Chapter 1

Introduction

Mankind has always throughout its history had the necessity for communication. Initially communication was done through signals, voice or primitive forms of writing. As time passed by there was a need to communicate through distances, to pass information from one place to another. Many different ways to exchange information over long distances have been used throughout history, some of them exotic such as the use of pigeons and smoke signals. All these methods were the evolutionary steps, which have led to today's modern technologies of long-distance communication. Today's long distance communications involve the transmission and reception of a large amount of information in a short period of time. This thesis investigates certain aspects of one of these technologies, wavelength-division multiplexing, a technique that involves the transmission of multiple signals over a single optical fiber using different wavelengths of light as the optical carriers.

Optical communications are not a privilege of the modern era. In fact, one could say that the Egyptians invented optical communications almost 5000 years ago when they discovered glass and experimented using it together with the sun to transmit signals. In the VI BC century, the Greeks used torches to transmit the fall of Troy. And in 1791 Claude Chappe invented the *Semaphore*, which is considered to be the first high-speed digital communications system [1]. The *Semaphore* was a system which consisted of mechanical arms, that was installed on the top of a tower and operated manually. Using a chain of such devices it was possible to transmit messages over distances of around 150 miles in only 15 minutes [2]. All these inventions can be considered to be the ancestors of modern day optical fiber communications systems.

1.1 Optical Fiber Communication Systems

The most elementary type of communication system consists mainly of three components, the transmitter, the receiver and the channel [3]. The channel in this system is the medium, be it wire, coaxial cable, air, or an optical fiber. Figure 1.1 illustrates one such system where the fiber is used as the medium.

When the telephone was invented in 1876 there was a complete revolution in the world of communications and for many years metallic cables consisting of twisted wire pairs were the media of choice. However, metallic cables had limitations and with the demand for telephone services increasing it was necessary to find an alternative medium for telephony to cope with the high demand.

In 1966 Kao and Hockham [4] solved this problem by proposing the use of the optical fiber. The optical fiber was a perfect match for the laser, which had been invented in 1960 by Maiman [5] and up to then, had no practical use in communications. The light- guiding properties of optical fiber had been known for many years, but prior to the work of Kao and Hockham their attenuation was greater than 1000 dB/km. Kao and Hockham showed that these high attenuations were a result of impurities, and that low attenuation might be achieved if the impurities were controlled. This was first achieved in 1970 when Kapron et. al. fabricated the first low-loss optical fiber with attenuation around 20 dB/km at a wavelength of 0.63 μm. Eventually, this led to the first commercial deployments of practical fiber systems in 1977-78 [1]. These operated at 0.85 μm, had a bit rate of 50-100 Mb/s and used electrical repeaters spaced 10 km apart to amplify and reshape the signals.

Current optical fiber communication systems operate at 1.3 μm and 1.55 μm where the attenuation is lower than at the shorter wavelengths [6]. These advances are due to not only better fibers but also because of the design of compatible light sources (transmitters) and photodetectors (receivers) at these wavelengths. The emergence of optical amplifiers has also contributed to improvements in this field. However, it should be noted that research in the fiber optics communications area is far from done as we have not yet even come close to achieving the transmission capacity offered by the fibers.

1.2 Wavelength Division Multiplexing

In the last few years there has been an enormous increase in telecommunications services that demand large amounts of bandwidth. Services such as interactive multimedia, video conferencing, and streaming audio have made the capacity of the existing optical fiber systems insufficient. To increase this capacity, time division multiplexing (TDM) has been used traditionally; a TDM scheme is shown in Figure 1.2 [7,8]. However, TDM has a few drawbacks. One of the biggest is that the existing electronic technology allows multiplexing only up to about 10 Gb/s.

Thus, an alternative optical multiplexing technique that avoids the 10 Gb/s electronic bottleneck is very attractive. Wavelength-division multiplexing (WDM) is one such promising technique that can be used to exploit the huge available bandwidth of the optical fiber. Figure 1.3 illustrates a typical WDM system [9,10].

In WDM, the optical transmission spectrum is divided into a number of non-overlapping wavelength bands, with each wavelength supporting a single communication channel operating at peak electronic speed [11,12]. Thus, by allowing multiple WDM channels to coexist on a single fiber, the huge bandwidth can be tapped into.

Besides the higher capacity, WDM has also some other advantages [7,9]. One advantage is the easy upgradability. By employing multiple wavelengths within the passband in the optical fiber it is possible to reuse the same optical fiber cable without changing the in-line equipment. The potential lower cost is also another advantage; optoelectronic chipsets with multiwavelength sources, amplifiers, multiplexers, and filters on a single package might be available commercially in the near future. The use of wavelength for add-drop multiplexing and routing in networks is also an attractive feature in WDM.

While WDM is very attractive, it has some disadvantages also [7]. One such disadvantage is the appearance of fiber nonlinearities. Normally, each channel requires about 1 mW, and with the use of multiple channels, several miliwatts are injected into the fiber. Such high powers lead to the appearance of different nonlinear effects in the fiber, such as the Stimulated Raman scattering (SRS), Stimulated Brillouin scattering (SBS), Four wave mixing (FWM), and the Cross Phase Modulation (XPM). These nonlinear effects lead to the degradation of system performance.

1.3. Spectrum-Sliced WDM Systems

Conventional WDM systems utilize narrowband coherent laser diodes as transmitters. These laser diodes are normally fabricated to be tunable over a wide range of wavelengths. If the number of channels in a WDM system is increased so does the number of laser diodes used in the system and consequently the cost. This motivated researchers to look for a lower-cost alternative. Spectrum-slicing provides a low-cost alternative by utilizing narrowband spectral slices of a single broadband noise source for creating the multichannel system. Figure 1.4 illustrates a generic spectrum-sliced WDM (SS-WDM) system [9].

Spectrum-slicing was first proposed in 1985 by Pendleton-Hughes *et al.* for short-haul LAN applications [7,13]. In 1988, this same system was also demonstrated by Reeve at the British Telecom Research Laboratories by using LEDs and a singlemode optical fiber [14]. This initial system had four wavelength channels, each operating at 2 Mb/s, and used identical LEDs at the wavelength of 1.3 μm.

The first SS-WDM systems were limited to small distances and low transmission capacity. In 1993, a major breakthrough in spectrum-sliced WDM systems came about when Lee *et al.* from the AT&T Bell Labs proposed the use of broadband amplified spontaneous emission (ASE) noise obtained from erbium-doped fiber amplifiers (EDFA's) [15]. This development permitted high bit rate transmissions using spectral slices. It should be noted that as the high power ASE is already in the fiber, it is more efficient to divide it into multiple channels by using integrated optic demultiplexers.

There have been some significant developments lately [7]. One of them is the design of a 100-mW spectrally uniform broadband amplified spontaneous emission (ASE) source by Sampson *et al.* at the University of Melbourne in Australia. Also, various erbium-doped fiber amplifiers (EDFA)-ASE source-based transmission experiments have been made, with Han *et al.* from KAIST, Korea reporting the best transmission capacity, 2.5 Gb/s over 200 km of dispersion-shifted optical fiber.

In the near future, the experimental results will become reality and spectrum-slicing is a strong candidate for fiber-to-the-home networks, and has even potential for cost-sensitive local area network applications which require channel bit rates of several Mb/s over distances of several kilometers [16].

1.4. Motivation for this Thesis

The main objective of this thesis is to advance the analysis of spectrum-sliced WDM systems, particularly in the case where there is interchannel interference. We evaluate receiver performance when interchannel interference caused by filter overlap is present [17]. Previous works have analyzed the performance of SS-WDM systems either by using the Gaussian Approximation, a popular method due to its simplicity, or a Chi-Square Approximation to evaluate the receiver performance. In this work, an alternative method called the Saddlepoint Approximation is used to evaluate the receiver performance. It is initially used in the ideal case where no interchannel interference is present; this is done for purposes of proving the validity of the method. Later, the use of the method is extended to evaluate the effect of interchannel interference on the system, which is our main objective.

The Chi-Square Approximation assumes that the distributions of the data signal and the noise are both chi-square as well as the received signal, which is their sum [7,18]. However, in general, the sum of two chi-square random variables is not chi-square distributed. Although the evaluation of the probability density function for this case is difficult, the moment generating function (MGF) may be obtained rather simply. In this thesis, the Saddlepoint Approximation is used to evaluate the performance of the receiver from the MGF. The main contribution of this research is to show that for small filter overlap, use of an equivalent chi-square distribution is valid, but when the overlap becomes larger, the performance approaches that calculated using the Gaussian approximation. For larger values of channel overlap the Chi-Square approximation yields results which are too optimistic, and the Gaussian approximation gives results which are too pessimistic for smaller values of channel overlap.

It is also shown that there is a small improvement in the total system transmission capacity when there is some interchannel interference present which proves that it is possible to operate the system with some interchannel interference while also improving the performance. The results obtained in this thesis are important in the performance analysis of practical spectrum-sliced systems as they illustrate the maximum achievable limits of these systems and also they will aid in the design of future systems.

1.5 Thesis Outline

This thesis is organized as follows:

In **Chapter 2** the system model used in the analysis is presented along with the mathematical formulation for the receiver when an OOK modulation scheme is used. This initial mathematical formulation is important as it defines the decision statistics of the received signal in terms of its Moment Generating Function (MGF). The use of the MGF of the received signal is the idea behind the use of the saddlepoint approximation in calculating the receiver performance. After presenting the idea of using the MGF to evaluate receiver performance, the Saddlepoint Approximation is presented and it is used to evaluate the receiver performance when a rectangular filter is used and interchannel interference is not present. The results are validated then by a comparison with results obtained by the exact calculation [18]. Results obtained by the Gaussian Approximation are also presented, and it is shown that the results obtained by the Gaussian Approximation are very pessimistic in this case.

In Chapter 2 we assume the use of ideal, rectangular spectra for the signal and noise at the receiver. **Chapter 3** evaluates the effect of non-rectangular optical filter shapes on receiver sensitivity with the use of the Saddlepoint Approximation. The transmitter and receiver optical filters are both modeled as order N Butterworth filters, and it is shown that the receiver sensitivity degrades when the order of the filter is reduced. It is shown that the results obtained by the Saddlepoint Approximation, particularly with low-order filters, is more similar to the results obtained with the Gaussian Approximation rather than by those obtained with the chi-square analysis.

Chapter 4 is the main contribution of this thesis. The Saddlepoint Approximation is applied to the interchannel interference case caused by filter overlap. The results are then compared with those obtained with the Gaussian Approximation and also those obtained if an equivalent chi-square distribution is assumed. We demonstrate that for lower values of the overlap parameter, the chi-square approximation is valid, but as the interchannel interference increases the performance of the system resembles more to that obtained with the Gaussian approximation. We evaluate the effects of interchannel interference caused by one channel and also by both adjacent channels. It is shown that double-sided interchannel interference degrades system performance much more aggressively than single-sided interference.

We conclude this thesis with **Chapter 5**, where a summary of the principal contributions resulting from this work is given. Also, some recommendations for future research in this field are made.

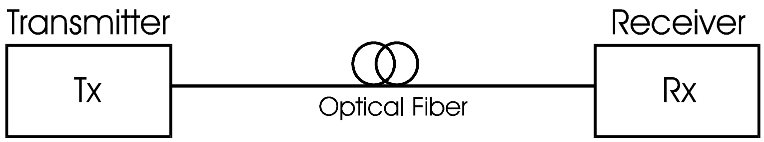

Fig 1.1: *Basic Fiber Optic Communication System*

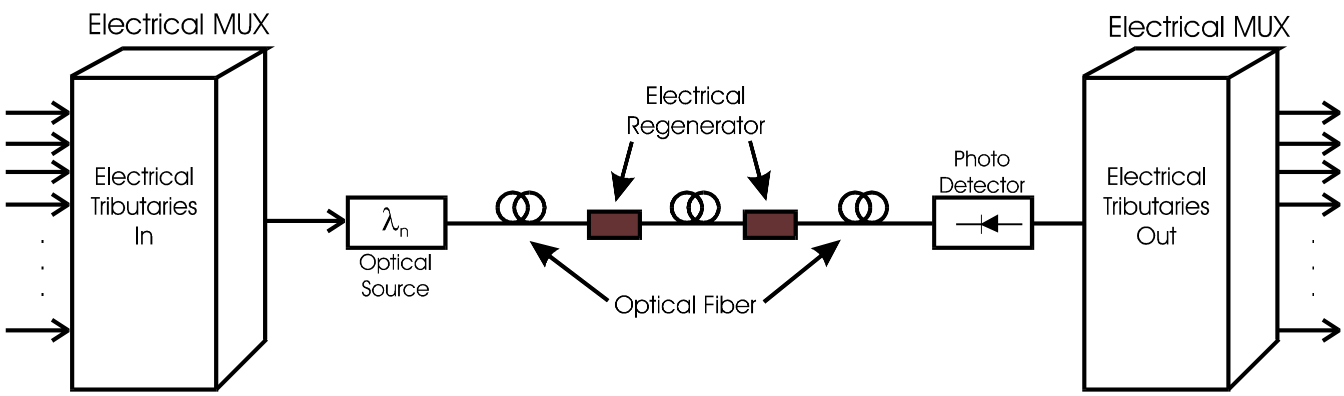

Fig 1.2: *TDM configuration for lightwave system*

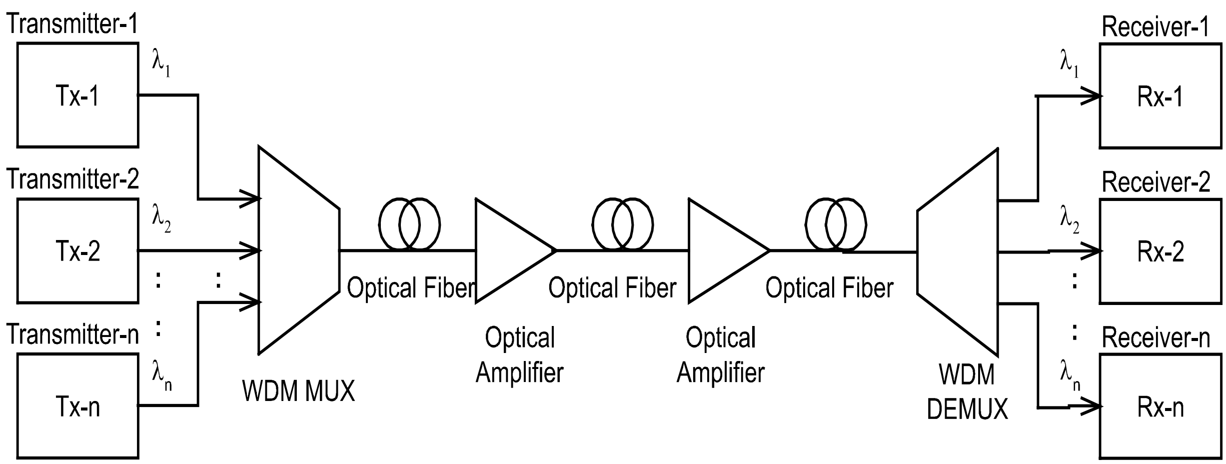

Fig 1.3: *Schematic of the wavelength division multiplexing (WDM) architecture*

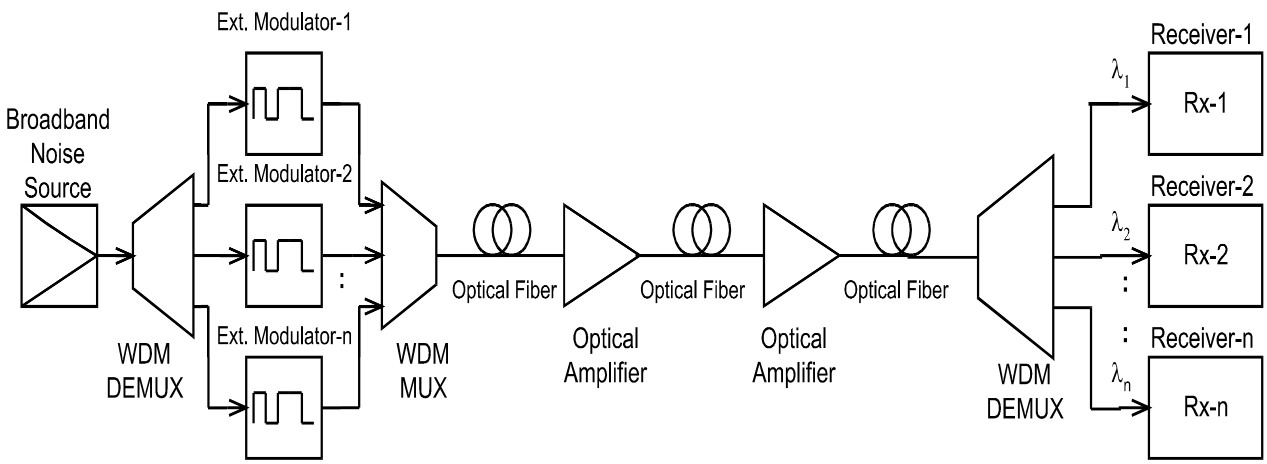

Fig 1.4: *Spectrum-sliced WDM system*