# Bandwidth Efficient and Dispersion Tolerant Modulation Schemes for Optical Communication Systems

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**Abstract:** An investigation into high spectral efficiency modulation schemes used in optical communication systems including the effects of fibre chromatic and polarisation mode dispersion and nonlinearity is described. The modulation schemes include optical duobinary AM-PSK and phase shaped binary transmission. The paper reports on transmission distances achievable for 16 10Gb/s DWDM channels over SMF for BER better than $10^{-9}$ and then for dispersion managed configurations. Simulation of the schemes was in VPI software (VPI TransmissionMaker$^{TM}$). The spectral efficiency of the modulation schemes, their dispersion tolerance, resulting in longer transmission distances, and the relatively small effect of PMD compared to chromatic dispersion are reported.

## 1. Introduction:

Network capacity demand, due to the growing amount of multimedia and interactive traffic, is continuing to expand. Optical fibre provides an enormous low-loss bandwidth which can be exploited by Wave Division Multiplexing (WDM) to build high capacity optical communications systems to satisfy this demand. WDM is also used in conjunction with optical amplifiers to provide long distance, high capacity systems.

In this paper, modulation schemes that provide an increased spectral efficiency and improved dispersion tolerance for long-distance, high data optical transmission systems are discussed [1, 2, 3]. In addition, these schemes are bandwidth efficient, allowing the WDM channel spacing to be brought closer together. Simulations of the schemes can be examined to test the achievable transmission distances. The reach of 10 Gb/s light wave systems beyond the 100 Km distance will be examined using the spectrally efficient polybinary signalling schemes [1, 3, 4], and comparing them with simple NRZ binary. The use of dispersion management is also investigated. Finally, a reduction in channel spacing is considered.

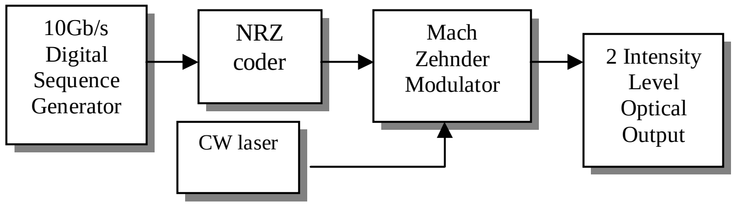
NRZ binary modulation corresponds to two-level signalling format whereas AM-PSK and PSBT represent polybinary signalling transmission. A polybinary signal is generated by introducing correlation among adjacent bits in a binary signal. For AM-PSK signals, the multiple levels are encoded in both the amplitude and phase of the carrier [1, 3]. This can be achieved by correctly driving a Mach-Zehnder modulator. The signal can be generated in two configurations: the first is to use a "delay and add" network and the second by using an electrical signal generated by a low pass filter with a sharp cut-off frequency (this method being referred to as PSBT) [1, 3]. These signalling techniques concentrate power at frequencies closer to the optical carrier where phase distortion of the optical field from chromatic dispersion is less severe.

## 2. VPI Models

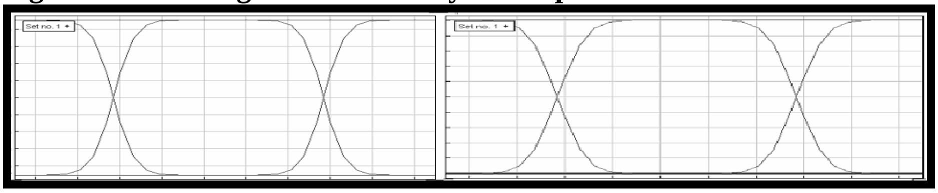
The modulation schemes mentioned above are modelled in VPI software. The 10Gb/s signal is produced by a PRBS with a length of ($2^{37} – 1$) with an NRZ encoder. Simulation time is set to 128 bit periods, and the sampling rate at 80GHz for all three schemes. The laser operates in CW mode with an optical power of 1mW and a spectral linewidth of 10 MHz. The MZM has its extinction ratio set at 13dB.

2.1 NRZ binary:

The investigation starts by using NRZ optical binary modulation as the benchmark. An NRZ-encoded digital signal is used to drive a Mach-Zehnder modulator (MZM) operating in its "linear" region, producing an output with two intensity levels. Figure 1.a shows the basic schematic for this scheme, and Figs. 1b and 1c show the corresponding eye diagrams.




**Figures 1.a: Arrangement for binary NRZ optical transmitter.**



**Figures 1.b& 1.c: MZM input and output Eye diagram.**

2.2 AM-PSK:

As stated, the AM-PSK scheme is realised by a delay and add network as shown in Figure 2.a. The electrical pulse (NRZ encoded) is passed through the delay and add network. This contains a delay parameter of 0.1ns, which equates to a 1-bit period at 10 Gab/s. The adder simply adds the current bit and the delayed one. The generation of the electrical duobinary signal is completed as the delayed and added signal is passed through an ideal Bessel low pass filter with an 11GHz 3dB cut off frequency, the resultant signal shown by the eye diagram, of Fig. 2.b. The optical AMPSK signal can be generated by applying the electrical duobinary signal to the Mach-Sender modulator. The modulator is biased at its maximum extinction point. This produces an optical output consisting of two intensity levels as shown in Fig. 2.c.

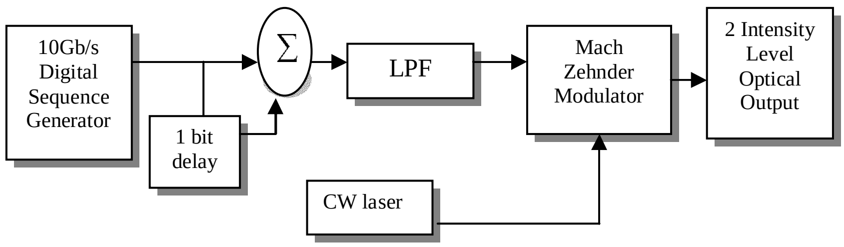



**Figure 2.a: Generation of AM-PSK signal.**

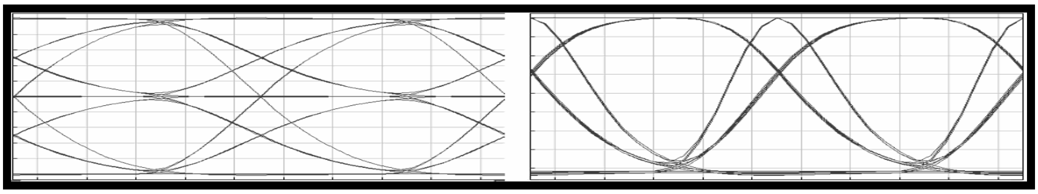


**Figure 2.b & 2.c: MZM Input and Output Eye diagrams; showing two intensity levels.**

2.3 PSBT:

The PSBT scheme is very similar to that of AM-PSK (Figure 2.a), but is realised without the use of the delay and add network shown in the figure. The low pass filter used in this case employs an ideal Bessel filter type with a 3dB cut-off frequency of approximately ¼ of the original bit rate (2.5 GHz). The signal is shifted by an MZM driver and is then used to drive the MZM again biased at its maximum extinction level. Figs 3.a, b show eye diagrams of the three-level electrical and the two level optical output signals.

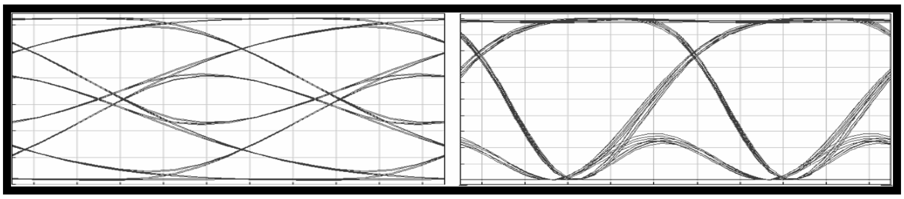


**Figure 3a & 3b: MZM input and output Eye diagrams for PSBT signalling.**

<u>2.4 Multiplexed transmission</u>

Each individual channel is multiplexed together in combination with the other available channels through 2-(8 **x** input) multiplexers, providing a 16 10Gb/s channel network. The 16 centre frequencies of the band-pass filters that are located in the multiplexers are set according to the laser emission frequencies. These emission frequencies range between 193.1THz and 193.7 THz, with a separation of 40 GHz between the channels. The combiner multiplexers have centre frequencies set to 191.26THZ and 193.52THz with a 30GHz bandwidth. The transmission medium in use is a standard SMF (standard mode fibre), with dispersion values of 16ps/nm/km and a 0.2dB/km attenuation. An inline optical amplifier compensates the optical power loss which is caused by fibre attenuation. The gain is set to 18db to avoid signal distortion caused by saturation.

The simulations are also carried out over dispersion managed configurations; i.e. over non-zero dispersion shifted fibre (NZ-DSF) with dispersion values of (2.5ps/nm/km) and dispersion compensation fibre. The DCF has a large negative dispersion value, in the range of -340 ps/nm/km; the precise value used depends on the length of the SMF preceding, and is used to compensate the dispersion caused by the SMF in a relatively short length of DCF.

## 3. Simulation results

<u>3.1 Dispersion-limited transmission</u>

Electrical pulses recovered at the photoreceiver output are shown in the eye diagrams of Figure 4 a, b, c, for arbitrary WDM channels, for the NRZ-bainary, AM-PSK and PSBT schemes, respectively. The longest transmission distances that the schemes could tolerate without too detrimental an effect on the eye diagrams was first examined only by using SMF and an inline optical amplifier to compensate for optical attenuation.

The NRZ Binary scheme achieved a transmission distance of 90km, whereas AM-PSK and PSBT achieved 100 km and 185 km respectively for BER rate target of $10^{-9}$. The effect of chromatic dispersion is visible on both AM-PSK and NRZ binary; The PSBT duobinary signalling emerged largely unaffected by the chromatic dispersion in these simulations.

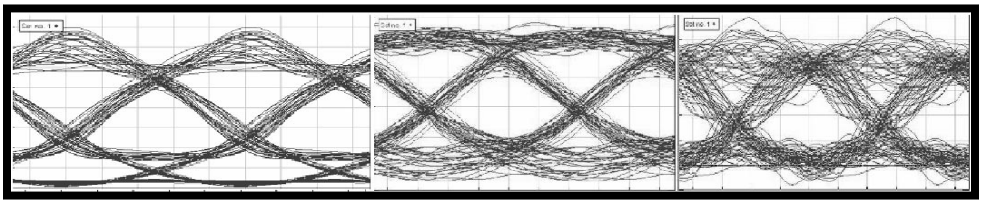


**Fig. 4 a, b, c: dispersion limited eye diagrams for NRZ Binary, AM-PSK and PSBT.**

<u>3.2 Dispersion managed schemes</u>

Dispersion management should allow increases of the maximum distances found above. This was first achieved by introducing NZ-DSF (2.5 ps/nm/km) fibre instead of SMF. The maximum distance was increased to 120 and 160 km for NRZ Binary and AM-PSK respectively. Alternatively, DCF dispersion management (to compensate for the SMF dispersion) can be implemented. In this case, NRZ Binary and AM-PSK achieved similar transmission distance of approximately 120 and 150 km, respectively, with a BER target around $10^{-9}$.

It is worth mentioning, that the dispersion management using NZDSF or DCF does not markedly influence the transmission distances achieved when the PSBT modulation scheme is used. This is attributed to the fact that PSBT has strong dispersion tolerant characteristics credited to its generation method.

Although fibre non-linear effects were present during the simulations, it was verified in further simulations that these effects resulted in no significant change in the transmission distances achievable for the 16-channel WDM system tested.

3.3 Reduced channel spacing for bandwidth efficiency:

It was found that both duobinary modulation schemes achieved the same transmission distance when the optical carriers were brought closer to each other by reducing the channel spacing from 40 GHz to 25 GHz. The NRZ binary model however was affected and the transmission distance was limited to 78 km over standard SMF with 25 GHz spacing, a reduction of 12km in the previously achieved value (90km) using 40GHz spacing.

3.4 Polarisation Mode Dispersion:

PMD problems emerge from the polarisation properties associated with laser light (birefringence effect). The more birefringence there is, the quicker the pulses will disperse, and as with chromatic dispersion, higher bit rate systems have less tolerance to PMD. The work carried on shows that the amount of pulse spreading or dispersion accumulates with distance. This means that the PMD effect will cause shortening in the transmitted distance.

Initial investigations with standard SMF have verified that the PMD effect has negligible effect on the maximum transmission distance of amplified links compared to chromatic dispersion. These simulations used a PMD value of 0.2 ps/√km, as specified for SMF-28 fibre by Corning® [5]. In order to observe any effect of PMD on the transmission distance, the level of PMD would have to be an order of magnitude higher for the NRZ system, and about 25 times higher for the AM-PSK and PSBT systems. These results suggest that the duobinary schemes are more tolerant to PMD. Future work will need to include the study of the PMD effect on dispersion managed schemes, where it is expected to be significant, and may include analysis of PMD compensation methods [6].

## 4. Conclusion:

Simulation investigations on bandwidth efficient modulation schemes that increase the transmission distance in standard SMF beyond those achievable using NRZ-binary have been carried out. In addition, it has been shown that dispersion management can improve the reach of NRZ modulation, but not of a scheme such as PSBT which highly dispersion tolerant already. The effect of PMD on transmission distances showed that as its value increases, shorter propagation distances are achieved. Other high data modulation transmission methods are investigated in future work; for example, alternate mark inversion modulation (AMI) has been predicted in recent studies [7] to be a new method for increasing propagation transmission distances and achieving higher spectral efficiency.

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