Optical Modulation Methods

For High-Speed Networks and the Consequences for Test Equipment

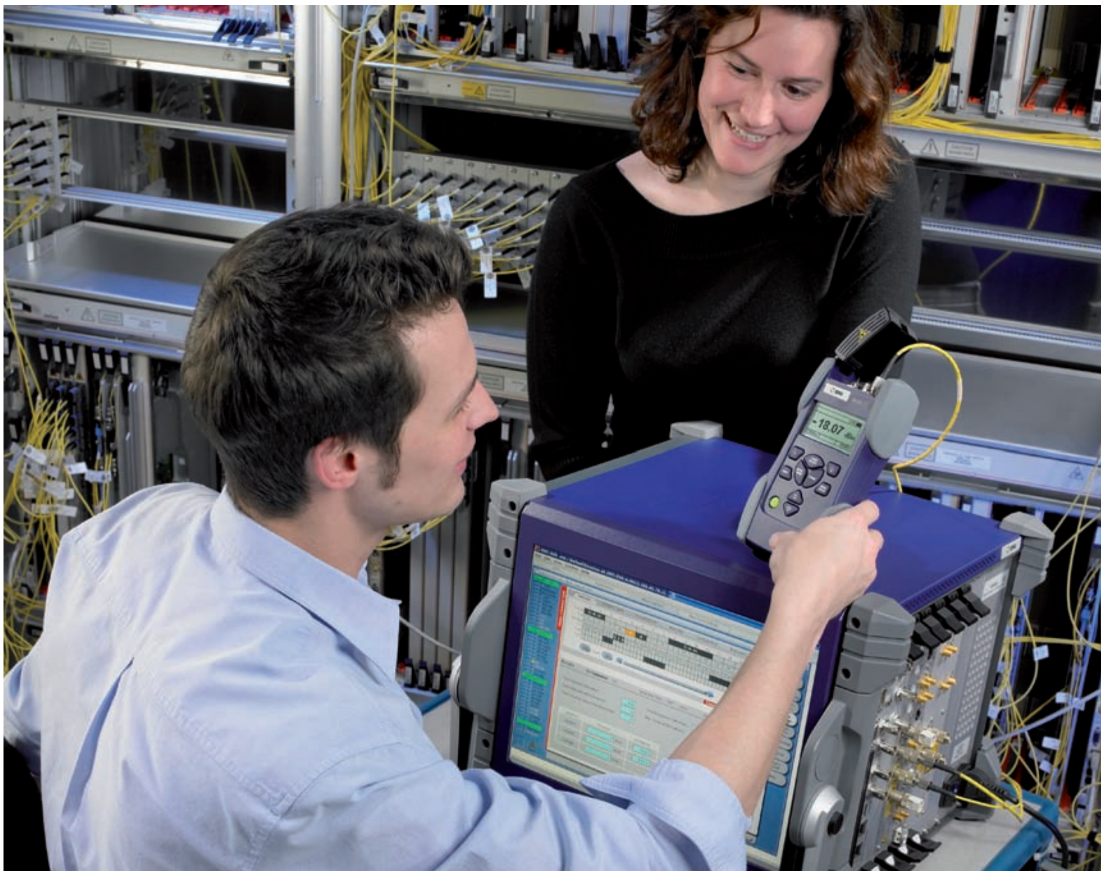

Figure 1: Using the ONT-506 to test modern DWDM systems

A range of newly developed fundamental communications technologies must be employed in order to reliably transmit signals of 40/43 Gbps and even 100 Gbps in the near future using telecommunications networks. One of these technologies involves the use of higher-level modulation methods on the optical side, similar to those which have been used for many years successfully on the electrical side in xDSL broadband access technology, for example. This article briefly examines the problems, why such methods are necessary, and the consequences of this for the measuring equipment needed for service turn-up and troubleshooting on such systems.

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Higher-order modulation methods

A lot of new abbreviations for optical modulation methods have sprung up with the introduction of 40/43 Gbps communications technology. Until now, just one modulation method was used for transmission rates of up to 10 Gbps, namely on/off keying or OOK for short. Put simply, this means that the laser light used for transmission was either on or off depending on the logical state 1 or 0 respectively of the data signal. This is the simplest form of amplitude modulation. Additional external modulation is used at 10 Gbps. The laser itself is switched to give a continuous light output and the coding is achieved by means of a subsequent modulator. Why are higher-level modulation methods with their attendant complexity needed at 40/43 Gbps?

There are many reasons for this

Every method of modulation broadens the width of the laser spectrum. At 10 Gbps this means that about 120 pm bandwidth is needed for OOK. If the transmission rate is quadrupled to 40 Gbps, the necessary bandwidth also quadruples, i.e. to around 480 pm. The greater bandwidth results in a linear increase in the noise power level in the communications channel. A four-fold increase in the noise power level corresponds to 6 dB and would result in a decrease in the minimum sensitivity of the system by this same factor. This results in a much shorter transmission range at 40 Gbps, and a consequent need for more regenerators. Increasing the laser power in sufficient measure to compensate for the missing balance in the system compared to 10 Gbps is not possible. Nonlinear effects in the glass fiber, such as four-wave mixing (FWM), self-phase modulation (SPM), and cross-phase modulation (XPM) would also adversely affect the transmission quality to a significant degree. Higher-level modulation methods reduce the modulation bandwidth and thus provide a way out of this dilemma.

One absolute necessity is the need to integrate the 40/43 Gbps systems into the existing DWDM infrastructure. The bandwidth required by OOK or optical dual binary (ODB) modulation only allows a best case channel spacing of 100 GHz (= approx. 0.8 nm) in a DWDM system. Systems with a channel spacing of 50 GHz (= approx. 0.4 nm) have long been implemented in order to optimize the number of communications channels in the DWDM system. For both technologies to be integrated into a single DWDM system, the multiplexers/demultiplexers (MUX/DEMUX) would have to be reconfigured back to a channel spacing of 100 GHz and the corresponding channel bandwidths, or hybrid MUX/DEMUX would have to be installed. Both these solutions are far from ideal, since they either result in a reduction in the number of communications channels or the loss of flexibility in the configuration of the DWDM system. Here, too, the answer is to use higher-level modulation methods that reduce the required bandwidth.

As well as other factors, the transmission quality of a communications path also depends on polarization mode dispersion (PMD) and chromatic dispersion (CD). CD depends on the fiber and can be compensated for relatively simply by switching in dispersion-compensating fibers. However, this once again degrades the loss budget. This is within acceptable limits for realizing the usual range distances in 10 Gbps systems. But this is not the case with 40 Gbps, where the system budget is already reduced anyway. For this reason, other compensation methods must be used, subject to the additional requirement for exact compensation at all wavelengths of a DWDM system because the maximum acceptable value for CD is a factor of 16 lower than that for 10 Gbps. The maximum acceptable PMD value for 40 Gbps is reduced by a factor of four. The PMD value is largely affected by external influences on the fiber, such as temperature and mechanical stress, and is also dependent on the quality of manufacture of the fiber itself. A requirement for any new modulation method would be a corresponding tolerance to PMD and CD.

When you take a look at the data sheets issued by systems manufacturers or in other technical publications, it is easy to be confused by the number of abbreviations used for new modulation methods. How do these methods differ, and which of them are really suitable for future transmission speeds? Unfortunately, there is no easy answer to that either. Apart from the technical requirements, such as

- Significant improvement in minimum OSNR by reducing the signal bandwidth
- Compatibility with the 50 GHz ITU-T channel spacing or at least with a spacing of 100 GHz
- Coexistence with 10 Gbps systems
- Transmission in networks that use ROADMs
- Scalable for 100 Gbps

The degree of technical difficulty and hence the economic viability also have to be taken into account.

Categories of modulation methods

- **Amplitude modulation**
  – NRZ/RZ on/off keying (OOK)
  Baud rate = bit rate
- **Single polarization state phase modulation (DPSK)**
  Normalized phase and amplitude *at the bit* center
  – DPSK differential phase shift keying
  Baud rate = bit rate

  – Differential quadrature phase shift keying (DQPSK)
  Baud rate = ½ bit rate
- **Dual polarization state phase modulation (DP-QPSK)**
  Absolute phase and amplitude at the bit center
  – 3D phase constellation diagram
  Baud rate = ¼ bit rate

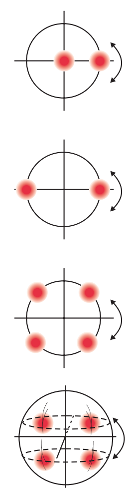

Figure 2: Modulation types and their constellation in the system of coordinates

The modulation methods can be basically divided into different categories (figure 2).

OOK amplitude modulation and optical dual binary (ODB) modulation can only be used in a very restricted sense for 40/43 Gbps for the reasons described above. Higher-level phase modulation methods represent the next category. DPSK improves the system balance by means of a much reduced OSNR limit value. In all the other aspects mentioned, this modulation method has similar characteristics to OOK. This modulation method can therefore only be used for DWDM systems with 100 GHz channel spacing because of the bandwidth it requires. It can only be employed with restrictions in ROADM based networks. Reconfigurable optical add/drop multiplexers allow routing of individual wavelengths in a DWDM system at network nodes. The basic components of a ROADM are multiplexers and demultiplexers with wavelength-selective filter characteristics and a switch matrix. The cascading of bandpass filters unavoidably leads to a narrowing of the communications channel pass band, with the resultant truncation of the DPSK modulated signal. Adaptive DPSK takes account of these restrictions and results in clear improvements when used in complex network structures.

Improvements in all areas are brought about by modulation methods in the next category, that of quadrature phase shift keying QPSK (figure 3).

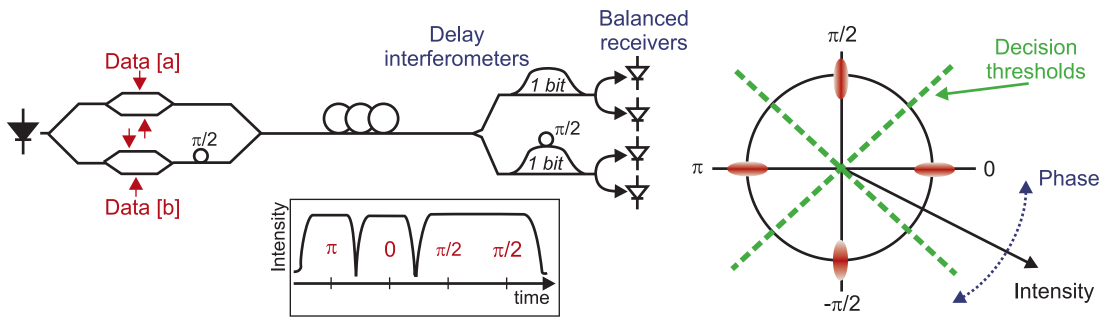

Figure 3: DQPSK - differential quadrature phase shift keying/differential detection

Return-to-zero DQPSK (RZ-DQPSK) has been around for some time now. The RZ coding requires slightly higher complexity on the modulation side compared with the more usual non-return-to-zero (NRZ) coding, but it considerably reduces the susceptibility to PMD and nonlinear effects. QPSK modulated signals use four possible positions in the constellation diagram. Each phase state now encodes two bits. The baud rate (symbol rate) is therefore halved, so the bandwidth requirement is also halved. Use in systems with 50 GHz channel spacing and in ROADM based networks is assured, with a simultaneous improvement in susceptibility to PMD. The technical complexity required in the realization of this modulation method is admittedly greater. Figure 3 shows the principle of modulation and demodulation of a QPSK signal and outlines the technical outlay on the optical side. Systems using dual polarization state DP-QPSK modulation methods have been tried out recently. This opens the way towards a coherent system of transmission and detection. Although this is by far the most complex method, the advantages are significant. Using a total of eight positions in what is now a three-dimensional constellation diagram, the baud rate is thus reduced by a factor of four. Each state encodes four bits. This makes the method ideally suited for 100 Gbps, and the bandwidth requirement is within a range that would fit within existing DWDM structures. An additional forward error correction (FEC) is applied to 100 Gbps signals, so the actual transmission rate is more likely to be around 112 Gbps. The symbol rate using DP-QPSK modulation would be in the range of 28 GBaud, which requires a bandwidth of about 40 GHz. Table 1 compares the characteristics of the different modulation methods.

Comparison of optical modulation methods for 40 Gbps

	ODB/PSPT	NRZ-DPSK	NRZ-ADSPK	RZ-ADPSK	RZ-DQPSK	PM-QPSK
OSNR sensitivty at BER = 2 x 10^{-3} [dB]	17.5	12.5	13	12.5	13.5	12.5
Nominal range using EDFA (1)	700	1600	1600	2200	1400	1700
Filter tolerant, suitable for 50 GHz channel spacing	Yes	Affects range	Yes	Yes	Yes	Yes
PMD tolerance with-out compensation (ps)	2.5	3	3.5	3.5	6	10
Sensitivity to non-linear distortion	No	No	No	No	Yes	Yes
Complexity/Cost	Low	Low	Low	Medium	High	High

(1) 100 km range (23 dB attenuation), EDFA noise figure = 6 dB, 100 GHz spacing

Table1: Comparison of optical modulation methods for 40 Gbps

Implementation of higher-level modulation methods for optical communications is still in the early stages. It is to be expected that further innovations will be triggered by the next level in the transmission rate hierarchy. In order to be as widely useful as possible, the measurement equipment would have to include facilities for testing the complete range of modulation methods. It is true that there will always be standardized interfaces on the client side of the network; these are 40 Gbps in SDH and 43 Gbps in OTN according to ITU-T Recommendation G.709 for the 40G hierarchy. However, there is an increase in the diversity of non-standardized solutions on the line side. Not only do the optical parameters vary, but manufacturer-specific coding is being used more and more frequently for FEC. Use of through mode in an analyzer for insertion into the communications path has so far been an important approach: It is important to check that the payload signal is correctly mapped into the communications frame on the line side, that the FEC is generated correctly, and that alarms are consistent. Or that the correct signaling procedure is followed in the receiver when an error message is received, and that error-free reception is possible in the presence of clock offsets or jittered signals. It is now the time to decide quickly on using just a few modulation methods, otherwise the cost of investment in measuring equipment will rise to astronomical levels. In contrast to the wide variety in electrical multiplexers for 10 Gbps, optical modulation methods each require a corresponding optical transponder. The cost of these transponders largely determines the price of the test equipment. The greater the diversity, the less likely it is that investment will be made in a tester for a particular optical interface. This will mean that important tests will be omitted from systems using the latest technology.

Figure 4: JDSU Test solution for 40/43 Gbps. ONT-503/506 cover all lab requirements, TS-30 for production and the MTS-8000 is the platform for field applications Transponders with DPSK modulator are available in ONT-5xx and TS-30

Access to the line side is probably the easiest route for network operators who in any case have had to keep up with a diversity of systems manufacturers over the years. The most important tests on installed communications systems are end-to-end measurements. Fully developed test equipment for such measurements is available for 40/43 Gbps.

Measuring equipment for 40/43 Gbps

JDSU is the leading manufacturer of 40/43 Gbps measuring equipment. As the first on the market, they now have three different platform solutions available for R&D, production, and on-site measurements. The ONT-503 is the "little brother" of the ONT-506 (page 1) and offers the greatest depth of testing for R&D, although the inclusion of jitter is only possible with the ONT-506. The TP-30 concept is designed for use in production while the MTS-8000 is the ideal platform for all interfaces encountered in on-site applications.

All three solutions are platforms that can be expanded with modules to provide all other interfaces for SDH, OTN and Ethernet from STM-1 through to STM-256, GE and 10 GE as well as FibreChannel.

Interfaces for higher-level modulation methods are now available for the ONT-506 and TS-30 for 40/43 Gbps, and also ODU multiplexers are available for OTN.

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