The demand for greater data throughput seems endless, and it is accelerating faster than many people expected, creating bottlenecks in fiber-optics networks. Digital transmissions of 100 Gbps, which are just now being introduced, are expected to alleviate some of these bottlenecks.

A year ago, most of the work surrounding 100-Gbps links started with ten 10-Gbps lanes over short distances. Since then, the first long-haul 100-Gbps link using four 25-Gbps lanes has been deployed ([Ref. 1](#)). With it comes complex modulation never before used in optical communications.

The new modulation schemes are necessary to handle long-distance transmissions. Short-haul communications, the so-called “client side” ([Figure 1](#)) used within campuses and local metropolitan areas, don’t need complex modulation because their distances are short enough to accommodate the higher speeds. On the client side (distances up to 40 km), 100-Gbps links may use four 25-Gbps lanes. ([IEEE 802.3ba](#) defines these data links; see [Ref. 2](#).) Because short-haul 100-Gbps links will use four wavelengths on a single fiber or even ten 10-Gbps fibers over the shortest distances, more fiber may be needed to increase over the current 10-Gbps speed. Installing additional fiber over the short distances between buildings on a campus isn’t very expensive.

Not so for long-haul transmissions—the “line side” of networks where service providers need transmissions of hundreds of kilometers. Adding fiber to compensate for additional lanes is just too expensive. “Carriers need to squeeze 100-Gbps throughput rates into their existing fiber plants, many of which were designed for 10 Gbps and some were designed for 2.5-Gbps fiber links,” said Pavel Zivny, product engineer at Tektronix.
Simply squeezing a 100-Gbps NRZ stream into existing fiber is impractical. Existing DWDM (dense-wavelength division multiplexing) fibers use 50-GHz spacing between channels. While that channel spacing is sufficient for 10-Gbps data streams sent using NRZ modulation, it is too narrow for 100-Gbps NRZ streams. “You can’t put 100-Gbps streams right on the carrier,” said Mike Schnecker, business development manager at LeCroy. That’s because for a 100-Gbps NRZ signal, each bit is just 10 ps wide.

Hiroshi Goto, optical product specialist at Anritsu, explained the problem. “Because of crosstalk between adjacent channels, 100-Gbps data streams can’t be used in DWDM systems. PMD [polarization-mode dispersion] and CD [chromatic dispersion] prevent that. There’s too much distortion. The pulses distort and overlap.”

To work around the problem, the OIF (Optical Internetworking Forum) has recommended using complex modulation to squeeze more bits/s/Hz from existing fiber. The OIF-proposed modulation uses QPSK (quadrature phase-shift keying) and two polarizations to achieve 100-Gbps throughput on a single wavelength. QPSK is common in digital RF communications, but it’s new to fiber-optics communications.

A 100-Gbps link will consist of two 50-Gbps streams in two polarizations—TE (transverse electric) and TM (transverse magnetic)—that propagate in two orthogonal polarization planes. Each 50-Gbps stream will consist of 25 Gsymbols/s. QPSK modulation packs two bits into one symbol.

Because the QPSK signal travels in two polarizations, it is called either DP-QPSK (dual-polarization QPSK) or PM-QPSK (polarization-mode QPSK)—the terms are interchangeable and both are commonly used. In this article, I’ll use DP-QPSK when referring to the two polarizations and QPSK when referring to one polarization.

**Complex modulation**

Figure 2 illustrates the modulation process. A single 100-Gbps bit stream splits into TE and TM polarizations. That produces two carriers at the same frequency. Each carrier is then I/Q modulated, resulting in two 25-Gsymbol streams. The total: 100 Gbps, but the actual data rate is somewhat higher (see “What’s in a ‘G’?”).
In Figure 2, the polarization splitter appears before the QPSK modulators. Some transceiver designs may place the I/Q modulators first, then split the modulated signals into two polarizations. It’s the designer’s choice.

QPSK modulation places two bits per symbol by phase-shifting a carrier of light in response to incoming bit pairs (00, 01, 10, 11). Each symbol represents two bits. A receiver will demodulate each symbol into its two bits and produce a 50-Gbps digital data stream. In addition, bits are precoded before modulation and decoded after modulation. (A technical note from Anritsu explains the coding details; see Ref. 3.) A receiver will then produce four 25-Gbps electrical signals after it demodulates and decodes the incoming DP-QPSK signal.

QPSK signals carry twice the number of bits per symbol that NRZ signals carry. Thus, the two modulations produce signals that degrade differently as they pass through fiber. Peter Andrekson, director of EXFO Sweden, explained that QPSK signals are more susceptible to noise and nonlinear phase distortion than NRZ signals. “Because of the higher noise susceptibility, QPSK-modulated signals will require higher power than NRZ signals.”

QPSK signals have an important advantage over NRZ signals, though. They’re less susceptible to bit errors from chromatic dispersion and group delay at the same bit rate. That’s because one UI (unit interval) of a 100-Gbps data stream is 10 ps wide. Because line-side transmissions use four 25-Gbps lanes, each symbol is 40 ps wide, which results in a lower bandwidth.

Compared to a 10-Gbps NRZ signal (100 ps wide), the 40-ps-wide symbol of a 25-Gsymbols/s stream is shorter and requires more bandwidth. Thus, the 25-Gsymbols/s signal is more susceptible to errors from dispersion than a 10-Gbps NRZ signal, but it’s less susceptible to degradation than a 100-Gbps NRZ signal. Andrekson explained, “There is a tradeoff between complexity and SNR [signal-to-noise ratio] versus dispersion tolerance and hardware bandwidth at a given bit rate.”

The DP-QPSK technology is so new that no transceiver modules exist for the line side. Chris Cole, senior member of the technical staff at Finisar, explained that line-side transceiver modules will be larger than client-side modules (Figure 3), which are currently defined in a multisource agreement (Ref. 4). Cole noted that line-side transceivers may even be implemented as line cards rather than as modules.
Test will change, too

The shift from NRZ to DP-QPSK modulation brings the constellation diagram to the forefront of fiber-optics test. While constellation diagrams are common in RF wireless transmissions, they’re new to optical communications. Constellation diagrams are the first measurement made on a QPSK transmission.

Constellation diagrams provide information about the transmitted signal’s integrity. Signal degradation caused by dispersion and nonlinearities can result in signal distortion. The left side of Figure 4 shows constellation diagrams for both polarizations in a DP-QPSK signal. The constellation’s points are clearly visible in Figure 4, but they can become indistinguishable in the presence of too much distortion.

![Figure 4](image)

**Figure 4.** Constellation diagrams will become a mainstream tool for analyzing DP-QPSK modulated signals. *Courtesy of EXFO.*

The two lower-right traces in Figure 4 show the QPSK-modulated signal’s magnitude (upper trace) and phase (lower trace). Note the apparent discontinuities on the phase-angle diagram. They result from phase shifts caused by the encoding of bit pairs in the QPSK modulation.

For testing the optical DP-QPSK signal, you can use an optical modulation analyzer or optical signal analyzer. These instruments produce constellation diagrams and decode them into electrical data streams and display them as eye diagrams. Agilent Technologies, Anritsu, EXFO, and Optametra serve this market (the Optametra product is based on a Tektronix oscilloscope).

Finisar’s Cole noted that “There’s no test specification for the 100-Gbps long-haul optical waveform, so test-equipment makers must talk to the optical module makers to find out what they need to measure. Each company will have different needs.” Cole also noted that test equipment will need to support 28-Gsymbols/s and 32-Gsymbols/s signals. “There are DP-QPSK test systems that run at 22 Gsymbols/s for 40-Gbps links, but new equipment will need to run at 28 Gsymbols/s and 32 Gsymbols/s to support 100-Gbps links.”

Testing the receive side of optical transceivers is even more up in the air because there are no specifications for stressed-receiver testing. Cole said he needs test equipment that can generate DP-
QPSK signals and that can introduce controlled impairments such as chromatic dispersion and polarization-mode dispersion. These impairments cause the TE and TM carriers to rotate as they pass through fiber. The impairments must produce stressed-eye patterns after demodulating and decoding so that engineers can measure the signals once they’re in electrical form.

Figure 4 also shows the two eye diagrams (upper right). The eye diagrams represent two 25-Gbps lanes from one polarization. “You’ll have to look at eye-mask margins, jitter, and extinction ratio; that’s the same as for 10-Gbps links,” said Cole.

Currently, engineers are using oscilloscopes and BER (bit-error rate) testers to analyze eye diagrams. Some engineers are using high-bandwidth oscilloscopes to capture DP-QPSK signals. “Because of the modulation, signals at the receiver look like noise,” said LeCroy’s Schnecker. “Signals are no longer repetitive and, thus, you need a real-time oscilloscope.” Zivny of Tektronix has also worked with engineers using real-time oscilloscopes on DP-QPSK signals. A four-channel oscilloscope lets you see all four decoded, demodulated data streams with high time-base correlation.

Engineers developing DP-QPSK transceivers also use BER testers to produce the 25-Gbps data streams for each I and Q phase of a QPSK signal. They also use BER testers to measure BER on the demodulated, decoded signals. BER testers from Agilent Technologies and Synthesys Research can measure BER at data rates up to 28 Gbps.

Over the next few years, the industry will continue to develop 100-Gbps line-side transmissions. Test specifications will also emerge as optical module manufacturers work with test-equipment makers and standards bodies to identify test issues and to develop test procedures and equipment.

**References**