

Chapter 6

Conclusions and Proposal for Future Research

The major result from the research performed for this dissertation has been the development of a general model to analyze on-off keying (OOK) and frequency-shift keying (FSK) based communication systems in which both the signal and noise are Gaussian stochastic processes. The specific example of the system considered for this application is a spectrum-sliced WDM system where the ‘signal’ is derived from a noisy, incoherent broadband source. The noise considered in the analysis is the amplified spontaneous emission noise (ASE) from an erbium-doped fiber amplifier (EDFA). In this final chapter we summarize the primary contributions of this research and provide suggestions for future work in this area.

6.1 Significance of Investigation

The motivation for this work was to gain a better understanding of a recently proposed technique, termed spectral-slicing, for implementing wavelength-division multiplexed systems. Although spectral-slicing avoids the stability and complexity problems associated with a transmitter using discrete coherent laser sources, the price that one has to pay is the excess intensity noise arising from the broadband source used for spectral-slicing. Hence our first step was to fully characterize the performance of noise-like systems in terms of the average receiver sensitivity required, relative to a coherent laser-based system. This was done by deriving closed-form expressions for the received photocurrent as seen at the receiver decision circuit. Since digital systems are being treated, a statistical approach was used where the occurrence of error is expressed in terms of a

probability, and this probability is dependent on the pdf of the signal and noise components existing in this system.

The second step was to analyze how the receiver sensitivity obtained by using conventional PIN-based detection could be improved by optically preamplifying the signal before photodetection. Optical preamplifier receivers are well-known for improving receiver sensitivity in coherent laser-based systems; however this is the first proposal and analysis for their use in a noise-like incoherent WDM system. Again, the same approach was used - find the pdf for the various signal and noise terms at the decision circuit and evaluate the corresponding probability of the occurrence of an error, in terms of system and preamplifier parameters. The above methodology was used with both OOK and FSK transmission and results expressed in terms of photons per bit required to maintain a standard error probability, at different values of the receiver optical to electrical bandwidth ratio. The results obtained are summarized as follows:

1. The main contribution of this research has been to propose and analyze, for the first time, an **optical preamplifier receiver** for spectrum-sliced WDM systems. Preamplifying the optical signal before photodetection offers an optimum optical bandwidth, operation at which provides a 10 dB advantage in power (in photons per bit). This is relative to a PIN receiver which offers NO optimum value of m . Moreover use of the preamplifier receiver in a spectrum-sliced system shows the potential of transmitting ~ 23 Gb/s at an error probability of 10^{-12} , assuming conservative values for power and bandwidth.
2. Operation at the optimum optical bandwidth results in the strong dependence of receiver sensitivity on the bit error rate (BER) in the system thus leading us to propose the use of Forward-Error Correction (FEC) coding with which **system capacity can be improved three-fold** (~ 75 Gb/s), for example with the use of Reed-Solomon (rate 0.94) FEC codes.
3. For the first time, a Frequency-Shift Keying (FSK) based spectrum-sliced WDM system has been evaluated and performance optimized, and it is shown that this configuration **performs better in peak-power limited optical systems** at the optimum bandwidths. Lower values of

transmission power also mean that the spectrum-sliced EDFA source can be operated at lower pump powers, and thus provide flatter gain bandwidths which can compensate for the poorer spectrum utilization of FSK transmission.

4. The effect of realistic optical filter shapes is accounted for and shown that spectrum-sliced systems will require sharp cut-off filters, **BUT that the usefulness of sharpening the filter cut-off produces diminishing returns** after a certain order of the optical filter design. For example, system penalties due to the optical filter can be reduced to < 1 dB if the filter order $N > 3$. Note that sharper cut-off filters should also allow closer spacing of the multiwavelength channels.
5. Analysis has shown that conventional methods to evaluate the performance of spectrum-sliced systems, such as the Gaussian approximation, are overly conservative, and the **chi-square distribution-based analytical techniques**, as presented in this research yields more realistic system parameters.

The development of a model to analyze such noise-like systems which employ optical preamplification to minimize the receiver detection sensitivity is of interest since the system parameters at the optimum performs much better than conventional spectrum-sliced systems. This improvement is with regards to the average power required at the receiver to maintain a particular BER performance. **Note that the accuracy of the developed model is dependent upon the degree of accuracy to which the energy at the receiver decision circuit may be assumed to be chi-square distributed.** Also it should be noted that the achieved performance is not really *optimal*; the model only serves to help analyze the performance of the system once the signal and noise properties are known. It does however give the system designer an insight into the various system parameters and their interplay, as well as suggesting specific system parameters which can be optimized, *e.g.* the optical and electrical filters.

6.2 Future Research

As this work has shown, spectrum-sliced systems offer a number of interesting problems which have to be addressed before they can be used in a commercial application. Some of those problems were addressed in this work and some possible solutions provided. We conclude the dissertation in this section with some suggestions for future work in this area.

6.2.1 Effect of Interchannel Distortion and Dispersion

Our initial analyses have assumed no inter-channel interference and no effects of dispersion. However, both phenomena will affect system design and performance. Although simulation and measurement are needed to properly evaluate these and other effects, further analysis is important to gain understanding of the physical phenomena, and to appropriately design the simulation.

As shown by Pendock and Sampson [53], chromatic dispersion not only produces ISI related power penalty, as in a conventional laser-based system, but also reduces the amount of spectral width falling within a bit period. This is equivalent to reducing the total number of degrees of freedom (m) in a bit interval. As we saw in Chapter 3 for the case of a PIN receiver, the receiver sensitivity in photons/bit becomes poorer as m reduces. Hence dispersion produces an excess power penalty in a spectrum-sliced system due to the intensity noise arising from the broadband source. However one interesting aspect of spectrum-sliced transmission in general is that the transmission system is inherently operating at very low optical signal-to-noise ratios (due to the large value of the optical bandwidth). This low optical SNR provides a certain resistance to interchannel interference effects due to their being insignificant compared to the large inherent noise in the signal. Hence further study of the effects of interchannel and intersymbol distortion due to chromatic dispersion through analysis and simulation will indeed be useful in designing practical spectrum-sliced systems.

6.2.2 Implications of varying the line coding scheme

Conventional spectrum-sliced WDM systems have been proposed and demonstrated with non-

return-to-zero (NRZ) pulses. The use of return-to-zero (RZ) coding schemes, however, is also very attractive because of their higher peak powers, spectral properties and simplicity of clock recovery circuits (as compared with NRZ pulses). Moreover RZ systems use lower pump powers, as compared to NRZ systems. This feature can be an advantage since it lowers the requirements placed on the laser diodes which are used for pumping the fiber amplifiers in the system. One disadvantage of RZ systems, however, is the increased spectral broadening, due to self-phase modulation (SPM), caused by the higher peak powers. The implications of using RZ pulses in the proposed optically pre-amplified spectrum-sliced WDM system can also provide further insight in increasing the performance of such noise-like systems.

6.2.3 Noise reduction techniques for the spectrally-sliced source

Feedforward noise reduction techniques were recently proposed for reducing the noise in the incoherent ASE source that is sliced for creating the multiple wavelength channels [59]. The feedforward noise-reduction (FFNR) circuit consisted of the fiber coupler, an optical attenuator, photodetector and electrical gain and phase matching elements. The coupler was used to tap-off a portion of the spectrum-sliced light from the broadband source and the detected noise subtracted from the mean signal using a lithium-niobate-based Mach-Zehnder modulator. Since conventional techniques are only able to perform the subtraction of the optical fields, the FFNR circuit required the Mach-Zehnder modulator to act as a multiplying element which multiplies the optical power by the applied RF signal. Thus the FFNR circuit was able to reduce the primary signal during overshoots and increase it during drop-outs and thus allowed the bandwidth of the incoherent optical slice to be reduced while maintaining a suitable SNR. The authors demonstrated successful transmission of a 2.5 Gb/s data stream over 40 km using a 0.23 nm slice of the spectrum-sliced source. It can be of interest to investigate the performance of such noise reduction techniques with the general analytical model developed in this dissertation to analyze spectrum-sliced systems.

6.2.4 Use of Alternate Broadband Sources

One of the most important issues for WDM systems is the appropriate multiwavelength light source. As described in Chapter 2, tunable lasers are generally used in most conventional WDM system experiments and commercial systems. The requirement for the next-generation of WDM systems, known as dense WDM (DWDM), is a channel spacing of less than 1 nm. It is obvious that the use of different sources to create the multiple wavelength channels places strict restrictions on their stability, cost, and maintenance. As shown in this thesis, spectral slicing prevents these problems by using a single broadband optical amplifier to create the different wavelength channels which may be modulated individually. Another candidate for use as a multiwavelength source in spectral-slicing applications is the supercontinuum (SC) spectrum of short pulses from an appropriate high energy laser. The majority of the experiments have used the supercontinuum of short pulses generated from a femtosecond mode-locked erbium-doped fiber ring laser (ML-FRL) as the multi-wavelength source. Since the modulation is external to the laser cavity, wavelength drifts of the laser are not a problem and unlike conventional integrated optic multi-wavelength lasers, the modulation speed is not limited by the cavity round-trip times. Moreover the noise properties of a mode-locked source are superior, as compared to an incoherent or a partially coherent source, thus allowing higher data rates and/or un-repeated distances. Furthermore as mentioned in [70], impulsive excitation of the receiver by the femtosecond SC sources has certain advantages in spectrum-sliced systems, as compared to the use of the EDFA ASE for the same purpose.