Optical Modulation for High Bit Rate Transport Technologies

By Ildefonso M. Polo | October, 2009

Scope

There are plenty of highly technical and extremely mathematical articles published about optical modulation formats, showing complex formulas, spectral diagrams and almost unreadable eye diagrams, which can be considered normal for every emerging technology. The main purpose of this article is to demystify optical modulation in a way that the rest of us can visualize and understand them. Nevertheless, some of these modulations are so complex that they can't be properly represented in a simple time domain graph, so polar (constellation) or spherical coordinates are often used to represent the different states of the signal. Within this document some of these polar diagrams have been enhanced with the state diagram (blue) to indicate the possible transitions and logic.

Introduction

Back in the early '90s, copper lines moved from digital baseband line coding (e.g. 2B1Q, 4B3T, AMI, and HDB3, among others) to complex modulation schemes to increase speed, reach, and reliability. We were all skeptical that a technology like DSL would have been able to transmit 256 simultaneous QAM16 signals and achieve 8 Mbit/s. Today copper is already reaching the 155 Mbit/s mark. This is certainly a full circle. We moved from analog to digital transmission to increase data rates and reliability, and then we resorted to analog signals (through modulation) to carry digital information farther, faster and more reliably. Back then, 155 Mbit/s were only thought of for fiber optics transmission.

It is also interesting to note that only a few years ago we seemed to be under the impression that 'fiber optics offered an almost infinite amount of bandwidth' or more than we would ever need. We often heard "but", there is too much dark fiber out there!', we were all happy switching light on and off (OOK – On-Off Keying), and the main challenge was about how to switch light faster. It worked well up to 10 Gbit/s, but in retrospect baseband OOK looks quite primitive. Granted that there have been huge DWDM deployments all over the world for 10, 10.7 and 11 Gbit/s (STM-64, OC-192, OTU2, OTU2e), which can be considered a simple form of carrier modulation.

Again, at the beginning of the 21st century there was a lot of hype around the almost infinite bandwidth capacity of the fiber optics networks, and it was common to talk about 12.5 GHz channel spacing, and hundred of channels for DWDM, but at the end of the day the industry settled around the more practical 100 and 50 GHz spacing, and relatively few wavelengths.

Today, we seem to have run out of bandwidth again. The 40, 43, 44, and now 100 Gbit/s, deployments have triggered the need to innovate again, to allow more bits to be reliably squeezed in per channel. This spurred the development of new line coding or modulation schemes for high speed digital transport networks. Just like it happened to copper lines back in the '90s, fiber optics transmission has started to move away from OOK NRZ, and to apply more complex modulation schemes.

Bandwidth demand is pushing network upgrades to 40, 43, 44, and 100 Gbit/s, but one big challenge is that carriers and service providers made big investments in their fiber optics network (DWDM, ROADM, repeaters,...) based on 10/10.7 Gbit/s requirements, and it is sensible to think that they would want to reuse as much of their original investment as possible, and avoid disrupting their current 10G links. A seamless upgrade would be ideal.

Reach: In the case of the traditional non-return-to-zero (NRZ) keying technique, the faster the light is switched, the less energy there is per bit, as the line is on for shorter period and pulses are closer to each other. Hence, the signal is more susceptible to attenuation, chromatic dispersion, polarization mode dispersion, and other impairments, so the reach is decreased substantially. A typical 40/43 Gbit/s signal can reach a few kilometers; while a similar 10/10.7 Gbit/s NRZ could reach 40 km. One huge impact to the network would be the number of extra repeaters required between nodes. Installing more repeaters would not be an easy decision to make, not just because of the cost, but because these DWDM networks carry multiple live channels, all full of customer traffic.

Spectral: As transmission rate increases from 10 Gbit/s to 40 or even 100 Gbit/s, the spectral characteristics of the signal become wider, and this has another list of consequences. In practical terms, the DWDM networks built in the past few years have filters (add/drop) designed for the spectral characteristics and channel spacing of 10/10.7G signals. This would imply replacing key network components in the nodes, at a great expense and downtime. Also, filter concatenation narrows optical channel bandwidth as DWDM channels pass optical filters at every Optical Add/Drop Multiplexer (OADM), becoming a problem at high spectral densities.

The solution: Let's make 40/43G and 100G signals behave like 10/10.7G signals, by increasing their spectral efficiency, so they can be used in existing DWDM networks with 'minor' adjustments! It may sound as 'crazy' as the ADSL DMT claims sounded back in the '90s, but today they are just taken for granted. Fortunately the industry took on the challenge and modulation was finally introduced to optical transport networks. If history is any indication, it could be said that optical transport modulation is currently at its infancy, and one should only expect it to grow in internal complexity, robustness, and - why not? - data rate, because we will always find ways to run out of bandwidth again.

Optical Modulation Schemes

Higher spectral efficiencies are not only required to match existing DWDM filters, but to reduce electrical speed of the signals by increasing the baud rate (number of bits transmitted per each optical symbol). Narrower spectral characteristics and lower symbol rate also have the benefits of higher tolerances to OSNR and linear impairments like Polarization-mode Dispersion (PMD) and Chromatic Dispersion (CD).

OOK (one bit per symbol)

The traditional On-Off Keying modulation (turning on and off a carrier) is non-return-to-zero (NRZ), which is analogous to unipolar encoding. It is the simplest line code. Its major disadvantage is that it is not self-clocking, which is addressed by scrambling the stream to increase the number of transitions and improve clock recovery (e.g. an all ones stream would not be transmitted as a constant laser on). NRZ has been the modulation of choice for 10 Gbit/s and below. For 40 and 43 Gbit/s, NRZ is used in the client side (optical cross connect or OXC) only, while more complex modulation schemes are used in the line side (long haul and DWDM).

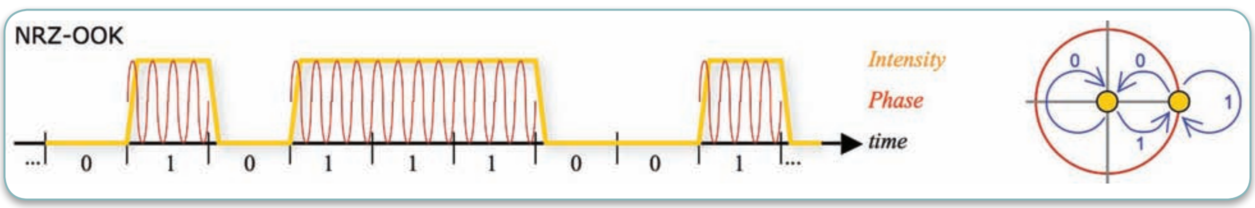


Figure 1. Simplified time domain (intensity) and phase representations of an OOK NRZ signal

Its return-to-zero (RZ) version improves the clock recovery by making the signal return to zero in the middle of the bit period so a constant stream of ones would be represented by an alternating signal. The bit stream is also scrambled to avoid long streams of zeroes. The disadvantages of RZ are having less energy per symbol than NRZ and higher frequency.

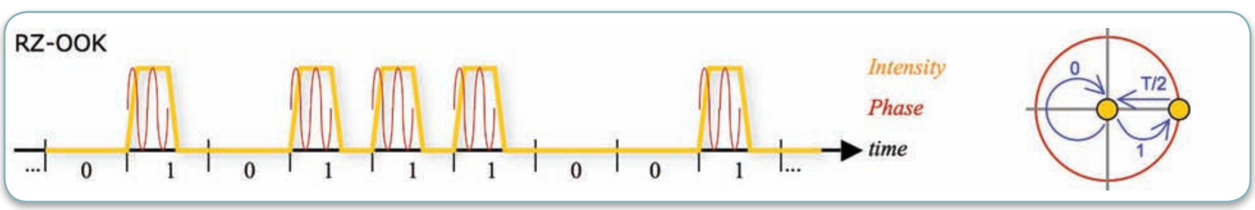


Figure 2. Simplified time domain and phase representations of an OOK-RZ (50%) signal

NRZ and RZ are the foundation for more complex modulations listed below, so these acronyms are usually prefixed to the modulation scheme to identify which base coding it starts with (e.g. RZ-DQPSK).

Since the phase of the laser does not carry any information, this transmission technique uses a very simple direct detection technique, just coupling the light to a photo detector to obtain the equivalent electrical bit stream. At 40 Gbit/s and beyond, this simple form of modulation offers fair dispersion tolerance, but poor noise tolerance and poor bandwidth efficiency so it can not be used in DWDM networks.

PSK or BPSK (one bit per symbol)
Phase-Shift Keying (PSK) or Binary PSK is a modulation scheme that modifies the phase of the optical wave (between 0° and 180°, or 0 and π), instead of the intensity of the light, distributing the optical power more evenly, as power is present on every time slot (bit). In theory, this may be represented as a constant intensity or continuous wave (CW), as the ones and zeroes are represented by two different phases of the light wave. The difficulty lies in the demodulation side, as it requires a demodulator that can detect the absolute phase of the incoming light wave.

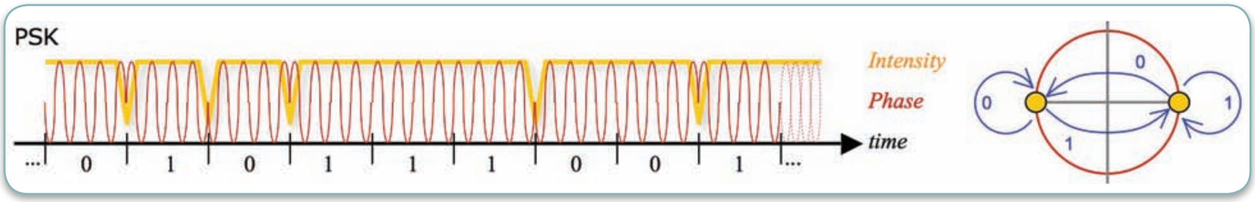


Figure 3. Simplified time domain and phase representations of a theoretical PSK signal

PSBT (one bit per symbol)
Phase-Shaped Binary Transmission, derived from Duobinary, consists of a 180° (π) phase-shift on any transition from 0 to 1 and vice-versa. It offers strong CD tolerance and reduced bandwidth in comparison to NRZ-OOK. This technique is known for its dispersion tolerance and reduced optical bandwidth, suitable for 50 GHz DWDM up to 40 Gbit/s.

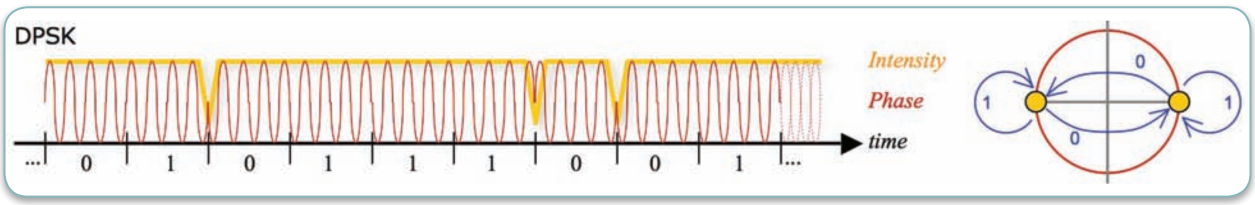


Figure 4. Simplified time domain and phase representations of a theoretical DPSK signal

DPSK (one bit per symbol)
Differential PSK consist of a PSK modulator differentially driven by a bit stream. In the Differential scheme, zeroes represent a 180° change in phase and ones represent no change at all, so every time a zero is transmitted the phase of the signal gets inverted. This technique offers superior OSNR tolerance but it uses more optical bandwidth (Figure 7) making it only acceptable for Long Haul (LH) and Ultra Long Haul (ULH) links and not for 50GHz DWDM networks.

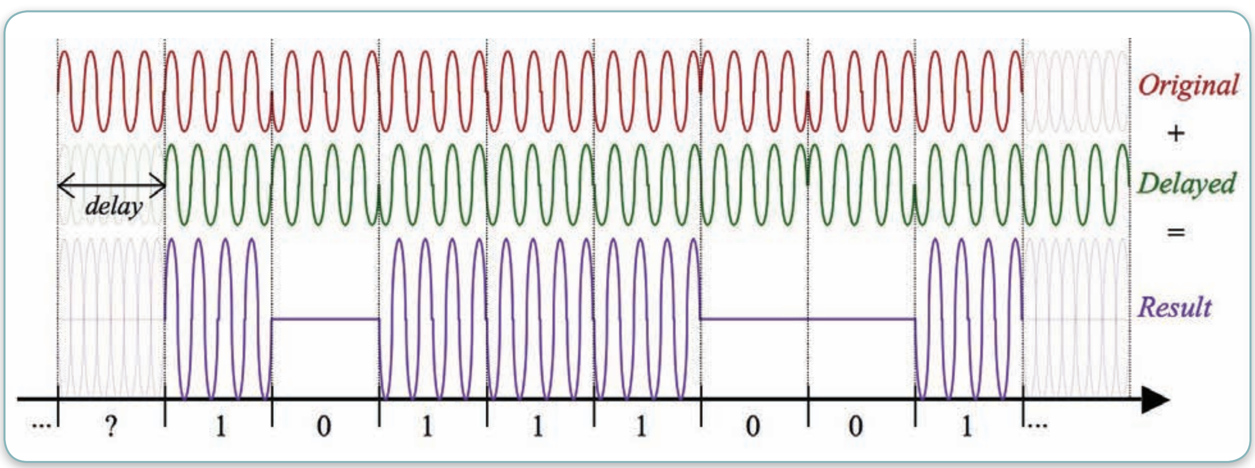


Figure 5. Simplified representation of the DPSK demodulation

One advantage of this differential method is the simplification in the demodulator side. The demodulator splits the signal in two, delays one of them by one bit period using a longer optical path, and then combines them, letting constructive (signals in phase) and destructive (signals with opposite phase) interference do the job. The output is an intensity-modulated optical signal, similar to NRZ-OOK that can be passed to a photo detector for direct conversion to electrical.

DQPSK (two bits per symbol)

Differential Quadrature Phase-Shift Keying splits the data stream in two, and uses DPSK to modulate each stream, then introduces a $\pi/2$ delay to one of the streams before combining them, resulting in four different phases (0, $-\pi/2$, $\pi/2$, and π). Hence DQPSK transmits two bits for every symbol and narrower optical bandwidth, which turn into additional advantages over conventional binary DPSK. The symbol information is encoded as a phase change from one symbol to the next rather than an absolute phase value, so the receiver only needs to detect phase changes and not the absolute value of the phase [1]. Nonetheless, it requires more complex modulators and demodulators.

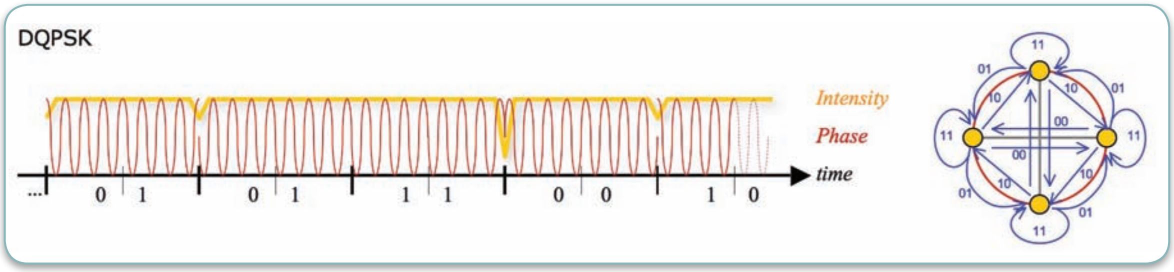


Figure 6. Simplified time domain and phase representations of a theoretical DQPSK signal

DQPSK's narrower optical spectrum tolerates more dispersion (both chromatic and polarization-mode) and allows for stronger optical filtering, enabling closer channel spacing. As a result, DQPSK allows processing of 40 Gbit/s data rate in a 50 GHz channel spacing system, making it suitable for use with ROADM (Reconfigurable Optical Add/Drop Multiplexer) in DWDM networks.

PM-DQPSK (four bits per symbol)

Used in 100 Gbit/s, Polarization Multiplexed DQPSK splits the bit stream in half, modulates each half rate using DQPSK, polarizes each sub-signal using two orthogonal optical polarization planes, and mixes them to form the final modulated the signal. This signal is modulated in intensity and optical phase, and then transmitted in two different polarization states. As the polarization is an important state of this modulation scheme, it is not difficult to conclude that this technique has lower tolerance to PMD.

PM-QPSK with Coherent Demodulator is also being used for 100 Gbit/s with excellent results.

And, of course, every major vendor has been pushing the benefits of their own techniques, nuances, and discoveries so you may find other acronyms like PDPSK (Partial DPSK), CS-RZ (Carrier Suppressed Return to Zero), among others, with their own sets of benefits. Some are optimized for long haul, ultra long haul, or for specific channel spacing, with emphasis in 50 GHz DWDM and ROADM networks.

All the modulations schemes discussed above are considered serial transport techniques, but you may have also heard about another alternative, commonly referred as 100G Parallel Transport, "Muxponders" (multiplexed transponder), or 10x10G. These systems use 10 different wavelengths with 10G modulators, and OTN VCAT (Optical Transport Network and Virtual Concatenation) to achieve 100 Gbit/s. Sometimes it is referred as "Inverse Multiplexing" and mainly used for short reach applications [4]. Of course, since it is already a DWDM signal by itself, it is not meant to be used in DWDM networks. Although some of the major carriers favor and have strong opinions about this early option, this may just be a natural transition technology (easier to implement and deploy in early field trials), but the future may look brighter for serial modulation techniques.

Performance Comparison

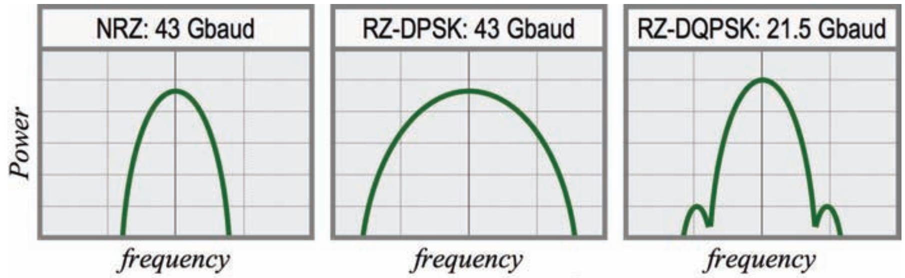


Figure 7. Spectral comparison between different modulation techniques at 43G (OTU3)

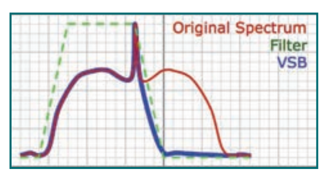
	PSBT	DPSK	PM-DQPSK	PM-QPSK (Coherent Demod.)
OSNR Sensitivity	Poor	Fair	Good	Best
Tolerance to PMD (1st order)	Poor	Poor	Good	Best
Tolerance to PMD (2nd order)	Best	Fair	Good	Best
Tolerance to Chromatic Dispersion	Fair	Poor	Good	Best
Reach/Distance	Poor	Fair	Good	Best
Spectral Efficiency	Good	Fair	Good	Good

Figure 8. Performance comparison for modulation techniques, based on 100 Gbit/s

Other Enhancements

Scrambling: Data streams are usually scrambled, before being modulated, to improve the density of one and zero transitions. Among other advantages, this helps with clock recovery at the far end.

Compensation: At higher bit rates, such as 40 or 100 Gbit/s, several compensation techniques are used at optical and electrical levels to improve the robustness of the transport signal. Besides Forward Error Correction (FEC and EFEC) techniques embedded in the OTN signal, other improvements are implemented at the physical level via electrical post-processing, like Multi-Symbol Phase Estimation (MSPE), dispersion compensation, etc., which translates into a perceived dB gain, helping compensate for some of the modulations' weaknesses.



VSB: Vestigial Side Band Filtering is a technique used to suppress one of the spectral sidebands created by some modulation techniques, hence reducing the total spectral requirements and making the signal more compatible with existing Optical Add/Drop Multiplexers (OADM) filters (e.g. 50 GHz spacing).

Coherent Demodulation: In contrast to traditional direct-detection optical system technology, an optical coherent detection scheme detects the optical signal's amplitude, phase and polarization. Better spectral efficiency and detection capability enable the transmission at higher rates within the same optical bandwidth. It also allows the use of advanced electronic compensation techniques.

Complicated? Apparently not enough. Researchers are already working on modulation schemes and compensation techniques to allow Terabit/s transmission over hundreds of kilometers, which may include more phases and much more levels.

References:

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