Duobinary Modulation For Optical Systems

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Introduction

Optical systems by and large use NRZ modulation. While NRZ modulation is suitable for long haul systems in which the dispersion of the single mode fiber is compensated for by another fiber with negative dispersion, it is not the best choice for uncompensated single mode fibers. Duobinary modulation turns out to be a much better choice in this case since it is more resilient to dispersion and is also reasonably simple to implement. In this paper the basics of duobinary modulation are explained and lab measurements are presented that clearly show its superiority to NRZ modulation for the uncompensated optical fiber channel.

What is Duobinary Modulation?

Duobinary modulation is a scheme for transmitting R bits/sec using less than R/2 Hz of bandwidth [1,2]. Nyquist's result tells us that in order to transmit R bits/sec with no intersymbol interference (ISI), the minimum bandwidth required of the transmitted pulse is R/2 Hz. This result implies that duobinary pulses will have ISI. However, this ISI is introduced in a controlled manner so that it can be subtracted out to recover the original values.

Let the transmitted signal be

$$x(t) = \sum_{k=-\infty}^{\infty} d_k q(t - kT), \;\; d_k = 0,1 \tag{1.1}$$

Here, $\{d_k\}$ are the data bits, $q(t)$ is the transmitted pulse, and $T = 1/R$ is the bit period. The pulse $q(t)$ is usually chosen such that there is no ISI at the sampling instances ($t = kT$, $k = 0, \pm 1, \ldots$, are the sampling instances):

$$q(kT) = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases} \tag{1.2}$$

NRZ is one such scheme and requires a bandwidth of R Hz to transmit R bits/sec (this is twice as large as the Nyquist bandwidth of $R/2$ Hz).

The simplest duobinary scheme transmits pulses with ISI as follows:

$$q(kT) = \begin{cases} 1 & k = 0,1 \\ 0 & otherwise \end{cases} \tag{1.3}$$

We then see from (1.1) and (1.3) that at the sampling instance *kT*, the receiver does not recover the data bit d_k, but rather $(d_{k-1} + d_k)$. However, this scheme allows for pulses with a smaller bandwidth. By allowing some ISI, the transmitted pulse *q(t)* can be made longer in the time domain, and hence its spectrum becomes narrower in the frequency domain. With a narrower spectrum, the distortion effects of the channel are also fewer. This outcome is one of the reasons why duobinary modulation is resilient to dispersion.

One way of generating duobinary signals is to digitally filter the data bits with a two-tap finite impulse response (FIR) filter with equal weights and then low-pass filter the resulting signal to obtain the analog waveform with the property in (1.3) (see Figure 1a). When the input to the FIR filter is binary (let these binary values be -1 and 1), the output can take on one of three values: 0.5*(–1 + -1) = –1; –1 + 1 = 0; or 0.5*(1 + 1) = 1. Hence the duobinary signal is a three-level signal.

An important property of the three-value sequence at the output of the FIR filter is that it is a correlated signal and hence all possible sequences of the three values cannot occur. For example, the output sequence of the FIR filter cannot contain a 1 followed by a –1, or a –1 followed by a 1; a 1 and a –1 will always have a 0 between them. Similarly, the combinations {1 0 1} and {–1 0 –1} also can never occur at the output of the FIR filter; only a {–1 0 1} or a {1 0 –1} can occur. As will be explained later, this sequence is another reason why duobinary modulation is resilient to dispersion.

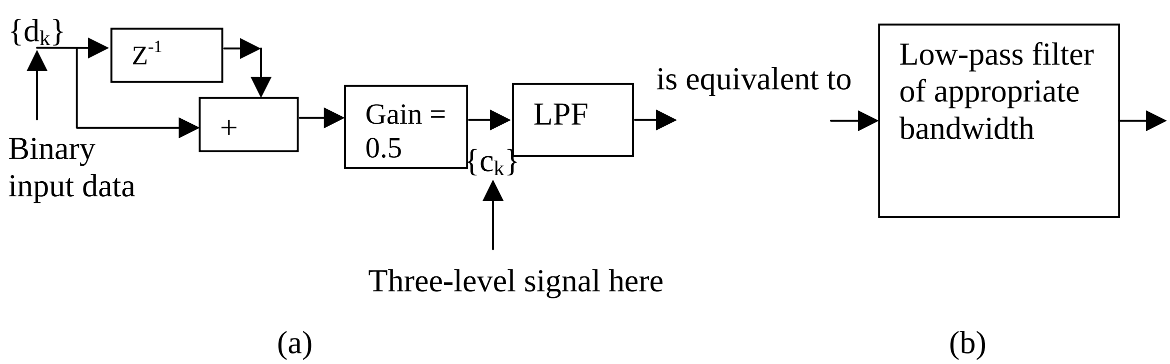


Figure 1. Duobinary encoder

On a final note, the FIR filter and the low-pass filter can be combined into a single analog filter for ease of implementation (Figure 1b). The two-tap FIR filter is after all a simple low-pass digital filter. For a 10 Gbps data stream, a good filter that combines the functions of the FIR filter and the analog filter is a 2.8 GHz Bessel filter.

Differential Encoding

The ISI introduced at the transmitter can be unraveled at the receiver by differential decoding [2]. At each sampling instance *kT*, the receiver assumes the value of $x_k = (d_k + d_{k-1})$, where $x_k = x(kT)$ and *x(t)* satisfies (1.3) . If the previous decision at the output of the receiver is $\hat{d}_{k-1}$, this decision can be subtracted from the sampled value to obtain $\hat{d}_k$:

$$\hat{d}_k = x_k - \hat{d}_{k-1} \tag{1.4}$$

However, a single error at the receiver will propagate forever, causing a catastrophic decoding error. To avoid this catastrophic error propagation, it is better to move this differential decoding to the transmitter and differentially precode the data. The data bits d_k are differentially encoded as follows:

$$c_k = c_{k-1} \oplus d_k \ \ (\oplus \text{ is modulo 2 subtraction}) \tag{1.5}$$

The transmitted signal is now

$$x(t) = \sum_{k=-\infty}^{\infty} c_k q(t - kT)\,, \tag{1.6}$$

with *q(t)* satisfying (1.3). Hence at the sampling instance *kT*, the receiver samples the value $c_k \oplus c_{k-1} = c_{k-1} \oplus d_k \oplus c_{k-1} = d_k$.

Implementing a High-Speed Differential Encoder

One circuit that can be used to implement a differential encoder is an exclusive-OR (XOR) gate (Figure 2). However, it can be difficult to implement the 1-bit delay in the feedback path at high data rates such as 10 Gbps.

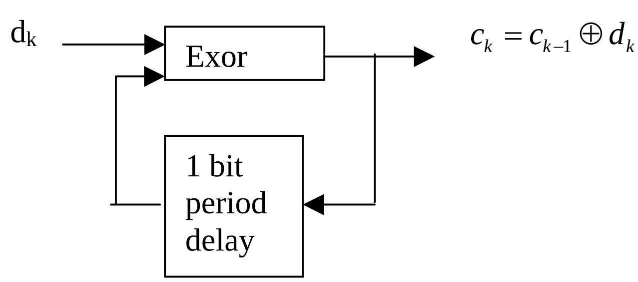


Figure 2. Differential encoder with an XOR gate

Another circuit that does not involve delay in the feedback path is shown in Figure 3. Here, a divide-by-2 counter has a clock gated with the data. When the data is high, the counter changes state, which is equivalent to adding a 1 modulo 2. When the data is low, the counter state remains the same, which is equivalent to adding a 0 modulo 2.

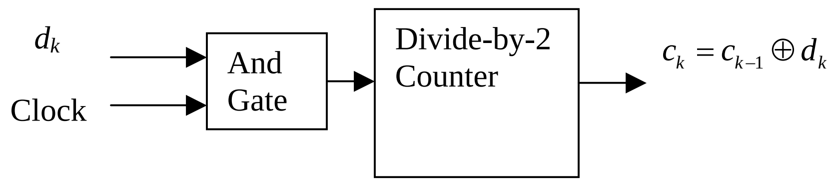


Figure 3. Differential encoder with a divide-by-2 counter

The Optical System

The final step is to modulate the light with the three-level duobinary signal, which implies a three-level optical signal. This result is achieved with a Mach-Zehnder (MZ) modulator biased at its null point. With a zero input, no light is transmitted, but the +1 and –1 inputs are transmitted as +E and –E electric fields [4, 5]. While this is a three-level signal in terms of the electric field, it is a two-level signal in terms of optical power. This choice significantly reduces the complexity of the receiver (the first optical duobinary systems used a mapping that requires three levels of optical power [3]). One of the key components is a driver that can produce a voltage swing of $2*V\pi$ volts at high data rates such as 10 Gbps in order to drive the MZ modulator.

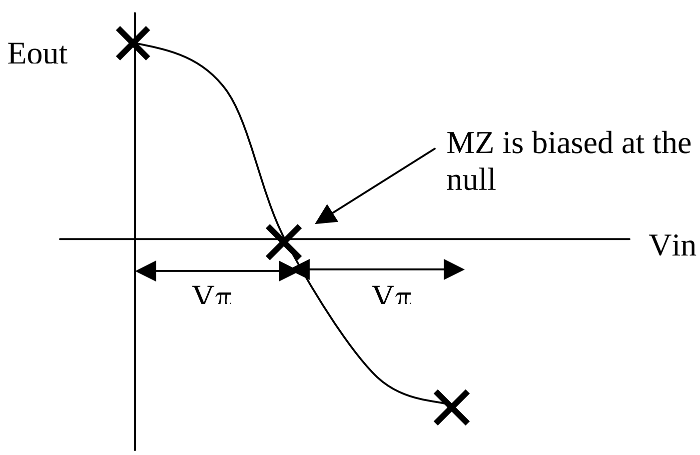


Figure 4. Biasing of the Mach-Zehnder modulator

The combination of the duobinary encoder and the above mapping to electric fields helps further reduce the effects of dispersion in the fiber [5]. As the pulses travel down the fiber, they spread out in time owing to dispersion. In an NRZ scheme, a data sequence of {1 0 1} is mapped onto the optical domain as {+E 0 +E}. In the encoded duobinary sequence, a {1 0 1} sequence cannot occur, but a {1 0 –1} does occur, which is mapped to {+E 0 –E} in the optical domain. The effect of dispersion in the two cases is shown in Figure 5 below, which depicts why the resulting dispersion is less in the case of duobinary modulation.

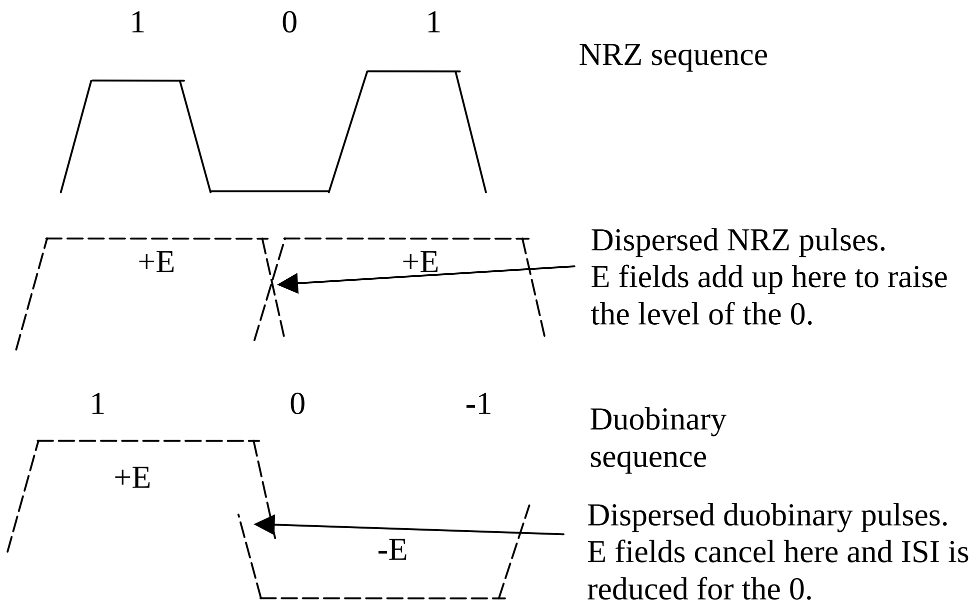


Figure 5. Effect of dispersion on NRZ and duobinary sequences

The same receiver that is used for a NRZ modulation scheme can be used for duobinary modulation. The power detector squares the electric field to detect power and hence the +E and –E outputs of the fiber get mapped to the same power level and are detected as logical 1s.

The Complete Duobinary Transmitter

The complete duobinary transmitter is shown in Figure 6. An inverter is added at the input to the differential encoder; without it, the data at the receiver is inverted. This inverter can be placed either at the receiver or the transmitter. Since signal paths are usually differential, the inverter is not an additional piece of hardware that is required but instead can be implemented by reversing the differential lines from the data source to the AND gate. The exact sequence of transformations that occur in the data path at each stage is given in an example in Figure 7.

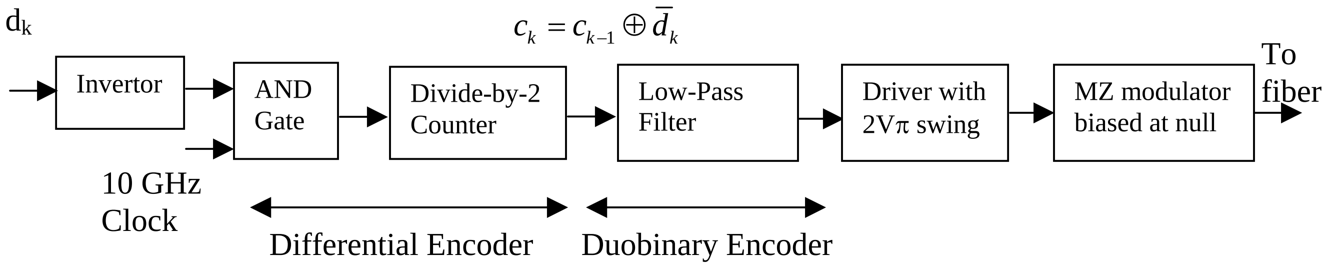


Figure 6. A complete duobinary modulator

K	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
d_k		0	1	0	1	1	1	0	0	0	0	1	0	1	0	1	0
$\overline{d}_k$		1	0	1	0	0	0	1	1	1	1	0	1	0	1	0	1
Diff encoder	0	1	1	0	0	0	0	1	0	1	0	0	1	1	0	0	1
Bit to voltage mapper	-1	1	1	-1	-1	-1	-1	1	-1	1	-1	-1	1	1	-1	-1	1
Duobinary encoder		0	1	0	-1	-1	-1	0	0	0	0	-1	0	1	0	-1	0
Electric field		0	+E	0	-E	-E	-E	0	0	0	0	-E	0	+E	0	-E	0
Optical power		0	E^2	0	E^2	E^2	E^2	0	0	0	0	E^2	0	E^2	0	E^2	0
Receive bits		0	1	0	1	1	1	0	0	0	0	1	0	1	0	1	0

Figure 7. An example showing the transformation of data in a duobinary system

Lab Measurements

Measurements were carried out to determine the performance of duobinary modulation and compare it with that of NRZ modulation at 10 Gbps. The measurements were made at 1550 nm over standard single-mode fiber (SMF). This fiber has a dispersion of 17 psec/nm Km at this wavelength and an attenuation of 0.2 dB/Km. The experimental setup is depicted in Figure 8. An optical amplifier was added after the MZ modulator to compensate for the loss in the MZ modulator and to launch sufficient power to transmit through 120 Km of fiber. The power launched into the fiber was kept at a level low enough to avoid any self-phase modulation effects.

An interesting property of the 2^7-1 PRBS sequence used (generator polynomial = $1 + x^6 + x^7$) is that following differential encoding, it is the same PRBS sequence shifted by 6 bits. (The property that a differentially encoded PRBS sequence is a delayed version of the original sequence holds true whenever the generator polynomial is of the form

$1 + x^{n} + x^{n+1}$, $n > 0$, and the resulting delay between the PRBS sequence and the differentially encoded sequence is (n-1)). Since the BERT is capable of aligning the transmitted and received data streams, the delay is of no consequence, and the step of differentially encoding the data can be eliminated.

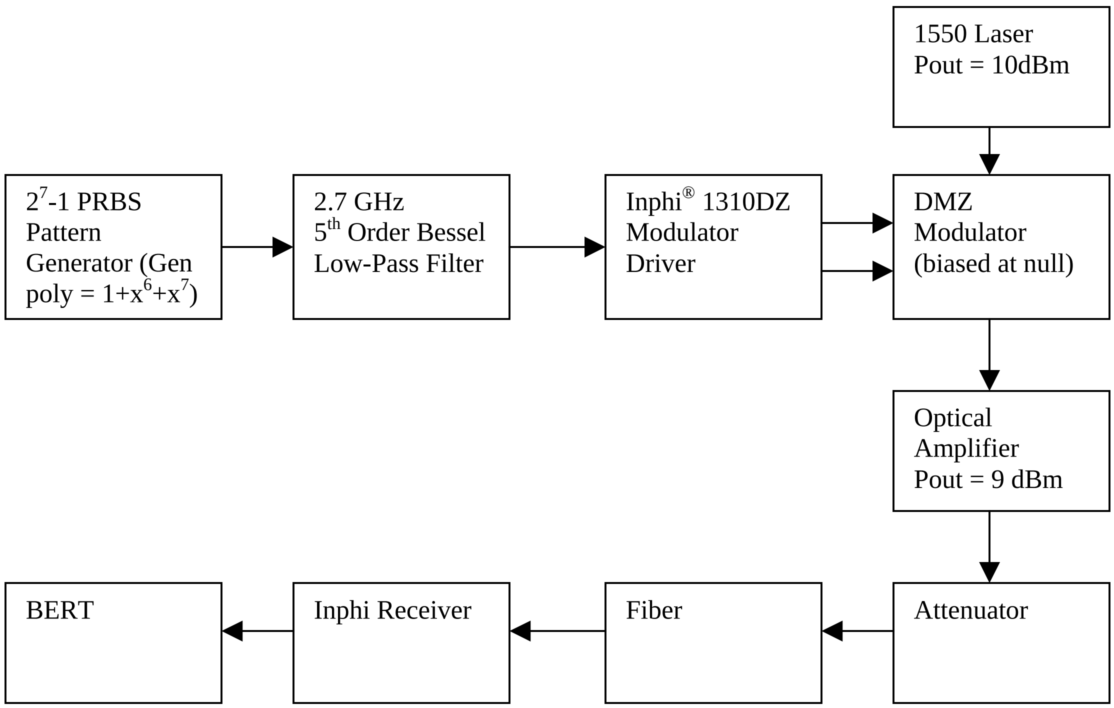


Figure 8. Experimental setup for BER testing

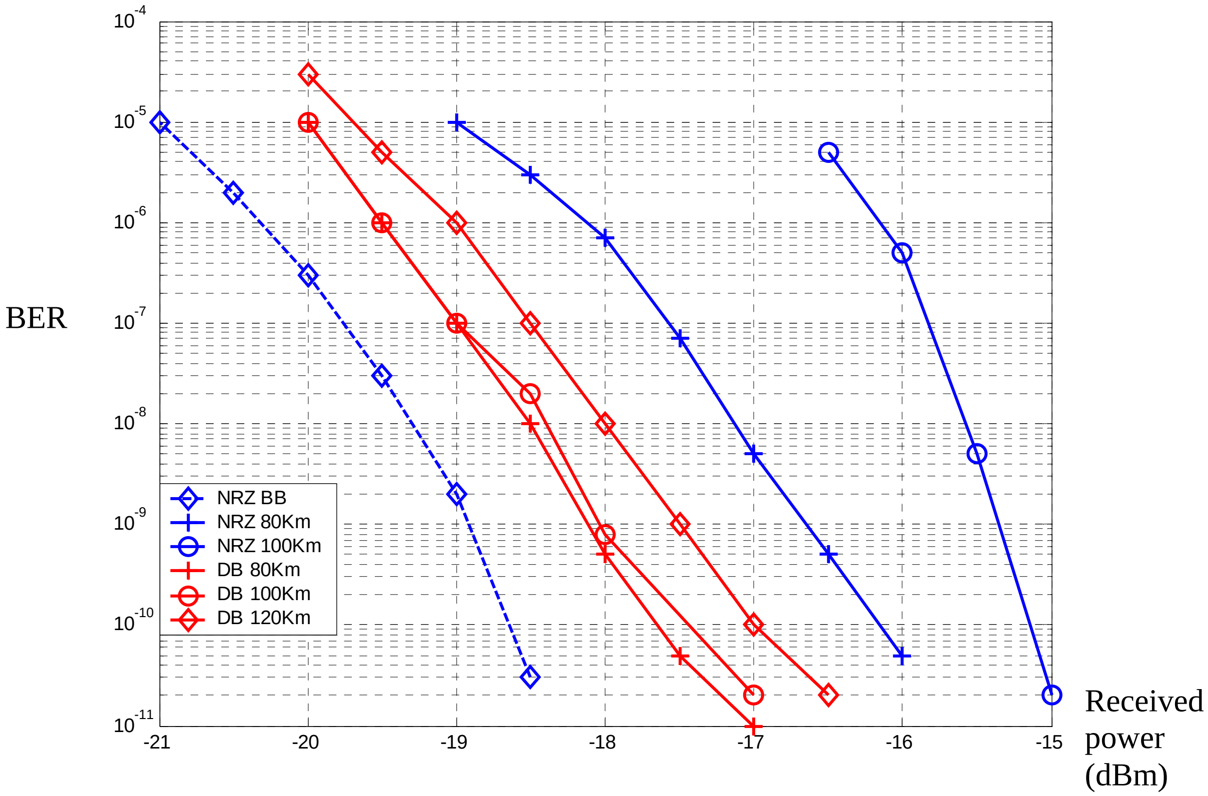
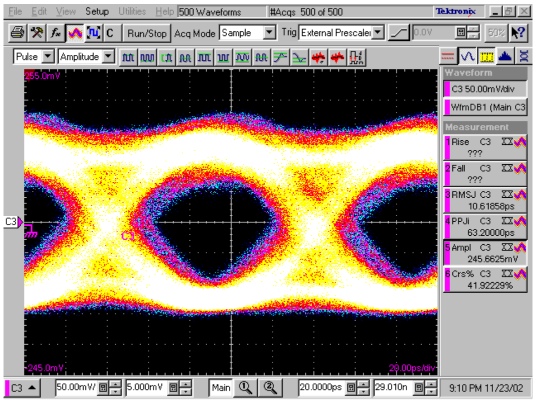


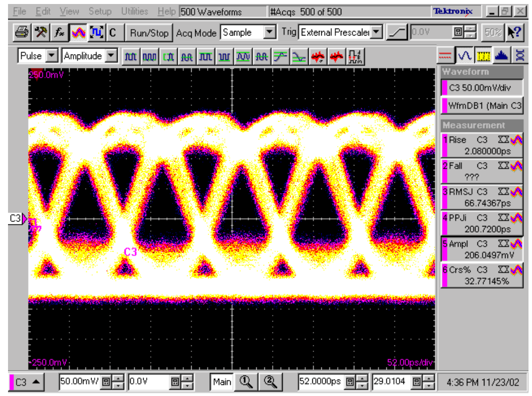
Figure 9. BER curves for NRZ and duobinary modulation schemes
(Key to legend: BB = back-to-back; DB = duobinary)

Fiber Length (Km)	Dispersion Penalty for NRZ (dB)	Dispersion Penalty for Duobinary (dB)
80	2.5	1
100	3.5	1
120	Infinity	1.5

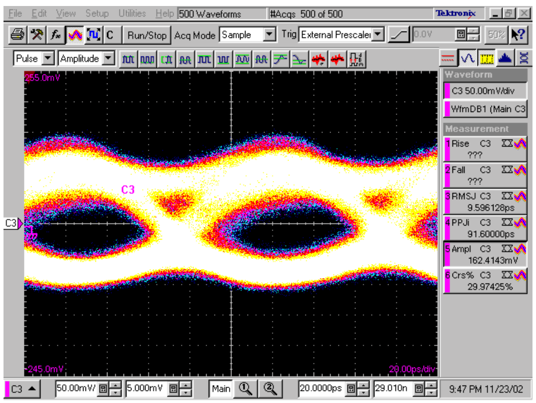
Figure 10. Dispersion penalty for NRZ and duobinary modulation schemes



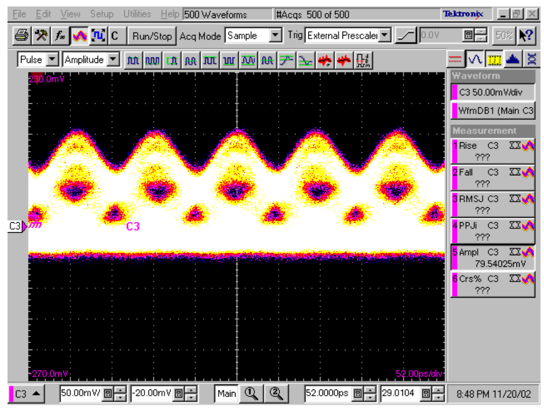
Duobinary eye after 80 Km of SMF



NRZ eye after 80 Km of SMF



Duobinary eye after 120 Km of SMF



NRZ eye after 120 Km of SMF

Figure 11. Eye diagrams comparing duobinary and NRZ modulation schemes

Conclusion

Duobinary modulation is a much more resilient modulation scheme compared with NRZ modulation in the presence of chromatic dispersion. It is possible to extend the reach of NRZ systems from 80 Km to 120 Km without the use of dispersion compensating fibers. While a NRZ system is dispersion limited at 120 Km, a duobinary system is power limited at this same 120 Km length of SMF fiber. The components are available today to implement such systems.

Acknowledgements

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