{1cm} (4.4)

These simplified formulas will not be correct when the noise is signal dependent, which is the case with e.g. noise from optical amplifiers and shot noise. In spite of this they are still useful, and one should note that the noise power is proportional to $\sigma^2_t$. Roughly speaking the total noise power will be proportional to the number of noise sources, and the SNR$_0$ will be inversely proportional to the number of noise sources $N$. The BER can then be approximated as [21]

$$\text{BER} = Q \left( \sqrt{\text{SNR}_0/N} \right) \approx \frac{\exp(-\text{SNR}_0/N/2)}{\sqrt{\text{SNR}_0/N}\sqrt{2\pi}}.$$  \hspace{1cm} (4.5)

From this equation one can see that small changes in the SNR can have a very large impact on the BER due to the exponential dependence. As a result a system designed for a certain transmission distance, number of channels, and bit rate can generally not be easily upgraded without degrading the performance.

### 4.1 Optical amplifier noise

Each time the optical signal is amplified in an optical amplifier, noise will be added to the signal. This noise is called amplified spontaneous emission (ASE) and depends on the optical bandwidth, the gain and the spontaneous emission
4.2 Noise in 2R reshaping repeaters

The power of the ASE which is added in an optical amplifier is \[ P_{sp} = 2 \cdot S_{sp} B_o = 2 \cdot n_{sp} (G - 1) \cdot B_o \] (4.6)

where \( G \) is the gain, \( S_{sp} \) the noise spectral density per polarization, and \( B_o \) the optical bandwidth. The spontaneous emission factor \( n_{sp} \) is always larger than 1, and approximately equal to half the noise figure. If many amplifiers are cascaded, the ASE powers of all amplifiers are added. At the receiver, a square-law detector converts the signal and ASE to an electric signal. In this process beating products are generated between the signal electric field and the noise electric field. Of these, the signal-spontaneous beating noise is often the dominating noise contribution in the receiver. The noise variance after detection can be written as

\[ \sigma_s^2 = \sigma_{sig-sp}^2 + \sigma_{sig-sh}^2 + \sigma_{sp-sp}^2 + \sigma_{sp-sh}^2 + \sigma_{th}^2 \] (4.7)

where the terms on the right side are signal-spontaneous noise, signal shot noise, spontaneous-spontaneous noise, spontaneous shot noise, and thermal noise. The four first terms are given by [21], [65], [66]:

\[ \sigma_{sig-sp}^2 = 2R^2 \cdot P_s P_{asc} B_e / B_o \] (4.8)
\[ \sigma_{sig-sh}^2 = 2qRP_s B_e \] (4.9)
\[ \sigma_{sp-sp}^2 = R^2 P_{asc}^2 B_e / B_o \] (4.10)
\[ \sigma_{sp-sh}^2 = 2qRP_{asc} B_e \] (4.11)

\( P_s \) is the signal power, \( P_{asc} \) is the total ASE power, \( R \) the responsivity, \( q \) the electron charge, \( B_o \) the optical bandwidth, and \( B_e \) the electrical bandwidth. The thermal noise \( \sigma_{th} \) is determined by the electrical characteristics of the receiver. Depending on the actual configuration, signal-spontaneous beating noise or thermal noise usually dominates over the other contributions.

For simpler calculations the expressions above are quite sufficient, but if higher accuracy is needed, one has to use a more detailed description of the optical amplifiers and the noise spectrum. Both the gain and noise properties of real amplifiers are non-uniform with respect to wavelength and depends on the input power. The amplifier characteristics can be measured with relatively simple methods [67], [68] which will give the required information for more detailed modeling.

4.2 Noise in 2R reshaping repeaters

As can be seen from eq. (4.5) the scaling properties in an linear system are not very good. The BER increases very rapidly when the signal-to-noise ratio decreases, due to e.g. an increased number of amplifiers. This is in
Figure 4.2. A signal corrupted by noise will have its ONE and ZERO levels restored by the 2R reshaping function. If the signal is above the threshold (· · ·) it is pushed up to the original ONE level, and if it is below it is pushed down to the original ZERO level. At the edges, noise will displace the threshold crossing, which introduces jitter after reshaping.

contrast to systems using full 3R regeneration, where a clean signal is transmitted after each regenerator and the BER increases linearly with the number of 3R regenerators. The cost and complexity of 3R regenerator made people look into systems using simpler 2R regeneration. This simpler functionality would also be easier to implement all-optically, or in an optoelectronic integrated circuit, compared to a full-scale 3R regenerator. Some of the transparency (in terms of bit rate), would also be kept, which could allow a more flexible network.

If a signal is corrupted by noise, the nonlinearity in a 2R repeater can clean up the signal by removing the amplitude noise as illustrated in figure 4.2. This example shows how a step function acts as a reshaping function. When the signal is above the threshold, it is pushed up to the original ONE level, and when it is below, it is pushed down to the original ZERO level. In a system with many noise sources, the power of each noise source is usually quite low, and the probability that a single one of these weak noise sources will make the signal go below the threshold and cause an error is very low. However, their combined effect will make it much more likely to have an error. The idea behind 2R (and 3R) reshaping is to compensate for each weak noise source before they have a large combined effect.

Modeling of strongly nonlinear systems, e.g. 2R repeaters, to find the noise properties is not a simple task. In linear systems the noise spectrum and the SNR are powerful tools to calculate the BER performance. For weakly nonlinear systems, one can usually simulate the signal part and the noise part of the system separately and combine them in the end using standard methods. Fiber nonlin-
4.2. Noise in 2R reshaping repeaters

Earities in “linear” all-optical transmission is an example of a weakly nonlinear system where this approach can be useful. In a strongly nonlinear system, the SNR is not very useful. One could define an equivalent SNR, but in the end it is the BER at the final receiver that is important and these two figures might not have a clear relation. For nonlinear systems one often has to resort to extensive simulations [69], [70] or approximate methods tailored to a specific problem.

The most general approach is probably the Monte Carlo simulation methods. It is a time-domain simulation method where the noise sources are modeled in the time domain. In its original form it is very similar to actually making the full experiment in a computer which is very time consuming. If one wants to simulate a system for a target BER of $10^{-9}$ it is necessary to have at least 10 errors even for low accuracy. To get these errors it is necessary to simulate also the vast majority of the bits that do not produce an error. Such a simulation can easily last a lifetime. There are ways to shorten the simulation time by use of importance sampling, extreme value theory, and tail estimation [69], [70]. In importance sampling, the noise distribution is biased to produce more errors than would normally occur in a system, to get a biased BER. It is then possible to unbias the result to obtain the unbiased BER. The idea is fairly simple, but requires prior knowledge of the system. Before simulation, a proper bias level and memory length for each noise source have to be determined to get good results, which is not always a simple task. Extreme value theory and tail estimation are based on some assumptions on the noise distribution at the receiver. Samples of the true distribution that in most cases are not within the tail, are used to estimate the distribution in the tail.

If only the amplitude noise is considered, and no time aspects of the problem are considered, one can use standard probability theory to find some properties of noise in nonlinear elements. For a noise signal $x$ at the input to a monotonic nonlinear function $f(\cdot)$, the distribution of the output noise signal $y = f(x)$ is given by

$$p_y(y) = p_x(x)/f'(x)$$

(4.12)

Here, $p_x$ and $p_y$ are the probability distributions of $x$ and $y$ respectively. This type of calculation has been performed for different systems with applications in optical communications, in most cases for one single stage of nonlinearity. The sinusoidal transfer function in an all-optical wavelength converter [71] and an OEO with a Mach-Zehnder modulator [72] have been shown to suppress noise and improve the BER. Similar results have been shown in an OEO with an electro-absorption modulator [73] and in a phase-sensitive optical amplifier [74], [75]. In paper B this is done for many cascaded nonlinearities and different shapes of the nonlinearity. For cascaded nonlinear elements, one finds that the accumulation of BER from amplitude noise will approximately be linear, but there will be a penalty from the non-ideal reshaping as explained in paper E.
4.3 Jitter in 2R reshaping repeaters

Even though the signal levels are restored to their original value, the 2R repeater can not remove the signal degradation from noise totally. The inset in figure 4.2 shows how amplitude noise causes a displacement of the threshold crossing. The position of the signal edge after the repeater is then determined by the threshold crossing, which will cause a timing noise called jitter. This jitter will accumulate when more repeaters are passed [64], because there is no restoring force for the jitter in a 2R repeater. At a receiver, the eye will have less noise in the vertical direction, but instead, there will be a significant noise in the horizontal direction as illustrated in figure 2.3. If one looks a single ONE surrounded by ZEROs, several different things can happen because of this jitter. The pulse representing the ONE symbol can become broader or narrower than it originally was. If both edges move in the same direction, the pulse can slide out of its bit slot. When the final receiver integrates the energy contained within a bit slot, an error can occur. The most dangerous event is when the pulse width has been reduced due to jitter, and this is the case considered in the following.

If the amplitude noise at a specific edge is $s$, the corresponding time displacement of the edge after reshaping is $\Delta \tau = s/\kappa$ where $\kappa$ is the slope of the signal edge. This occurs in every 2R repeater and the displacements of the edges will accumulate. The variance $\sigma_\tau^2$ of the total displacement for a specific edge after $N$ repeaters is

$$\sigma_\tau^2 = N \cdot \sigma_s^2 = N \cdot \frac{s^2}{\kappa^2}$$  \hspace{1cm} (4.13)

where $\sigma_s^2$ is the variance $\Delta s$ and $\sigma_\tau^2$ the variance of $\Delta \tau$. When the signal arrives at the final receiver, its energy will be integrated and a decision will be made based on the energy contained within the bit slot. It was shown in paper D that the BER due to jitter only, can be approximated as

$$\text{BER} = \frac{1}{4} Q \left( \frac{\kappa}{\sqrt{2}} \sqrt{\frac{\text{SNR}_0}{N}} \right)$$  \hspace{1cm} (4.14)

The main result is that the BER due to jitter will also scale as $\text{SNR}_0/N$, which is the same as for amplitude noise in a 1R system (cf. eq. (4.5). The difference is the factor $\kappa/\sqrt{2}$ which will be larger if the edges are steeper, decreasing the effect of jitter. The edges can be made steeper if the bandwidth increases, but then the noise bandwidth will also increase, which lowers the signal-to-noise ratio. However, it turns out that $\kappa$ will increase faster than $\sqrt{\text{SNR}_0}$ is decreased, giving an over-all improvement. This is true as long as jitter is the dominating source of errors. When the bandwidth is increased, there will be a point where the amplitude noise is so large, that the signal is likely to fall below the threshold in figure 4.2. This would result in a “dip” within the bit slot. The errors caused by this effect would start to increase, and at some point dominate over the errors caused by jitter. This is analyzed in more detail in paper D, where an optimum point is found after making some simplifying assumptions.
4.4 Crosstalk

In communication systems and electronic circuits where several signals are present, they will in general disturb each other. In optical systems this usually happens when optical signals are switched or one wavelength channel is filtered out in a WDM system [20],[21],[76]–[83]. The optical switch in figure 4.3 has two inputs, 1 and 2, and one output. When signal 1 is selected, signal 2 will also be present at the output although it is greatly suppressed. The power ratio between the undesired signal and the desired signal, $\varepsilon$ is called the crosstalk suppression or simply the crosstalk of the switch. When the optical output signal is converted to an electronic current, the total power of both signals will be detected. Assume that the electric field amplitudes of the two signals are equal to $E_0$ with optical frequencies $\omega_1$ and $\omega_2$ and a phase difference $\phi$. The signal from the square-law detector at the receiver will be proportional to the optical power at the detector which is given by

$$P_{rx} = \left| E_0 e^{-i(\omega_1 t + \phi)} + \sqrt{\varepsilon} E_0 e^{-i(\omega_2 t)} \right|^2$$

$$= (1 + \varepsilon) P + 2\sqrt{\varepsilon} P \cos((\omega_1 - \omega_2)t + \phi)$$

(4.15)

if the two optical signals have the same polarization. This is an assumption that can be motivated by the fact that it is the worst case, and that a random polarization distribution gives a bias towards the worst case [77]. It can be seen that the second term is oscillating with the difference frequency $\Delta\omega = \omega_1 - \omega_2$. This term will be filtered in the receiver. Depending on the difference frequency and the detector bandwidth, it will be filtered out or cause interferometric crosstalk [78],[79]. The magnitude of this kind of crosstalk will be $2\sqrt{\varepsilon}$, which means that the crosstalk suppression in dB has to be twice as high compared to the case of non-interferometric crosstalk. This can put very high demands on the components used and should be avoided whenever possible. In the literature, different authors use different terminology for describing these different types of crosstalk, but one can identify three main types of crosstalk. If $\Delta\omega$ is much larger than the detector bandwidth, the last term of eq. (4.15) is filtered out and the optical

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Figure 4.3. Two optical sources and a switch with a limited extinction ratio are shown along with the frequency spectra of the signals at the inputs and the output. The optical frequency separation is $\Delta\omega$ and the suppression of signal 2 is $\varepsilon$. 

4.4 Crosstalk
powers will be added giving a suppression of the order of $\varepsilon$. When the crosstalk signal is turned on and off, the desired signal would be disturbed. If the crosstalk comes from a second light source, but the optical frequency difference is within the receiver bandwidth, the optical fields will be added, giving a crosstalk power of the order of $\sqrt{\varepsilon}$, but with a rapidly varying amplitude given by their relative phase. Sometimes light from a single source will take different paths and then interfere. For this case, $\omega_A = \omega_B$ and $\phi$ will be given by path length difference if it is well below the coherence length. This results in a slowly varying crosstalk amplitude, also of the order of $\sqrt{\varepsilon}$. Eq. (4.15) can be generalized to include many modulated crosstalk sources and both polarizations, but the important points are highlighted with the simplified approach used here.

Although crosstalk has some similarities to noise, the differences are quite important. While the probability distribution of noise for most practical purposes can be considered as Gaussian, crosstalk will be close to Gaussian only for a large number of crosstalk contributions. For non-interferometric crosstalk, the crosstalk power will only depend on the number of crosstalk channels that are turned on, or transmitting a ONE. The crosstalk will be data driven and have a binomial probability distribution. For a large number of crosstalk sources, it will approach the Gaussian distribution. For the interferometric case the situation is more difficult since both the number of crosstalk sources and the optical phase difference is important. Depending on how fast the optical phase is changed, different approaches have to be taken. Crosstalk from a single source can have very different behavior depending on the path-length difference, but crosstalk from different sources have a probability distribution approaching a Gaussian distribution for many crosstalk contributions. Sometimes more accurate methods have to used, such as series methods [80] or the saddle-point approximation [81], [82] that will give more accurate results for few contributions. However, a Gaussian approximation of crosstalk will generally over-estimate the BER, and can be quite useful to get an upper bound.

There are several situations where crosstalk is generated, in switches as illustrated above as well as in optical filters and wavelength (de)multiplexers. Although crosstalk will appear at the wavelength demultiplexer, even in a simple WDM transmission system, it has more severe implications in optical networks where many switching nodes are interconnected. This is both due to the fact that interferometric crosstalk can appear, and that the number of crosstalk sources can be much larger. As crosstalk has some similarities to noise, the use of 2R reshaping to reduce crosstalk impairments have been investigated. It has been found experimentally [83] that a wavelength converter with a 2R reshaping capability would increase the allowed crosstalk level, but there is still a critical point where the penalty starts to increase rapidly. Paper F shows how crosstalk is transformed to jitter in a 2R repeater which will degrade the system. A method to evaluate the limits set by noise and crosstalk is developed and used to analyze this effect for different crossconnect architectures. Whereas the signal-to-noise ratio can be increased by increasing the signal power, the signal/crosstalk ratio will not be increased when the overall signal powers are increased. Instead
4.4. Crosstalk

it depends on the crosstalk suppression and the number and type of crosstalk contributions as well as the node architecture. As a result, crosstalk will force the optical power to be increased to improve the SNR and achieve error-free operation. When the amount of crosstalk is too large error-free operation is not possible and a so called BER floor is reached. In order for a system to be robust, it should operate far from this point.
In optical communications there is a strong drive to push the performance of the systems further which is illustrated by the capacity evolution shown in figure 1.1. Lately WDM has been quite successful in this race with a few experiments reaching a capacity of around 3 Tb/s [84], [85]. WDM can be used in combination with high-speed optical technologies, and systems where the capacity of a single channel is pushed to its limit still has a great interest. State-of-the-art technology has shown transmission of 640 Gb/s [86] on a single wavelength channel. At such extreme bit rates, optical time-division multiplexing is needed today, as present electronic solutions reaches limitations at around 40 Gb/s. These systems have their main interest in applications where very a high-speed data channel is needed and when low latency is essential. The use of time-division multiplexing (TDM) could simplify a bandwidth-on-demand concept, where one network node can use all of the capacity for a short time to transmit a burst of data. There is also a fundamental interest of researchers for pushing every limit to its extreme. Due to their presently high complexity, an optical TDM system should not be limited to a bit rate that can be implemented in electronics within a few years. Electronics that can handle 40 Gb/s is not very far away, and an optical system should support at least this bit rate and be scalable further.

5.1 Technologies for optical TDM systems

The architecture of an optical TDM system is somewhat different from the standard system described in section 2.1. RZ modulation is commonly used because it is relatively easy to multiplex short pulses optically, and due to the compatibility with solitons for transmission. We will now describe optical multiplexing of four 10 Gb/s channels to one 40 Gb/s channel, which is illustrated in figure 5.1. Instead of a CW laser, a laser generating a stream of short pulses is used in the transmitter. Each pulse from this laser is split into four pulses which are modulated individually at a bit rate of 10 Gb/s. The pulses are then delayed with 25 ps relative to each other and combined to form a 40 Gb/s data stream.
Figure 5.1. A system using optical time-division multiplexing (OTDM). Short optical pulses are split into four pulses which are modulated individually. The pulses are delayed relative to each other and then combined to form an interleaved bit stream at a higher speed. After transmission, the pulse stream is split into four pulse streams, and four fast optical gates selects the proper pulse in its respective bit stream. Finally standards receivers are used for each OTDM channel.

Each bit has a bit slot of 25 ps, but the pulses have to be sufficiently shorter than this. If not, adjacent pulses will interfere and the multiplexing process will introduce interferometric noise. Due to this, the pulse shape is important, and the pulse power should decrease rapidly in the tails. Short pulses suitable for optical multiplexing can be produced by an actively mode-locked fiber ring laser [87], [88]. Such a laser is tunable and can produce high-quality pulses with high output power. Other approaches use mode-locked [89] or gain switched [90] semiconductor lasers which can potentially give a compact pulse source. However, they usually introduce a significant amount of chirp in the pulses which is not desirable.

For transmission of the high-speed RZ data, it is common to use solitons, which do not suffer from dispersion-induced pulse broadening [21], [58], [59]. To form solitons, a dispersion-shifted fiber with a low amount of anomalous dispersion is needed. Lately, there has been an increasing interest in dispersion-managed solitons [60], [61], which are not true solitons but have similar properties. Dispersion managed solitons can be formed if the fiber dispersion is alternating between normal and anomalous. At the receiver, the 40 Gb/s RZ signal is demultiplexed optically to four 10 Gb/s channels by use of one fast optical gate for each channel. This gate can be optically controlled as the fiber-based nonlinear loop mirror [86], [91], [92] and different semiconductor-based interferometers [93], [94]. Another approach is to use electro-absorption modulator [95] controlled by a sine signal where the nonlinearity of the modulator contributes to producing a short switching window. After demultiplexing, a more or less standard electrical receiver is used to convert the four TDM channels to digital data.

5.2 High-speed wavelength conversion

There can be a need for wavelength conversion in a high-speed OTDM network by the same motives as for standard WDM systems. In addition, there are also
5.3 Optical packet switching

other applications. A tunable wavelength converter combined with an optical filter, such as a WDM demultiplexer, can be used as a switching element. This can be of interest in optical crossconnects or in optical packet switching as have been demonstrated in e.g. [96],[97] as well as in paper H. If the tuning speed is fast enough, optical packets can be converted to different wavelengths on a packet rate basis, depending on which output port it should be sent to. Then a passive wavelength selective element is used at each output port to select the correct packets.

Most wavelength converters rely on nonlinear properties in the used components. At bit rates up to 10 Gb/s, it is common to use cross-gain or cross-phase modulation in semiconductor optical amplifiers. Through the carrier dynamics in the gain material, it is possible to control the gain and phase of one light signal by injecting light at a different wavelength. This can be used directly (cross-gain) or in an interferometer (cross-phase) to make a wavelength converter. The speed limitations in semiconductor materials start to be important at 10 Gb/s, and are governed by dynamic properties of the used materials. There is work in process to increase the possible bit rate [34], and wavelength conversion of 40 Gb/s NRZ data has been shown using cross-gain [33] and cross-phase [35] modulation in semiconductor optical amplifiers (SOAs). For wavelength conversion of RZ data, many wavelength converters would also convert the RZ data to NRZ data [35] due to their limited bandwidth. Other approaches have to be taken, and successful experiments have been carried out with 40 Gb/s RZ data using an SOA-based differential Mach-Zehnder interferometer [36],[37]. Still, other methods need to be investigated which use inherently faster nonlinear processes. Wavelength conversion of high-speed RZ data has been demonstrated with four-wave mixing in fiber [42] and in SOAs [46] and also by use of cross-phase modulation (XPM) in a nonlinear optical loop mirror [43]. It has been proposed to use XPM and soliton formation in fiber [44] and XPM and polarization discrimination [45]. It can also be made by use of XPM and optical filtering [41] which is the method investigated and used in paper H - J. A general drawback of such approaches is that the utilized nonlinearities are quite weak and high optical powers are needed.

5.3 Optical packet switching

In a high-speed TDM system, it is possible to have both circuit switching as well as packet switching. Circuit switching can be accomplished by dividing the data stream into frames, containing a fixed number of data pulses. In each frame, the first pulse would belong to channel 1, the second pulse to channel 2, and so on. These channels can then be switched, analogous to the situation in WDM crossconnect. In addition, a channel could also allocate a higher capacity by using more than one pulse in each frame, and still retain the order of the bits. The other approach is to use packet switching where the data is organized into packets containing a payload (part of the data) and a header with address
and control information. The packets are multiplexed asynchronously and each node examines the information in the header to determine which output port it should be sent to. In most cases the information in the header is updated at each node to reflect the present state of the packet and the network. Emerging routing protocols such as multi-protocol label switching also require replacement of the header, and optical packet switching architectures often support header erasure and rewriting\cite{98}–\cite{100}.

In optical packet switching there is work on ultra-high-speed optical logic for processing address information\cite{101} but the bulk of the work that has been made encode the header at a lower bit rate and use electronic circuits to read the header information, send the packet to the correct output port based on the header, and finally update the header before the packet is sent to the next node in the network. The header information can be encoded in the time domain, before the packet, within the same frequency band as the payload. Another approach is to use different frequency bands to encode the header and the payload, which are transmitted simultaneously on a subcarrier. The difference between these approaches are shown in figure 5.2. The left part of the figure shows a header that is encoded before the payload, separated in time. The right part shows a header encoded on a subcarrier, i.e. on a frequency outside the payload frequency band but transmitted in parallel with the payload. To update the header in an optical packet-switching node, the header is erased and then rewritten while the payload remains in the optical domain. A time-domain header can be erased by using a fast optical gate which requires active control and additional synchronization. It can also be done without active control if filtering properties of e.g. a wavelength converter is used in combination with a suitable header modulation format. In \cite{99}, \cite{100}, the header information is encoded on a subcarrier that is not converted by the wavelength converter used. In paper H,J a high-speed RZ payload is used together with a NRZ header with a lower bit rate which is not converted to the new wavelength.

Switching in an optical packet switch is quite different compared to an optical cross-connect, where connections typically persist for time spans of minutes to months, or even longer. For packet switching, switching is performed at the packet rate which requires switching times in the order of nanoseconds or less.
To achieve these switching times, it is possible to use e.g. electro-optic crystals such as LiNbO$_3$ [102] or semiconductor optical amplifier gates [98]. Another approach, is to use a fast tunable wavelength converter and a wavelength selective element to switch the packets [97]. An incoming packet is wavelength converted to different wavelengths depending on the destination. After the wavelength converter, a wavelength selective element with one output port for each wavelength can be used to send the packets to different output ports. This is the approach used in paper H, where a fiber-based wavelength converter [41] is used together with a fast tunable laser [103].

Technologies for optical packet switching are not close to the maturity that the electronic systems have reached. All of the experimental work demonstrate a subset of the functionality needed for a full-scale optical packet switch. One of the main problems in optical packet switching is buffering [104] that needs solutions based on e.g. optical delay lines or loop memories to put packets in a queue. Experimental work in optical packet switching often focus on improving functionality while not pushing the date rate to its extreme, or show simple functionality at extreme data rates. The most comprehensive work in this area has been made within the ATMOS [105],[106] and KEOPS [98],[107],[108] projects which address many issues in optical packet switching and related component technology.
Chapter 6

Conclusions & discussion

This thesis has mainly been concerned with 2R reshaping optoelectronic repeaters, focusing on associated scalability issues in fiber-optic transport networks. It has been widely recognized that noise, crosstalk and dispersion will put limits on the scalability of a linear optical network. While the use of all-optical and optoelectronic reshaping elements has been shown to improve the signal quality in digital optical transmission, cascading of such elements will introduce jitter. Here, the accumulation of jitter originating from noise, crosstalk, dispersion and pattern-dependent effects has been analyzed, leading to the conclusion that reshaping alone is not sufficient to improve the scalability of optical networks. In addition the jitter needs to be removed by retiming in a 3R regenerator, something that in practice is done exclusively in the electronic domain. The results have contributed to the increasing awareness of these problems in optical networking, and larger efforts have gone into all-optical 3R regenerators [109], [110] as an alternative and complement to electronic solutions.

It is important to note that while a limited scalability means that it can be hard to extend an installed system, it does not mean that large systems cannot be built, as is amply shown by systems in use today, mainly based on WDM and all-optical transmission. Optoelectronic and all-optical components with 1R and 2R reshaping have a potential use in future optical networks, mainly as wavelength converters, and it is important to have a good understanding of their capabilities and limitations. The scalability problems of 1R and 2R devices brings up the issue whether it can be motivated to use components without retiming in the future. With the present development of high-speed electronics, the relative complexity and cost between single-channel 1R, 2R and 3R solutions is likely to drop, leaving only the bit-rate transparency as a motivation for the 1R and 2R types. While being of the 1R type, the EDFA still has a major benefit in its multi-channel operation.

With the large-scale deployment of fiber-optics for transmission, the time it takes for research efforts to go into commercial products is decreasing rapidly and can be as short as a year. WDM and all-optical transmission is well established,
and smaller optical networks are a reality today. Due to the limited scalability such optical “islands” are interconnected with electronic regenerators and switching nodes, and fiber-optics is used to connect the nodes more efficiently. Most likely the performance and size of these optical networks are going to be improved, and can take a larger responsibility for the network functionality. At the same time, electronic systems are likely to get more efficient and to operate at higher speeds. However, so far high-speed optical systems have reached bit rates well beyond today’s electronic limits with 640 Gb/s for single-channel optical systems and a few experiments around 3 Tb/s for multi-channel optical systems. The development of technologies for high-speed optical networking is still in its infancy, and the final part of this thesis has made some advances in the wavelength converter and switching technology needed for high-speed OTDM systems.

Both parts of this thesis have investigated technologies to better utilize the capacity in optical transmission systems. However, with today’s modulation methods the available bandwidth is not used very efficiently. Recent experiments have demonstrated impressive transmission capacities of 3 Tb/s while the best achieved spectral efficiency of 0.6 bits/s/Hz still calls for improvement. The ultimate limit for the capacity can be evaluated with a famous and fundamental result by Shannon [111], which relates the signal-to-noise ratio to the channel capacity. If an optically preamplified receiver is used as a reference point, one can calculate the required optical signal-to-noise ratio for BER = 10^{-9}. With this signal-to-noise ratio Shannon’s theorem gives an upper limit on the capacity that is about 5 times the present capacity. By increasing the signal-to-noise ratio it is possible to increase the capacity further. As the demand for capacity continues to grow, advances coding methods are likely to gain more interest. There has been a fair amount of theoretical work in this area, but advances in experimental work has been more limited. To some extent this can be explained by the idea of the “infinite” bandwidth of the optical fiber when most people could not see the need for the vast capacities that have recently been achieved. Still, in order for a development in this direction on the system side, breakthroughs are probably needed in the component technology, or radically new ideas for efficient coding schemes.
Summary of original work

Here a short description of the original work included in this thesis will be given. In cases with several co-authors, a coarse description of the author’s contribution is given.

**Paper A**, “Transmission of Stationary pulses at 1.55 \( \mu m \) over 3600 km Standard Fiber Concatenated with optoelectronic Repeaters”:

This paper experimentally demonstrates a concept proposed in [63]. If linear (in optical power) optoelectronic repeaters are cascaded, it was theoretically shown that it is possible to obtain stable pulses, and extend the dispersion limit. Here this concept was experimentally investigated in a fiber-optic loop [112] built for this purpose. Different effects that were theoretically predicted are shown, including stability of the pulses, collapse of two closely spaced pulses into one single pulse. Transmission of the pulses over 3600 km was shown by use of eye diagrams.

*Contribution of the author:* All the experimental work in the paper. E. Berglind and L. Thylén suggested the experiment and participated in writing the paper.

**Paper B**, “Noise Accumulation and BER estimates in Concatenated Nonlinear Optoelectronic Repeaters”:

The noise accumulation in a 2R reshaping optoelectronic repeater is analyzed with a simple model. The noise probability distribution functions are simulated by use of a stair-case approximation, taking only amplitude noise into account. Similar contributions to the literature typically study one single stage, whereas the concatenation of many stages is the present interest. Three different nonlinearities are evaluated and it is found that the general behaviors of the different nonlinearities are similar. Further, the accumulation of the BER due to only noise amplitude is roughly linear also for a smoother nonlinearities.

*Contribution of the author:* The stair-case approximation to evaluate the noisy distribution function was made by P. Öhlén and E. Berglind. All the simulations was made by P. Öhlén.

A simple model of a 2R reshaping optoelectronic repeater is used to evaluate its properties in conjunction with transmission in an optical fiber. The vertical and the horizontal eye closure were used to find the maximum transmission distances. It is found that the use of 2R reshaping can extend the dispersion limit. If the signal is inverted in the repeater, the dispersion limit is extended even further when there is a significant amount of dispersion present.

Contribution of the author: Development of the simulation software and all simulations were made by P. Öhlén. P. Öhlén and L. Thylen came up with the idea of inverting the signal to extend the transmission distance, and all authors took part in discussion and presentation of the results.

Paper D, “BER caused by jitter and amplitude noise in limiting optoelectronic repeaters with excess bandwidth”:

A model for the transformation of noise into jitter by a reshaping function is developed. It is found that the accumulation of jitter is similar to accumulation of amplitude noise in linear systems. The result is close to [64], but the different model shows that steeper signal edges will decrease the amount of jitter. With steeper edges a larger bandwidth is needed, increasing the noise bandwidth and the noise power. In spite of this, an overall initial improvement is found as the effect of the edges increases faster than the noise power, up to a point where BER caused by amplitude noise dominate over BER caused by jitter and the total BER starts to increase again. A simple model is presented which estimates this optimum point.

Contribution of the author: The jitter model was jointly developed by P. Öhlén and E. Berglind, while the model for amplitude noise and all simulations were made by P. Öhlén.

Paper E, “Scalability issues in Optical Networks”:

This is an invited paper which is mostly composed of the results of papers A–D. In addition to this, an explanation is given for the roughly linear accumulation of bit errors also in the case of a smooth reshaping function. This is compared to the BER from jitter to find out how steep a nonlinear reshaping function has to be to be able to neglect the errors from amplitude noise, leading to the conclusion that also in the case of quite a smooth reshaping function, jitter will be completely dominating if more than 10 repeaters are passed.

Contribution of the author: The explanation of the linear accumulation of BER from amplitude noise in the case of a smooth reshaping function and the comparison with BER from jitter is made by P. Öhlén. The paper was jointly written by all authors.


A novel method for evaluating the influence of crosstalk in optical cross-connects with reshaping wavelength converters is presented. Crosstalk as well
as noise will be converted to jitter in a reshaping wavelength converter. The method gives a required signal-to-noise ratio which depends upon the crosstalk suppression in the crossconnect and the number and types of crosstalk contributions. Using this method, three different crossconnect architectures that could be built with components available at that time were analyzed with realistic values of e.g. losses and crosstalk suppression.

**Paper G**, “Measurements and modeling of pattern-dependent BER and jitter in reshaping optoelectronic repeaters”:

A reshaping optoelectronic repeater is investigated in a loop experiment [112]. It was found that the BER was quite pattern dependent whereas the RMS jitter varied only slightly, similar to results in [64]. To explain these results we use a model of a reshaping repeater, consisting of a linear filter with a long “tail” in the impulse response followed by an ideal reshaping function. With this model the experimental behavior here and in [64] could be explained quite well considering its simplicity.

**Contribution of the author:** All the experimental work and the numerical calculations were made by P. Öhlén. The model of the repeater, consisting of a desired head and a parasitic tail, was developed by both authors in cooperation.

**Paper H**, “Wavelength routing of 40 Gbit/s Packets with 2.5 Gbit/s Header Erasure/Rewriting using an All-Fiber Wavelength Converter”:

Packets consisting of a 2.5 Gb/s NRZ header and 40 Gb/s RZ payload were generated. A switching subsystem for an optical packet switch was built using a fast tunable wavelength converter. In the switch, the packet header is erased, partly due to its lower amplitude and the nonlinear transfer characteristic of the wavelength converter. The header is then rewritten, and alternate packets are converted to two different wavelengths corresponding to two different output ports. BER measurements were made on all interesting outputs. Earlier experiments of this kind have been limited to lower bit rates, or much simpler functionality.

**Contribution of the author:** The basic laboratory infrastructure for OTDM experiments was built by B.-E. Olsson. This experiment was an effort of the whole group with the main contributors being B.-E. Olsson and P. Öhlén.

**Paper I**, “Wavelength dependence and power requirements of a wavelength converter based on XPM in a dispersion-shifted optical fiber”:

The 40 Gb/s wavelength converter of [41] is investigated in more detail, by experiment and simulation. The wavelength converter is based on cross-phase modulation in a dispersion shifted optical fiber, and the most important parameter is the dispersive walk-off in the fiber between the pump and the probe. Also, depending on how the conversion is made different performance is achieved. Simulations verify the experimental results, and indicate the feasibility of wavelength conversion of 2 ps pulses, suitable for 160 Gb/s.

**Contribution of the author:** The measurements and the simulations in the paper were made by P. Öhlén. The planning of the experiments and simulations was made by P. Öhlén and B.-E. Olsson.
Paper J, “All-optical header erasure and penalty-free rewriting in a fiber-based high-speed wavelength converter”:

A method to erase and rewrite the header, somewhat different from paper H is investigated. With this approach, some stability issues for the rewriting of the header in paper H are eliminated, but an optical gate with high extinction ratio is needed. In the erasure of the header, the lower bit rate of the header information is essential. The differentiating nature of the wavelength converter only converts the high-speed RZ payload, while erasing the lower-speed NRZ header.

Contribution of the author: The idea to use only the differentiating nature of the wavelength converter, and the measurements were made by P. Óhlén. The planning of the experiments were made by P. Öhlén and B.-E. Olsson.
Bibliography


Bibliography


