Chapter 7

SUMMARY AND CONCLUSIONS

The main objective of this dissertation is to analyze and compare our proposed modulation format, which we term continuous-wave square-wave (CWSW), with various modulation formats proposed in the literature. Emphasis is focused on comparisons between CWSW and alternate mark inversion (AMI) signal formats because both formats are shown to be superior to other modulation formats considered in the literature. Both CWSW and AMI are more robust to the impairments caused by dispersion and nonlinearity in the optical fiber compared with other modulation formats. The performance of the conventional RZ modulation format (no phase modulation) is also investigated for reference purposes. The bit rate considered in this dissertation is 40 Gb/s. Since the investigation is at the system level where many system components are involved and the optical fiber itself is not a linear transmission medium, it is difficult to find a closed-form expression that thoroughly describes the system performance. Numerical simulation is utilized as a tool to analyze system performance. Two criteria are used as the performance measures: the Q value and the eye profile. The Q value is an effective signal-to-noise ratio from which the probability of bit error may be estimated. The eye profile at the receiver is a more qualitative measure that indicates the nature of the waveform distortion caused by the dispersion and nonlinearity. Different transmission fiber configurations are used as bases for performance comparisons. In this dissertation, a dispersion-shifted fiber (DSF) represents a transmission fiber having small local dispersion. Due to its small dispersion the dispersion compensation is not necessary in such a system. A TrueWave™ reduced slope fiber (TRSF) and standard single-mode fiber (SSMF) are used for representing the transmission fibers having moderate and large local dispersion, respectively. It should be noted that for these systems, the dispersion compensation is necessary due to large accumulated dispersion.

Two types of dispersion compensating fibers are utilized for performing dispersion compensation in this dissertation. They are an extra-high-slope dispersion compensating (EHS-DK) fiber, and reverse-dispersion fiber (RDF). The former is designed for being used as a modular dispersion compensating fiber whereas the latter is specifically designed for the system employing two transmission fibers. In that system, the first and second transmission fibers are SSMF and RDF, respectively. The benefit of this system is that RDF is utilized not only as the transmission fiber, but also the dispersion compensating fiber; hence, the loss associated with the dispersion compensation process is counted as the transmission loss. The system performance of multiple-span systems employing in-line optical amplifiers and an optical preamplifier receiver is also investigated in this dissertation. The principal contributions and conclusions of this dissertation are summarized in this chapter. Additionally, suggestions for future research are provided at the end of this chapter.

7.1 PRINCIPAL CONTRIBUTIONS

The key contributions of this dissertation are the identification of the principal mechanisms causing degradations in high-bit rate long-distance fiber optic systems, the proposal of a new transmission format that is highly resistant to these impairments, and detailed performance comparisons that indicate when and why specific transmission formats are desirable.

Generally, an optical fiber is a dispersive nonlinear medium. This dispersion causes pulses to spread, resulting in overlaps between pulses. Although the fiber nonlinearity can cause pulses to compress during initial propagation when the operating wavelength is in the anomalous dispersion regime, pulses still overlap each other at sufficiently large transmission distance. The overlaps between pulses result in the growth of spurious pulses and ISI in empty bit slots in the systems not using dispersion compensation. The growth of spurious pulses in effect distorts the eye profile at the receiver so that it is no longer RZ and reduces the peaks of original pulses. The latter can be understood from energy conservation. The energy is transferred from the original pulses to those spurious pulses. In dispersion-managed systems where the accumulated dispersion is compensated, there still exist impairments caused by the nonlinearity. Those impairments are intrachannel cross-phase modulation (IXPM) and intrachannel four-wave mixing (IFWM).

The effects of IXPM and IFWM can be considerably reduced, and the growth of spurious pulses can be suppressed when adjacent pulses have opposite signs. The modulation formats that possess that beneficial characteristic are SWM and AMI. The difference between those two formats is that two consecutive pulses always have opposite signs regardless of the number of empty bit slots in between in the case of the AMI signal format. For SWM, two consecutive pulses have opposite sign when they are separated by an even number of empty bit slots. The unique characteristic in the case of AMI comes at the cost of the encoding circuit at the transmitter. In this dissertation, a novel variant of the SWM signal format is proposed. The proposed signal format, which is called CWSW, offers several advantages compared to the SWM signal format in terms of implementation and performance.

7.1.1 CWSW

The SWM signal format is generally implemented with a Mach-Zehnder (MZ) modulator driven by sinusoidal signals, resulting in adjacent RZ pulses having opposite signs. The drawback of SWM signal generation is that the MZ modulator requires two out-of-phase sinusoidal signals, each for one arm of the modulator, which is a lithium niobate ($LiNbO_3$) phase modulator. Due to the fact that both arms of the MZ modulator are not identical in practice, the amplitudes of those sinusoidal driving signals have to be independently tuned to avoid residual chirp at the modulator output, thus increasing system complexity. In addition, both arms have to be driven synchronously. In our proposed technique, the generation of an alternate-sign RZ pulse train requires only a single lithium niobate phase modulator and an optical filter. The CW output from a laser is phase modulated by a square-wave phase function having a frequency of half the bit rate and amplitude of $\pi / 2$. An optical filter performs phase-to-amplitude conversion, resulting in the generation of an alternate-sign RZ pulse train. In this scheme only one driving signal is required, thus avoiding complicated system setup and adjustment at the transmitter. Moreover, the power consumption is less compared with the generation of a SWM signal because the phase modulator requires only a single electrical amplifier to adjust the amplitude of the driving signal and the optical bandpass filter is a passive component.

7.1.2 Peak Intensity Enhancement (PIE)

A further advantage of the CWSW format is that in the presence of dispersion it exhibits a peak intensity enhancement. This is because an individual pulse generated from this technique generally has very sharp (steep) edges on each side unless the optical filter bandwidth is small. For a conventional pulse, the fiber dispersion broadens the pulse as it propagates along an optical fiber, also resulting in a decrease in the pulse peak. Although dispersion also broadens a CWSW pulse similar to a conventional shape, the peak of the CWSW pulse does not decreases monotonically with transmission distance. In fact, the interaction between the CWSW pulse and dispersion causes the pulse peak to initial increases and then decreases with the increase in transmission distance. That is, the dispersion desirably distorts the pulse such that the pulse peak is higher than that at the fiber input when the transmission distance is not too large. This phenomenon is called peak intensity enhancement (PIE). The PIE in effect delays the reduction of the signal level for bit 1 at large transmission distance, therefore improving the system performance in term of eye opening. It should be noted that PIE is a linear process, and requires only dispersion.

In order to theoretically confirm and explain our discovery, an analytically tractable model of the pulse is developed. It is found that the sum of twin displaced Gaussian pulses is a suitable model for explaining the occurrence of PIE in the presence of dispersion. For a conventional pulse, the dispersion uniformly chirps the pulse, resulting in the leading edge of the pulse being uniformly advanced while the trailing edge of the pulse being uniformly delayed with respect to the pulse center. Therefore, a pulse is broadened by dispersion, and a decrease in the pulse peak results. However, the monotonic decrease in the pulse peak due to dispersion during propagation is not always true for all pulse shapes. The analysis indicates that when a pulse has sufficiently steep edges, PIE can be induced during propagation, which is consistent with observations in the case of a CWSW pulse. The interaction between such a pulse and dispersion results in the pulse not being uniformly chirped. The nonuniform chirp causes the leading edge of the pulse near the pulse center to retard and the trailing edge near the center to advance when the transmission distance is not too large. This results in the pulse components around the center moving toward the center during initial propagation, hence increasing the pulse peak at the center.

Note that dispersion still causes the signal components on the leading edge and the trailing edge that are sufficiently far away from the pulse center to advance and to retard, respectively. Therefore, the rms pulse width of such a pulse increases monotonically with transmission distance similar to a conventional pulse. For the peak of a conventional unchirped pulse to increase during initial propagation, nonlinearity is required to induce the pulse compression effect, and this can occur only when the operating wavelength is in the anomalous dispersion regime. The important feature of PIE is that the peak of an unchirped pulse can be increased during initial propagation under the absence of the nonlinearity, provided that the pulse shape is properly manipulated.

7.1.3 System Performance of CWSW Signal Format

Although the phase characteristic of both the CWSW and AMI signal formats can prevent the growth of spurious pulses, and minimize IXPM and IFWM, we have found that a filter at the transmitter is also essential to maximize the system performance. In the case of small local dispersion fiber where dispersion compensation is not required, the PIE as well as spurious-pulse suppression possessed by the CWSW signal formats provides significant improvement compared with AMI and no PM in terms of the maximum transmission distance and the eye profile at the receiver. Due to the presence of dispersion in this case, large transmitter filter bandwidth is preferable for CWSW to take advantage of PIE. On the other hand, small transmitter filter bandwidth yields better performance than large transmitter filter bandwidth to avoid the severe effect of dispersion in the case of AMI and no PM. Note that for systems employing DSF as the transmission fiber, channel spacing is generally large to avoid interchannel impairment, hence allowing large signal bandwidth.

For dispersion-managed systems, in which dispersion is compensated, there is no PIE; therefore, large transmitter filter bandwidth is not beneficial for CWSW. Moreover, the pulse peak, representing the signal level for bit 1, decreases with increase in the transmitter filter bandwidth. Consequently, small transmitter filter bandwidth provides better system performance in terms of the Q value than large filter bandwidth for CWSW. In the case of a transmission fiber having moderate local dispersion (TRSF), the dominant nonlinear impairment is IXPM, causing timing jitter. At sufficiently large transmission distances, dispersing the pulses as quickly as possible is an effective mean for combating IXPM. Hence, large transmitter filter bandwidth is desirable for AMI and no PM. In terms of Q values and the eye profile, both the CWSW and AMI signal formats are comparable, and significantly outperform no PM. Minimizing the effect of IFWM indirectly helps reduce the effect of IXPM, which is the dominant intrachannel impairment in this case. In terms of the transmitter filter bandwidth, CWSW has a narrower filter bandwidth than AMI, which is advantageous in a WDM system.

In the systems employing SSMF as the main transmission fiber, the dominant intrachannel impairment is IFWM due to strong pulse spread. IFWM causes amplitude jitter and the generation of ghost pulses. The later results in ISI in empty bit slots. It is found that narrowing the signal bandwidth by employing a filter at the fiber input helps improve system performance for CWSW and AMI. This is due to the fact that the effect of IFWM increases with pulse overlaps. In order to decrease the pulse spread, the signal bandwidth has to be reduced. Due to the additional phase property of AMI resulting from encoding at the transmitter, AMI is more resistant to IFWM than CWSW. It should be noted, however, that although AMI has higher optimum transmitted power than CWSW, the eye profile for AMI suffers severely from intrachannel impairments at such high transmitted power. In the case of single-span systems, the eye profiles for both CWSW and AMI are comparable at the optimum transmitted power for CWSW. The advantage of AMI over CWSW becomes apparent in multiple-span systems where the accumulated dispersion is large. The generation of ghost pulses caused by IFWM results in noticeable ISI in empty bit slots in the case of CWSW whereas this does not occur in the case of AMI. However, that advantage comes at the cost of encoding at the transmitter, which increases system complexity. Summarized in Table 7.1 are maximum transmission distances ($Q = 15.6$ dB) and corresponding system parameters that can be achieved for different types of fiber configurations investigated in this dissertation. It should be noted, however, that in the case of multiple-span systems the maximum transmission distances may not truly reflect the system performance because the transmission distance is increased at steps of the amplifier spacing. Thus, the Q values at those transmission distances are also listed.

7.2 FUTURE RESEARCH

In our proposed modulation technique, the signal driving the phase modulator is assumed to be an ideal square-wave signal, which may be difficult to produce in practice. It would be interesting to investigate the impact of a nonideal square-wave-like signal that drives the phase modulator. That signal can be modeled as a square-wave-like signal having finite rise time and fall time. Due to the periodic nature of the signal at the phase modulator output, a filter having special magnitude and phase responses may help reduce the effect of a nonideal square-wave-like signal. That is, the combination of nonideal square-wave-like signal and the filter having special characteristic could be used to generate a CWSW pulse train. In addition, the filters used throughout the investigations presented in this dissertation are Butterworth filters. In practice, there are different types of filters, such as Chebyshev and Bessel. Different types of filters have different magnitude and phase responses, which may further improve system performance.

It is clearly seen that perfect dispersion compensation in dispersion-managed systems does not favor the occurrence of PIE, which requires dispersion. The PIE could improve the system performance in dispersion-managed system provided that there is residual dispersion; i.e., the accumulated dispersion is not fully compensated. This can be accomplished by either performing post-compensation or tailoring the length of the dispersion compensating fiber such that there exists residual dispersion. Although the fiber configurations investigated in this dissertation are commonly used in practice due to their simplicity, fiber configurations which differ from those investigated in this dissertation may provide additional performance improvement. For example, consideration should be given to the case where the accumulated dispersion is under or over compensated in each span resulting in either positive or negative residual dispersion at the receiver.

Table 7.1: Summary of maximum transmission distance $z_{\max}$ and corresponding optimum system parameters for different fiber configurations investigated in this dissertation.

	CWSW	AMI	No PM
Single-Span System employing DSF when $D = +0.5$ ps/(km·nm)	$z_{\max} = 195$ km $P_{avg,Opt} = 10$ dBm $BW_{Tx} = 4$	$z_{\max} = 187$ km $P_{avg,Opt} = 8$ dBm $BW_{Tx} = 1.5$	$z_{\max} = 179$ km $P_{avg,Opt} = 9$ dBm $BW_{Tx} = 1.5$
Single-Span System employing DSF when $D = -0.5$ ps/(km·nm)	$z_{\max} = 162$ km $P_{avg,Opt} = 7$ dBm $BW_{Tx} = 4$	$z_{\max} = 159$ km $P_{avg,Opt} = 6$ dBm $BW_{Tx} = 1.5$	$z_{\max} = 161$ km $P_{avg,Opt} = 6$ dBm $BW_{Tx} = 1$
Single-Span System employing TRSF and EHS-DK Fiber	$z_{\max} = 206$ km $P_{avg,Opt} = 10$ dBm $BW_{Tx} = 1$	$z_{\max} = 208$ km $P_{avg,Opt} = 10$ dBm $BW_{Tx} = 4$	$z_{\max} = 200$ km $P_{avg,Opt} = 9$ dBm $BW_{Tx} = 4$
Single-Span System employing SSMF and EHS-DK Fiber	$z_{\max} = 184$ km $P_{avg,Opt} = 11$ dBm $BW_{Tx} = 1$	$z_{\max} = 188$ km $P_{avg,Opt} = 13$ dBm $BW_{Tx} = 2$	$z_{\max} = 180$ km $P_{avg,Opt} = 11$ dBm $BW_{Tx} = 4$
Single-Span System employing SSMF and RDF Fiber	$z_{\max} = 216$ km $P_{avg,Opt} = 11$ dBm $BW_{Tx} = 1$	$z_{\max} = 221$ km $P_{avg,Opt} = 13$ dBm $BW_{Tx} = 2$	$z_{\max} = 211$ km $P_{avg,Opt} = 11$ dBm $BW_{Tx} = 4$
Multiple-Span System employing TRSF and EHS-DK Fiber (Amplifier Spacing of 160 km)	$z_{\max} = 480$ km $P_{avg,Opt} = 5$ dBm $BW_{Tx} = 1$ $Q = 16.0$ dB	$z_{\max} = 480$ km $P_{avg,Opt} = 6$ dBm $BW_{Tx} = 4$ $Q = 16.5$ dB	$z_{\max} = 320$ km $P_{avg,Opt} = 6$ dBm $BW_{Tx} = 4$ $Q = 16.8$ dB
Multiple-Span System employing TRSF and EHS-DK Fiber (Amplifier Spacing of 120 km)	$z_{\max} = 960$ km $P_{avg,Opt} = 1$ dBm $BW_{Tx} = 1$ $Q = 16.0$ dB	$z_{\max} = 960$ km $P_{avg,Opt} = 1$ dBm $BW_{Tx} = 4$ $Q = 16.4$ dB	$z_{\max} = 840$ km $P_{avg,Opt} = 1$ dBm $BW_{Tx} = 4$ $Q = 16.3$ dB
Multiple-Span System employing SSMF and RDF Fiber (Amplifier Spacing of 160 km)	$z_{\max} = 480$ km $P_{avg,Opt} = 6$ dBm $BW_{Tx} = 1$ $Q = 18.2$ dB	$z_{\max} = 640$ km $P_{avg,Opt} = 8$ dBm $BW_{Tx} = 2$ $Q = 16.9$ dB	$z_{\max} = 480$ km $P_{avg,Opt} = 6$ dBm $BW_{Tx} = 4$ $Q = 17.3$ dB
Multiple-Span System employing SSMF and RDF Fiber (Amplifier Spacing of 120 km)	$z_{\max} = 1080$ km $P_{avg,Opt} = 1$ dBm $BW_{Tx} = 1$ $Q = 16.4$ dB	$z_{\max} = 1320$ km $P_{avg,Opt} = 3$ dBm $BW_{Tx} = 2$ $Q = 16.0$ dB	$z_{\max} = 960$ km $P_{avg,Opt} = 1$ dBm $BW_{Tx} = 4$ $Q = 16.5$ dB