Chapter 1

Introduction

Generation, transfer, and utilization of information using novel means has been the primary motivation of technological advances in the latter half of this century. Rapid advances in four areas: microelectronics, photonics, software and networking have been key factors contributing to this evolutionary process. Perhaps the single-most important factor in the genesis of the global village, served by the information highways and byways, has been the explosive growth in lightwave communication systems and networks. This has manifest itself in the ability to send and receive millions of bits of voice, video and data information around the globe in real time and with no apparent distortion. This dissertation will attempt to investigate one of the key enabling technologies, termed wavelength division multiplexing, which is making lightwave systems and networks useful and cost-effective for not only long-haul transoceanic distances, but also for local access and distribution systems.

The history of building tools, which could be used to inform and communicate, dates back to the 1st century AD when the paper and graphite pencil were invented [1]. Subsequent related innovations in later years, particularly in the last century, have been astonishing. The advent of the telephone, transistor, personal-computer, optical fiber and present day wireless radio communication systems has been instrumental in spawning multi-billion dollar technology-driven markets around the globe. The main effect of these efforts has been a chain-like reaction where technology feeds itself and grows at an explosive pace. Today, fax machines, cellular phones, LCD displays, electronic mail, the World Wide Web and the telephone act as ubiquitous carriers of information and have become a way of life. The trend now is towards the design and implementation of digital,

mobile, and interactive multimedia systems, as opposed to the analog, fixed and primarily voice/text oriented systems of earlier years. The key technologies that are making this possible are wireless and lightwave systems, display technologies, battery technology, and new hardware/software with increased processing powers. The regulatory climate around the globe has responded to this evolutionary process with increasing liberalization, modernization, and deregulation of its communication infrastructure [2].

1.1 Optical Fiber Communication Systems

The application of light as a communication medium dates back to antiquity when fire and smoke signals were used to convey information. Signaling lamps, flags and other semaphore devices of the 18th century were subsequently replaced by the invention of the telegraph which gave light the back seat and started the era of electrical communications. The invention of the telephone in 1876 fueled the demand for communication services and led to many advances in the design of coaxial cables and twisted wire-pairs. However the limited capacity of the coaxial cable due to increasing losses at higher frequencies (~10 MHz) forced communication engineers to investigate alternate systems, and led to the design of microwave systems (~ few 10's of GHz). By 1970, systems with bit rate (B) and inter-repeater distance (L) products (BL) of 100 Mb/s-km were available; however it was realized that the electrical communication systems had reached their technological tethers due to fundamental limitations.

The ability to use optical waves as carriers to increase the BL product by several orders of magnitude was realized comparatively recently, as late as the latter half of the 20th century. The main objective then was to find a) a suitable device which could emit a coherent high power light beam, and b) a suitable transmission medium. The first requirement was fulfilled in 1960 with the invention of the first laser. The second requirement, *i.e.* of a suitable medium to transmit light pulses with very little distortion, was solved in 1966 when the first optical fiber was proposed by Kao and Hockham in their seminal paper [3]. However fibers available during the 1960s had an attenuation of greater than 1000 dB/km. This obstacle was soon overcome by researchers led by

Donald Keck at Corning when they fabricated the first low-loss optical fiber in 1970 with attenuation around 20 dB/km in the wavelength region around 0.63 μm [4]. These research developments eventually led to commercial deployments of practical fiber systems operating at 0.8 μm, in 1978 at a bit rate of 50-100 Mb/s, and with electrical repeaters spaced 10 km apart to amplify and reshape the signals.

Subsequent refinement in the fiber fabrication process have led to lightwave systems at 1.3 μm and 1.55 μm. These advances have been made possible by the design of compatible light sources (optical transmitters) and photodetectors (optical receivers). Table 1.1 charts the evolution of optical fiber technology in its first 25 years of existence. The most notable achievement in recent years has been the emergence of optical amplifiers, fabricated by doping the core of the optical fiber with active rare earth ions (erbium, neodymium, praseodymium). Such all-fiber amplifiers are rapidly replacing the electronic regenerators of earlier years [1,5].

Table 1.1: *Progress in lightwave communications technology.*

Generation	Year	*BL* (Mb/s-km)	Technology Features
1	1974	5	• 0.85 μm based systems using multimode optical fiber • systems limited by fiber intermodal dispersion and intrinsic fiber loss
2	1977	200	• 1.3 μm based systems using singlemode optical fiber • systems characterized by reduced fiber loss and negligible dispersion
3	1980	500	• 1.55 μm based systems using singlemode optical fiber • systems characterized by lowest fiber attenuation but finite fiber dispersion
4	1984	750	• 1.55 μm based systems employing coherent detection • although higher SNRs achievable, system more complex
5	1987	> 100,000	• linear 1.55 μm systems employing erbium-doped fiber amplifiers, WDM, and dispersion-shifted fiber • nonlinear soliton-based systems which offer theoretically perfect resistance to dispersion

1.2 Wavelength Division Multiplexing

Conventional optical fiber systems are based on intensity modulating the output of a laser diode by the information carrying signal. After traversing through the optical fiber, this signal is detected using incoherent (direct) detection at the receiver. Such intensity modulated/direct detection (IM/DD) high bit rate systems have traditionally been used as the backbone of the telecom network which is characterized by low-bandwidth data rate (64 Kb/s) channels. However contemporary user services, which include bandwidth voracious services such as interactive multimedia and video teleconferencing, put much more stringent demands on the capacity of the optical fiber system. The traditional approach to higher system capacities, as shown in Fig. 1.1a, has been to use a higher level of time division multiplexing (TDM). However present technology does not allow electronic TDM systems to be used for multiplexing in excess of 10 Gb/s; moreover a line rate of 10 Gb/s also gives rise to deleterious dispersive effects in the optical fiber [6]. The other problem with TDM is that intermediate nodes waste a lot of processing power for synchronization on information that is not of their relevance.

Optical multiplexing techniques that avoid the 10 Gb/s electronic bottleneck are currently in high demand. Two of the most attractive candidate systems for avoiding this obstacle are based on wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM) [7]. A schematic of an OTDM system is shown in Fig. 1.1b. The system employs a train of picosecond pulses from an appropriate laser source which are then split N ways. Each optical train is individually modulated at B Gb/s, optically delayed by a fraction of a bit period, and then synchronized for passive multiplexing to produce a line rate of $N X B$ Gb/s. Although recent advances in OTDM technology show it to be feasible for high data rate applications, the complex multiplexing and demultiplexing involved has been a stumbling block.

WDM based systems, shown in Fig. 1.2, employ the operating wavelength as the extra degree of freedom to maintain the same line rate, but reduce the individual data rates carried by the different wavelengths. The lower data rate per channel not only reduces the dispersion penalty, but also helps combat other degrading effects in the fiber system. The main advantages (A) and

disadvantages (D) of WDM systems, and their state-of-the-art are described in the following sub-sections.

1.2.1 Why WDM ?

WDM promises to be the supporting technology for the next generation of long-haul terrestrial and transoceanic systems, as well as short-haul LANs/MANs and local access/distribution networks. The major reasons for the widespread acceptance of WDM may be summarized as follows [6-8].

A1.   ***Higher capacity and upgradability:*** The capacity of the low attenuation passband (around 1.55 μm) in the optical fiber is theoretically around 25,000 GHz. By employing multiple wavelengths within this passband, it is possible to reuse the same optical fiber cable without changing the in-line equipment (true only for systems with optical amplification). Thus capacity is increased with little complexity; moreover this capacity can be easily upgraded. The new US Telecom Bill of 1996 promises all users *broadband* coverage which is only possible through high capacity WDM systems and networks.

A2.   ***Protocol transparency:*** Each information carrying wavelength in a WDM system, termed as a "lightpath," is like an independent fiber which can carry its individual maximum bit rate, framing convention and data protocol. This feature is not merely of academic interest since it provides a rich diversity to the resulting network, much like the traditional telephone line which is able to support different communication formats such as ASCII, binary, teletype, fax, voice, compressed video, 28.8 Kbaud *etc.*

A3.   ***Potentially lower cost:*** The cost of optoelectronic devices is gradually decreasing since most components are now being monolithically integrated on semiconductor substrates. Optoelectronic chipsets now have the multiwavelength sources, amplifiers, multiplexers, and filters on a single package. (Although the costs of WDM equipment are decreasing, they are

still not at a stage where fiber-to-the-home (FTTH) or fiber-to-the-curb (FTTC) are currently

cost effective)

A4.   *Network survivability and flexibility:* The multiple channels available with WDM

transmission can more readily withstand a sudden surge in traffic if there is an interruption in

another part of a network requiring data to be re-routed through this multiple-channel fiber.

Moreover the availability of multiple channels also allows the implementation of redundancy

into the system, or of reserving individual channels for special purposes such as out-of-band

signaling and network control [9].

As outlined above, WDM systems have a number of advantages which is making their widespread

acceptance a matter of time. However there are still some practical issues that need to be considered

while designing and installing a WDM system. These issues, or disadvantages (D), are

summarized as follows [6-8].

D1.   *Limitation on wavelength number:* The number of wavelengths that may be employed in

WDM systems is limited by the crosstalk requirements of the system, and more importantly, by

the gain flatness of the fiber amplifiers used in long-haul optically-amplified systems. The

gain-flatness of amplifiers is important since otherwise different channels experience different

amounts of attenuation along the system. Although a single optical amplifier has only 3 dB gain

variation in its passband, a cascade of such amplifiers results in a gain filtering effect which

further reduces the available flat-gain bandwidth.

D2.   *Fiber nonlinearities:* High optical power per wavelength channel is essential for long-haul

systems to traverse longer unrepeatered distances, and also for local access/distribution

networks which have large power losses due to couplers and taps along the network. Typically

1 mW of optical power is injected into the fiber per channel, which in case of multiple channels

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means several milliwatts into the same fiber. Such high powers give rise to diverse nonlinear effects in the optical fiber. The major nonlinearities that the WDM system is susceptible to are:

- *Stimulated Raman scattering (SRS)*: Basically a result of inelastic collisions, the strong light in the small fiber core reacts with the molecular vibrations of the fiber material to radiate light at a wavelength longer than that of the incident light. Thus energy is transferred from shorter to longer wavelengths.

- *Stimulated Brillouin scattering (SBS)*: Another form of inelastic scattering, here the strong light in the fiber interacts with acoustic vibrations in the fiber and results in a loss of signal energy.

- *Four wave mixing (FWM)*: High optical powers lead to a variation of the refractive index of the fiber core which produces an interaction between the signals that are closely spaced in wavelength. Hence new frequencies (wavelengths) are produced according to $\omega_{ijk} = \omega_i + \omega_j - \omega_k$ where $\omega_{i,j,k}$ correspond to the operating frequencies of three closely spaced channels *i, j* and *k*. This interaction is only possible when the propagation constants of the fundamental modes in the three channels are phase matched, or have the same group velocities. This condition is readily met when a zero or near-zero dispersion fiber is used.

- *Cross phase modulation (XPM)*: The refractive index variation due to high powers in a particular channel manifests itself as a nonlinear phase shift which depends on not only the optical power of a particular channel, but also on the power of adjacent channels. This crosstalk, called XPM, may occur due to the signal at one wavelength affecting the refractive index, and causing an interaction with a different wavelength signal.

D3.	***Emergence of OTDM:*** Optical time division multiplexing has shown the potential of multiplexing in excess of 100 Gb/s, with corresponding distances over 200 km. The main advantage of these systems is that they use only a single wavelength channel of around 1 nm bandwidth, to transmit the entire OTDM data. A comparable WDM system at 40 Gb/s, *e.g.*

implemented using 16, 2.5 Gb/s channels spaced 2 nm apart, would occupy the entire bandwidth of an optical amplifier. Moreover OTDM only requires a single laser source and does not place stringent requirements on control of filter and transmitter wavelengths, as needed in WDM.

Although the disadvantages mentioned above are a concern and have to be considered by system designers, a number of solutions are emerging which make WDM conceptually easier to implement and maintain. For example, recent research on erbium-doped fiber amplifiers has shown that by changing the base material from silica to fluoride, higher gain flatness may be achieved. Meanwhile, a number of gain equalizing filter configurations are also being demonstrated for silica-based EDFAs and gain bandwidths of over 40 nm have been reported [11]. Fiber nonlinearities are a big concern, but their deleterious effects are being reduced by channel allocation strategies which vary the channel spacing so that FWM products do not fall into the bandwidth of a particular channel. Other dispersion management schemes are also being investigated in which overall dispersion of the fiber link is nearly zero, but by varying the sign of the local dispersion and by keeping it finite, the effect of nonlinearities is minimized. OTDM is becoming more popular but it requires active demultiplexers and controlled channel assignment systems, hence practical deployment is complicated. Overall, WDM is promising to be the technology of choice for next generation high capacity systems (5-10 Gb/s). Commercial systems from major companies like Lucent Technologies, Ciena, and Nortel are already available.

1.2.2 State-of-the-art

As in most other technical fields, system performance achieved in the laboratory is often many orders of magnitude greater than that available commercially. WDM is no exception. The maximum transmission capacity that has been achieved to-date is a 2.6 Tb/s aggregate capacity. This result was reported by a group from NEC Corp., Kawasaki, Japan, who transmitted 126 channels, each at 20 Gb/s [12]. The first terabit per second results were reported by researchers

from three different companies: Fujitsu Labs (Kawasaki, Japan), AT&T/Lucent Technologies (New Jersey, US) and NTT Optical Network Systems (Kanagawa, Japan using primarily optically amplified WDM based systems [12], at the 1996 Conference on Optical Fiber Communications. These experiments bode a successful future for WDM technologies in both the short-term and the longer-term.

The maximum capacity system obtained commercially, however, is a 40 Gb/s (16 channels, each at 2.5 Gb/s) system from Ciena Corp., known as the MultiWave^{TM} 1600.

1.3 Spectrum-Sliced WDM Systems

Conventional WDM systems are based on using narrowband, coherent laser diodes, which emit over a bandwidth that is only a fraction of a nanometer. The traditional wisdom is to fabricate such devices to be tunable over a wide range of wavelengths. Accordingly there is also interest in designing narrow spectral width passband filters. However there exists a tradeoff between the speed, bandwidth, and tuning range of such devices with the major challenge being the achievement of high speed tuning over a wide spectral range [13]. This has motivated researchers to look for lower cost alternatives. Spectrum-slicing is one such attractive alternative which is based on taking narrowband spectral slices of a broadband incoherent source to create the multiple wavelength channels. A schematic of a spectrum-sliced WDM (SS-WDM) system is shown in Fig. 1.3.

The filtering or slicing of narrowband channels from a broadband source was first proposed in 1985 by Pendleton-Hughes *et al.* for short-haul LAN applications [14]. Reeve and his co-workers at the British Telecom Research Laboratories (BT labs) in the UK demonstrated the same using LEDs and singlemode optical fiber [15]. Four wavelength channels, each at 2 Mb/s, were created using identical LEDs at 1.3 μm, and the system was demonstrated for local-loop (central-office to subscribers) applications. The main motivation was to keep the wavelength selective components identical for easier maintenance. Researchers in the US soon took notice with Wagner *et al.* at Bellcore experimentally demonstrating [16] a 10 channel 150 Mb/s system over 7 km of singlemode fiber using superluminescent LEDs (SLED). The limitation in that system was the

severe power penalty incurred by the spectral slicing technique which rejected any power outside the passband of the component used to perform the WDM. Kilkelly *et al.* at BT Labs solved the power penalty problem by operating at 1.55 μm thus taking advantage of optical fiber amplifiers. Using a high power SLED, they transmitted 140 Mb/s on 3 channels, over a span of 110 km which incorporated one in-line EDFA. The authors reported the appearance of error floors when the input signal power to the EDFA was reduced [17]. Meanwhile, a number of other SLED-based spectrum-sliced systems were also reported [18].

The limitations on the maximum SNR placed by the incoherent, noisy source was first pointed out by Liu at IBM [19]. She identified an additional noise term, known as the excess beat noise, which arises because of the beating between the different frequency components of the incoherent stochastic light source. This noise term places an upper limit on the maximum SNR that may be achieved from a spectrum-sliced system. The author highlighted the fact that as the per channel optical bandwidth decreases, the increasing noise spectral density (due to source fluctuations) gives rise to irreducible error rate floors. A simple upper limit to the number of channels due to signal-signal beat noise alone was calculated to be a function of the ratio of the optical to electrical bandwidths.

1.3.1 Use of EDFA-ASE as Broadband Source

A major breakthrough in spectrum-sliced multichannel WDM systems came about in 1993 when Lee *et al.* at AT&T Bell Labs proposed and demonstrated the use of the amplified spontaneous emission noise (ASE - see Chapter 2) from an EDFA as a potentially inexpensive broadband source [20]. Since the high power ASE is already in the fiber, it is more efficient to divide it into multiple channels by integrated optic demultiplexers. A schematic of the proposed ASE source and the filtered channel is shown in Fig. 1.4. The experiment consisted of taking a 1.3 nm slice of the 40 nm ASE spectrum, and using the resulting source for the transmission of 1.7 Gb/s data. The authors identified the principal system degrading factor to be the spontaneous-spontaneous beat noise from the EDFA source. Error rate floors were observed when the channel optical bandwidth

was reduced, which was expected. Similar experiments were also reported with a 0.68 nm ASE bandwidth, using polarization-insensitive electroabsorbtion modulators to increase the amount of source (EDF-ASE) power [21].

Excess noise due to the beating between the spontaneous emission components is the primary reason for the upper limit on the performance of spectrum-sliced systems. The analysis of this is primarily treated by assuming the incoherent light to be continuous-wave (CW) and so the relatively simple expression for beat noise limited SNR (see Chapter 3)

$$\text{SNR} = \frac{n_p B_o}{2 B_e}$$

may not be an accurate representation for the practical system scenario where the optical carrier is modulated. Here B_o is the optical bandwidth, B_e is the electrical bandwidth, and n_p refers to the degree of polarization of the incoherent light with $n_p = 1$ for polarized light, and $n_p = 2$ for unpolarized light. The theoretical analysis and experimental correlation of this effect of optical modulation on the SNR of spectrum-sliced sources was reported by Lee [22]. According to his analysis, the above expression for SNR does not remain constant, but instead changes with time, as a function of the receiver electrical filter and the extinction ratio (on to off ratio), when the optical carrier is modulated. The effect of optical modulation, for example in a "1-0" pattern transmission are to cause the SNR to increase even when the "1" has completely terminated, due to delayed signal components from that mark and the present space adding in phase. On the other hand, the beat noise components do not add in phase, thus yielding a large SNR past the maximum signal value. Hence the receiver sampling (decision) time needs to be carefully controlled. The author also recommended use of the non-return-to-zero (NRZ) format for spectrum-slicing since the mark duration should be sufficiently long to stabilize SNR.

Other recent developments in spectrum-sliced WDM have included a) design of a 100 mW spectrally-uniform broadband ASE source by Sampson *et al.* [23] at the University of Melbourne, Australia, b) various transmission experiments, with the best capacity obtained by Han *et al.*, KAIST, Korea, reporting a 2.5 Gb/s transmission of spectrum-sliced WDM channels over 200 km

of dispersion-shifted optical fiber [24], and c) other proposals to use spectrum-slicing for optical interconnects [25], for synthesizing microwave filters [26], and for interrogating optical fiber-based sensors [27].

1.3.2 Spectral-Slicing for Local Access Networking

A rapidly emerging application area that is exploiting the low-cost potential of spectral-slicing is local access network applications, especially those using waveguide grating routers (WGR). Hailed as the most innovative product of 1995 by the Photonics Spectra magazine, the WGR was invented by Bell Labs researcher Corrado Dragone [28]. In its simplest form, shown in Fig. 1.5a, it consists of two star couplers connected by an array of waveguides, each with a progressively greater length. This phase progression provides the wavelength dispersion needed to separate multiple WDM wavelengths. Hence the router can route WDM channels, as shown in Fig. 1.5b, not only on the basis of their input ports, but also on their wavelengths. Since its inception, the WGR has proven to be extremely versatile, having been integrated monolithically with amplifiers to act as a multifrequency laser comb-type source [29], demultiplexer, and tunable receiver.

The primary goal of local access is to provide bi-directional communication channels, with the Optical Network Unit (ONU) at the subscriber end to Central Office (CO) channel, termed upstream, being very low-cost, and the reverse channel, termed downstream, serving as a multiple-access medium and distributing the high cost of components among a number of subscribers. Such local access systems, that use only passive filters and routers, are called Passive Optical networks (PON). Traditionally TDM has been used in such PONs because of its straightforward implementation. However the TDM-PON has an inherent N^2 power penalty due to splitting and time sharing. On the other hand, in WDM PON systems, downstream WDM channels are essentially independent of each other, thus simulating a one-fiber-per-ONU and receiving a dedicated wavelength channel. The WDM connectivity is then established by WGR's. Broadband sources used at the CO are spectrally-sliced by the WGR. Since the free spectral range (FSR) of the router is much smaller (~ 3-4 nm) than the 3-dB bandwidth of the broadband source (~ 60 nm

for an LED), multiple modes are directed towards each ONU. Thus almost equal power is directed towards each ONU, and the behavior is similar to that achieved with a star coupler. Using such system configurations, both baseband voice/data [30] and video [31] services have been transmitted.

1.4 Motivation for this Dissertation

The major objective of this dissertation is to investigate the performance of systems employing spectrum-slicing, for implementing wavelength-division-multiplexing (WDM) in optical fiber systems. Spectrum-slicing provides an attractive low-cost alternative to the use of multiple coherent lasers for such WDM applications by utilizing a spectral slice of a broadband noise source for the different data channels. The principal broadband noise source considered is the amplified spontaneous emission (ASE) noise from an optical amplifier. Each slice of the spectrum is actually a burst of noise that is modulated individually for a high capacity WDM system. The stochastic nature of both the signal and the additive noise in the system poses an attractive problem for performance optimization using diverse strategies which have not yet been investigated. This need for performance optimization of spectrum-sliced WDM (SS-WDM) systems is the primary motivation for this dissertation.

The main contribution of this research has been to analyze the performance of SS-WDM systems when an optical preamplifier-based receiver is employed. In that case, it is shown that there exists an optimum filter bandwidth which minimizes the detection sensitivity (in terms of the average number of photons/bit) for a given error probability. Moreover the evaluated detection sensitivity represents an order of magnitude (> 10 dB) improvement over conventional detection techniques for such spectrum-sliced communication systems. Analysis is performed using the commonly used Gaussian approximation, as well as a more exact chi-square distribution. Results from both these distributions are compared. Both OOK and FSK systems are treated in this work and it is shown, for the first time, that spectrum-sliced FSK may offer some very important advantages as compared to its OOK counterpart. Although initial analysis has assumed rectangular spectra, we also evaluate the effect of non-rectangular and more practical optical filter

shapes on receiver sensitivity. The potential application of performance-optimized spectrum-sliced WDM systems will be in both local loop and long-distance fiber communication systems which require low-cost WDM equipment for high data rate applications. We believe that the results from this work will be instrumental in understanding and designing future spectrum-sliced WDM systems.

1.5 Outline of this Work

This dissertation is organized as follows- **Chapter 2** presents a discussion on signal detection and estimation techniques commonly used in deterministic, or coherent laser-based systems. A discussion of optoelectronic receivers and related noise mechanisms is given. The performance of digital lightwave systems is often characterized by the average optical power required at the receiver to limit the errors in the received bits (bit error rate). Receiver performance is characterized by the normalized unit of photons per bit required to maintain a given error probability. Both the ideal and practical limits are discussed for receiver performance. This is followed by an overview of optical amplifiers, especially erbium-doped fiber amplifiers, which are now being used in most long-haul terrestrial and transoceanic lightwave systems, and are also finding applications in local access and distribution networks. Analytical expressions for the receiver sensitivity of fiber systems for different modulation schemes (OOK and FSK) employed in a transmission system that uses optical preamplifier receivers, are presented.
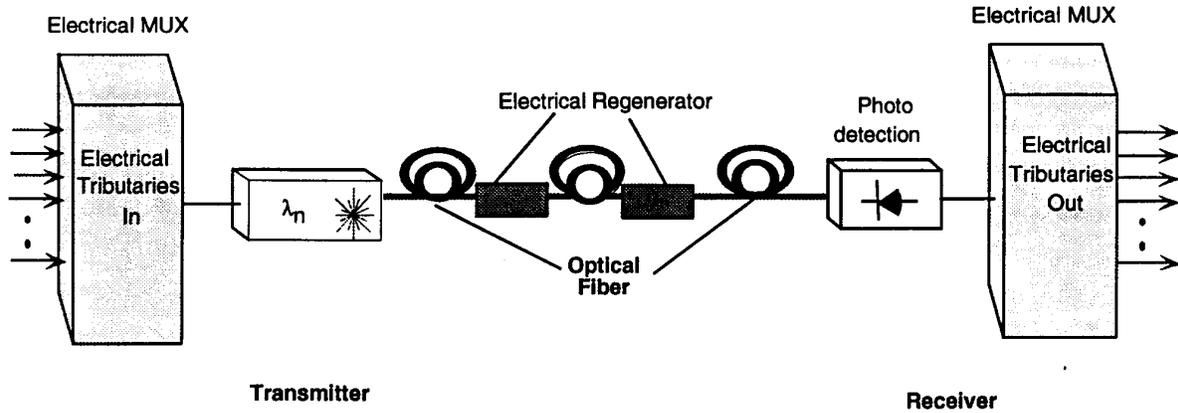
      Chapter 3 contains the main contribution of this dissertation. A mathematical model is developed to analyze the receiver sensitivity of spectrum-sliced OOK-WDM systems that employ PIN or optical preamplifier receivers. The incoherent detection of noise-like signals is treated using a standard receiver model, and mathematical formulation developed using both exact (chi-square) statistics for the signal and noise at the receiver decision circuit. Analysis is also performed using the more commonly used, but less accurate, Gaussian approximation, and it is shown that this approximation is overly conservative for treating spectrum-sliced systems, especially at low values of the receiver optical to electrical bandwidth ratio. However both the exact analysis and the

Gaussian approximation result in the existence of an optimum bandwidth where the required number of photons per bit is at its minimum. This optimum is quantified, and the transmission capacity and system power budget available by operating at this optimum are calculated. Finally, it is shown that operation at the optimum may result, in conjunction with error correction coding, in significant improvements in the system transmission capacity.
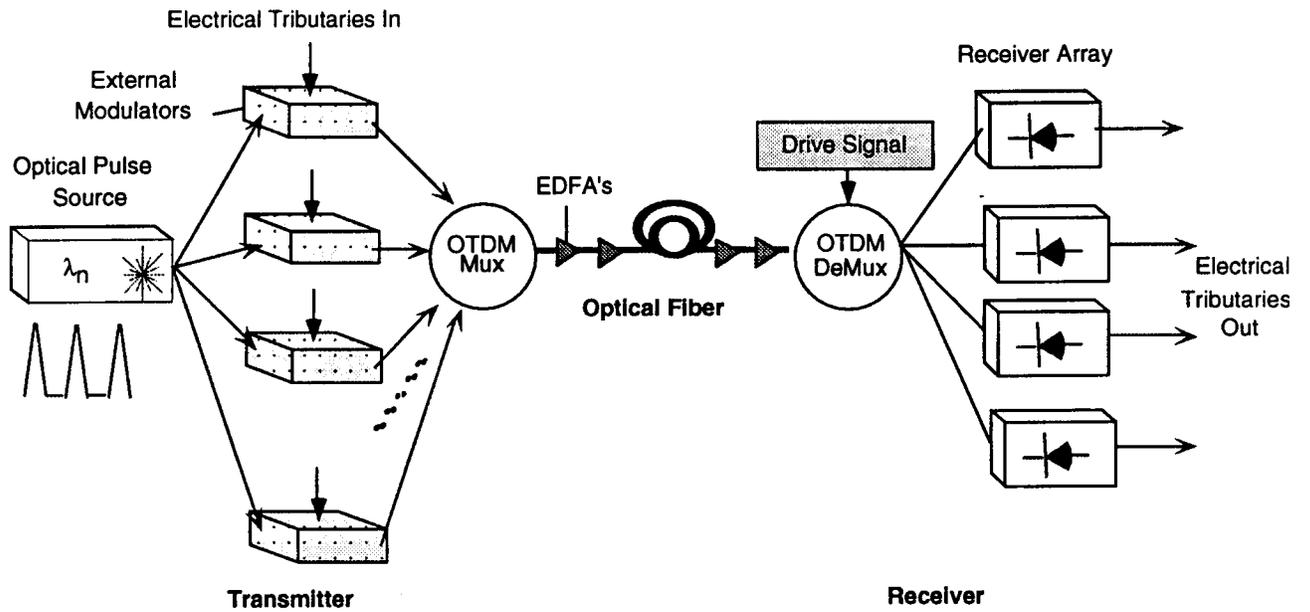
The case of spectrum-sliced FSK-WDM systems is analyzed in **Chapter 4** using a methodology similar to the one developed in the previous chapter. Although FSK systems use twice the number of wavelength bands per WDM channel, as does OOK, analysis shows that in the context of spectrum-slicing, FSK may also result in a number of advantages. Receiver sensitivity for both PIN and optical preamplifier receivers is calculated, using both the exact and Gaussian distributions. The chapter is concluded with a comparison of the performance of spectrum-sliced FSK and OOK transmission systems.

The preceding analysis has assumed the use of ideal, rectangular spectra for the signal and noise at the receiver. In **Chapter 5** we evaluate the effect of non-rectangular optical filter shapes on receiver sensitivity of both OOK and FSK systems. The transmitter and receiver optical filters are now modeled as order N Butterworth filters, and the corresponding degradation in receiver sensitivity is calculated as a function of the shape of the filter. It is seen that the shape of the filter has a strong influence on system performance, hence spectrum-sliced systems will require a careful control on the frequency response of components used in the system.

Chapter 6 concludes this dissertation with a summary of the primary contributions resulting from this work. Moreover, recommendations for future research in this area are made, in view of the recent interest in spectrum-sliced systems reported in literature.

Electrical MUX

Electrical
Tributaries
In

Electrical Regenerator

Photo
detection

Electrical MUX

Electrical
Tributaries
Out

λ_n

Optical
Fiber

Transmitter

Receiver

Time Division Multiplexing (TDM)

Electrical Tributaries In

External
Modulators

Receiver Array

Optical Pulse
Source

EDFA's

Drive Signal

λ_n

OTDM
Mux

OTDM
DeMux

Electrical
Tributaries
Out

Optical Fiber

Transmitter

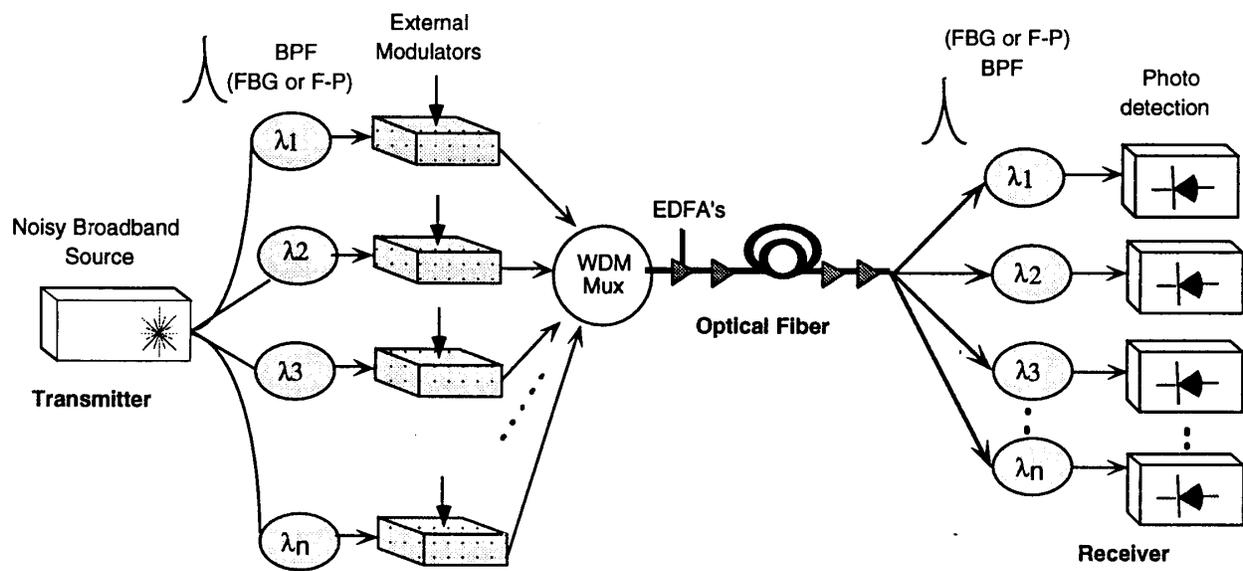**Receiver**

Optical Time Division Multiplexing (OTDM)

Fig. 1.1: *Multiplexing configurations for lightwave systems.*
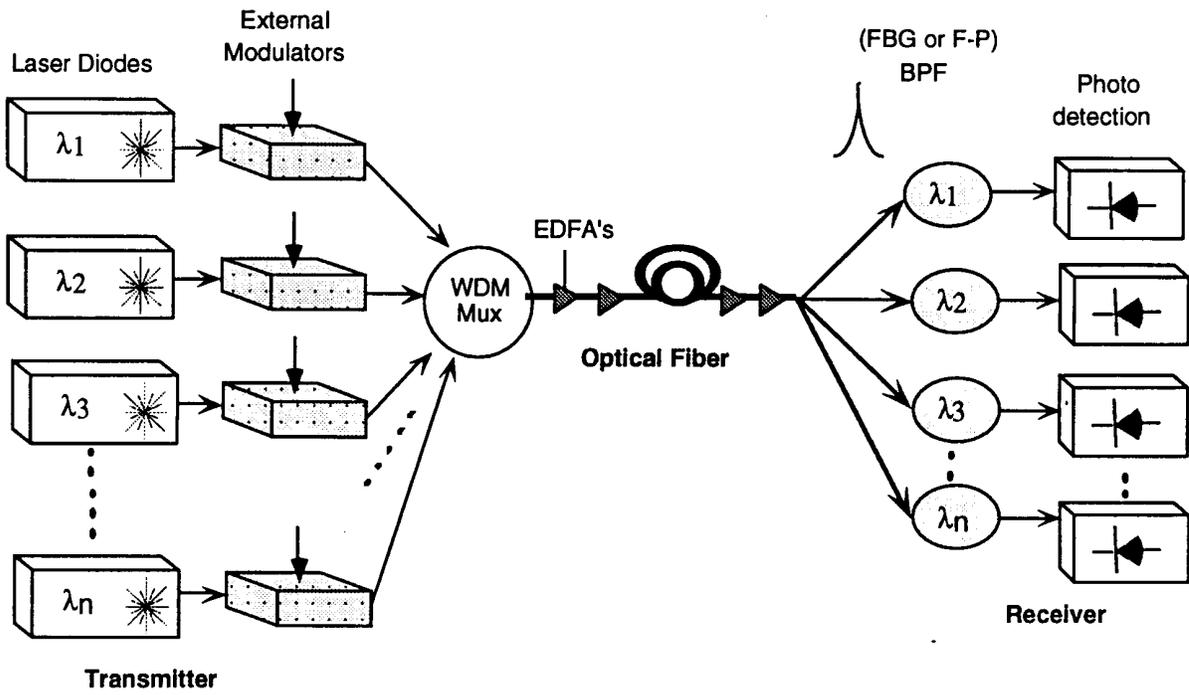
Fig. 1.2: *Schematic of the wavelength division multiplexing (WDM) architecture..*

Fig. 1.3: *Spectrum-sliced WDM.*

Erbium-doped fiber

2x2 Coupler

~ 20 mW

1.55 μm

1480 nm
laser diode

Erbium-Doped Fiber Amplifier (EDFA)
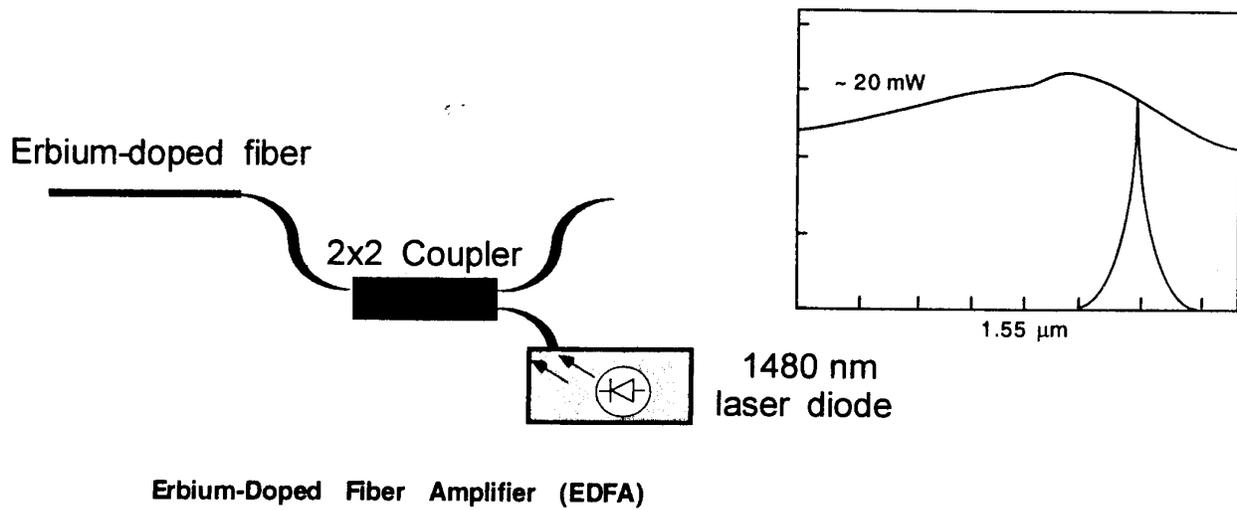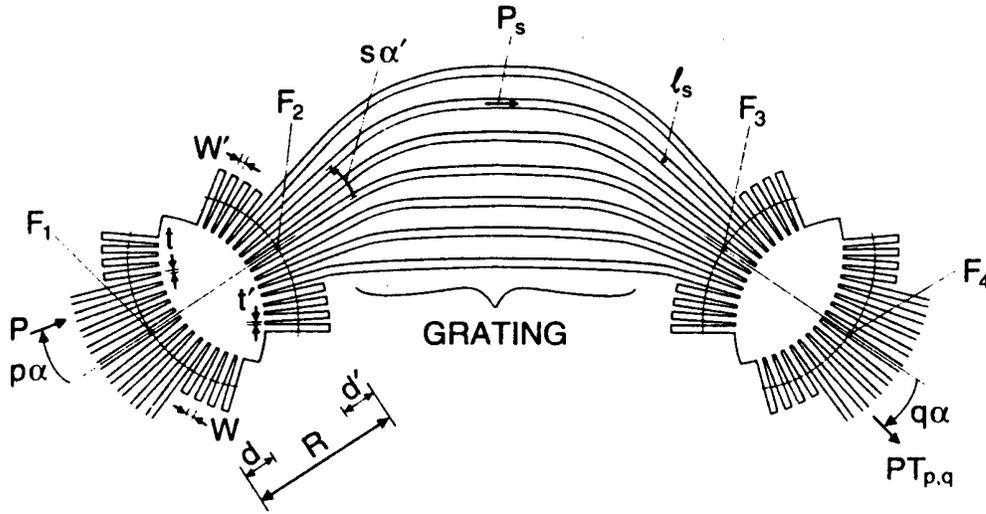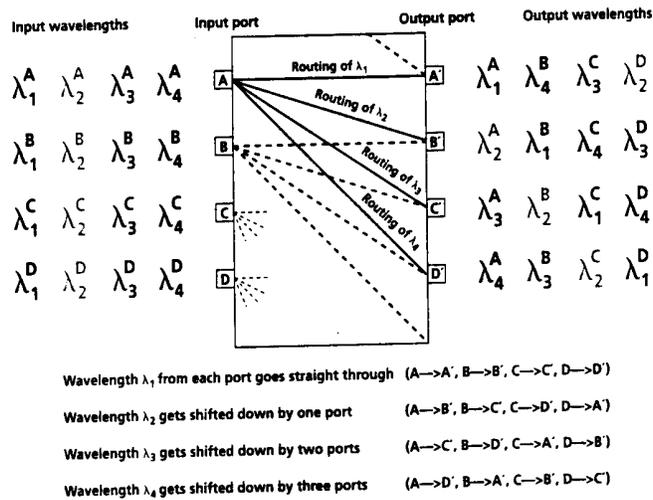
Source: Lee at al., IEEE Phot. Tech Lett., December 1993

Fig. 1.4: *SS-WDM amplified-spontaneous-emission (ASE) source and filtered channels.*

a) Device Schematic (from[28])

Input wavelengths   Input port   Output port   Output wavelengths

Routing of λ_1

Routing of λ_2

Routing of λ_3

Routing of λ_4

λ_1^A λ_2^A λ_3^A λ_4^A — A

λ_1^B λ_2^B λ_3^B λ_4^B — B

λ_1^C λ_2^C λ_3^C λ_4^C — C

λ_1^D λ_2^D λ_3^D λ_4^D — D

A' — λ_1^A λ_4^B λ_3^C λ_2^D

B' — λ_2^A λ_1^B λ_4^C λ_3^D

C' — λ_3^A λ_2^B λ_1^C λ_4^D

D' — λ_4^A λ_3^B λ_2^C λ_1^D

Wavelength λ_1 from each port goes straight through   (A—>A', B—>B', C—>C', D—>D')

Wavelength λ_2 gets shifted down by one port   (A—>B', B—>C', C—>D', D—>A')

Wavelength λ_3 gets shifted down by two ports   (A—>C', B—>D', C—>A', D—>B')

Wavelength λ_4 gets shifted down by three ports   (A—>D', B—>A', C—>B', D—>C')

(b) WDM Connectivity (from [28])

Fig. 1.5: *The integrated Waveguide Grating Router (WGR)*