Keysight Technologies

# Essentials of Coherent Optical Data Transmission

## The Concept of Complex Optical Modulation for More Efficient Data Transfer

Application Note

KEYSIGHT TECHNOLOGIES

# Introduction

Data centers are being built across the globe enabling medium and smaller size enterprises to also store and analyze big collections of structured and unstructured data in the cloud, in order to optimize the supply chain, marketing activities and more. The storage and analysis capacities are in place but the more critical question is if the infrastructure outside of the data centers can keep up the pace. The explosively growing amount of data is becoming an enormous challenge for our backbone networks. If they don't want to become the bottleneck of the future, the spectral efficiency needs to be increased in fiber optical networks. Today, fiber optical infrastructure and signal concepts need to support data rates of 100 Gbit/s, soon 400 Gbit/s and even higher. This is a problem for traditionally applied data coding schemes.

# The Beginning

Optical data transport started out like the electronic with the simplest and therefore cheapest digital coding schemes, which are 'return-to-zero' (RZ) or 'non-return-to-zero' (NRZ) on-off-keying (OOK). The signal here is ideally a rectangular sequence of ones (power-on) and zeros (power-off). This concept faced a limit when transfer rates reached for 40 Gb/s.

At 40 Gbit/ s and above, an additional limiting factor comes into the game. Due to the high clock rate, the bandwidth occupied by the signal gets larger than the channel bandwidth of a 50 GHz ITU channel. As can be seen in Figure 1, spectrally broadened channels start to overlap with the neighboring channel and the signals are shaped by the wavelength filters, resulting in crosstalk and degradation of the modulated information. At the latest then, we have to turn our back on OOK and move to more complex modulation schemes, like differential quadrature phase shift keying (DQPSK) for example. Complex modulation reduces the required bandwidth, depending on the symbol clock rate, and higher data rates can be transmitted again in the 50 GHz- ITU channel as illustrated in Figure 1 on the example of DQPSK.

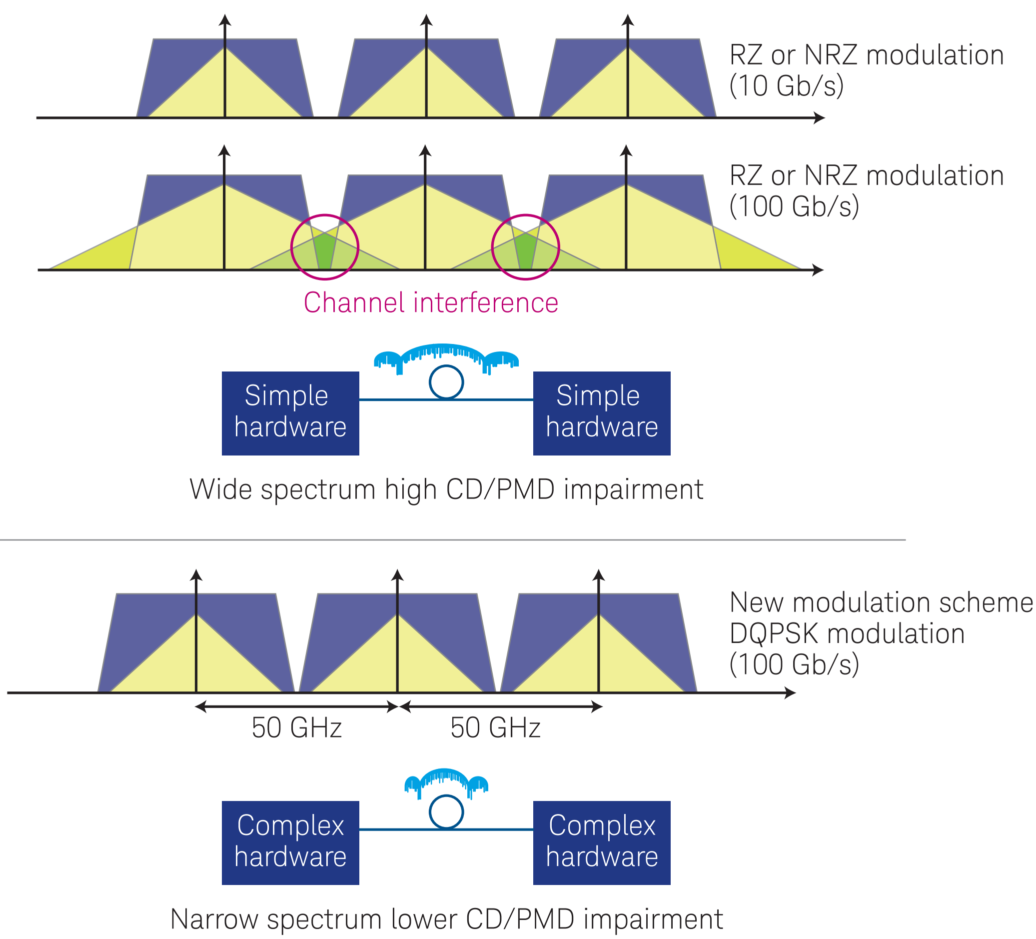



Figure 1. With OOK, we face channel interference or degradation at 100 Gb/s and beyond; complex modulation schemes can solve this problem

# Transmitting symbols instead of bits

The fundamental drawback of OOK methods is that on each channel, only one bit is transferred at a unit time.

This is where complex transmission comes into the game and demonstrates its huge potential: instead of transmitting a binary data stream, several bits are coded to a new ‘symbol’ and a stream of these symbols is transmitted. Figure 2 illustrates this for 2 bits being coded to one new symbol.

In this way, twice the amount of data can be accommodated in the same bandwidth.

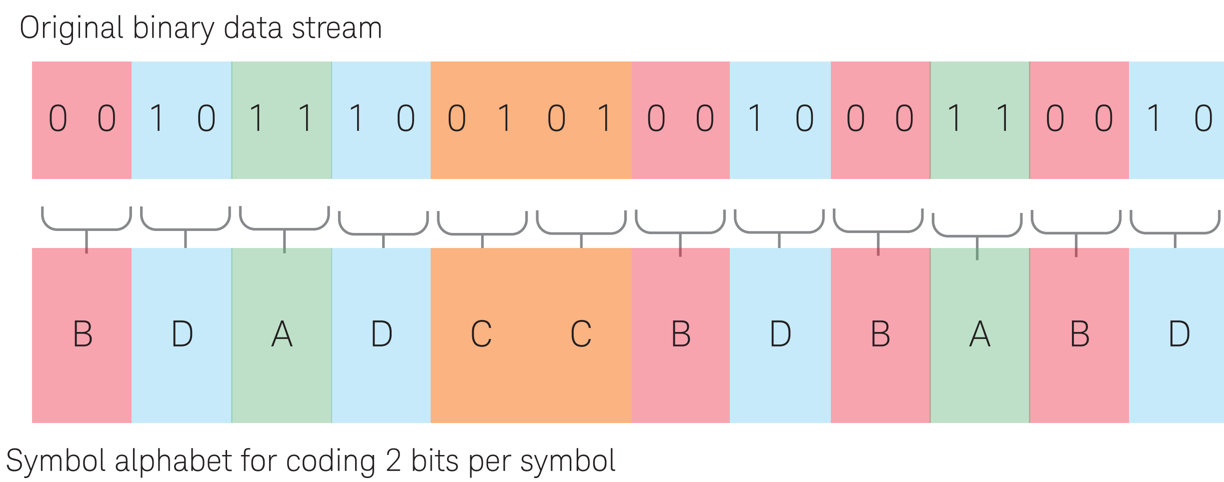



Figure 2. Coding concept: Use of symbols to represent a series of bits; here two bits are represented by one alphabetic symbol

Of course you can think of schemes where a much larger number of bits are defined by a single symbol which allows reaching a data rate many times higher than in conventional on-off keying (OOK) where a series of ones and zeroes is transmitted.

# How does this happen in practice?

In OOK the approach is basically, that when the laser source is turned on, this is interpreted as a one, and when it is turned off, this reflects a zero. In other terms, when the light amplitude exceeds a certain level, this is a one and a zero when the amplitude falls below this level.

But as a light wave is defined by more parameters than just amplitude, we also have more possibilities to encode information by using all degrees of freedom of a light wave. Figure 3 shows the mathematical description of the electric field of an electromagnetic wave with two polarization components Ex and Ey. These orthogonal components are used in polarization division multiplexing (PDM) like two different channels to transfer independent signals. In wavelength division multiplexing (WDM), different frequencies ω are applied as different channels for independent data transfer at these frequencies or wavelengths. For complex modulation schemes now, additionally to the amplitude E, the phase Φ of a light wave is modulated for defining the above described symbols.

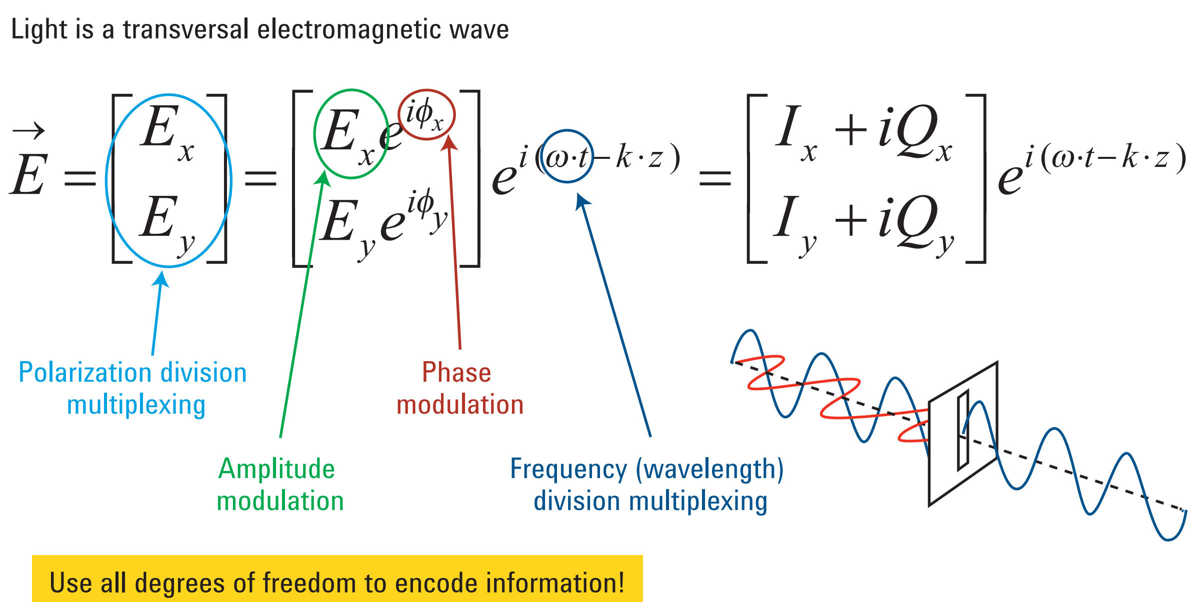



Figure 3. Mathematical description of an electromagnetic wave (electric field)

# How does this happen in practice? (continued)

The electric field of the modulated light wave can also be described in the complex plane with an I/Q diagram. Here, I is the in-phase or real part and Q the quadrature or imaginary part as shown in Figure 4 (after removal of time and space dependency of the wave and for one polarization plane only).

A symbol corresponds to a point, also called constellation point, in this diagram also referred to as constellation diagram and is defined by a Q and an I value or in polar coordinates by amplitude E and phase Φ. The constellation points correspond to the symbol clock times and are also called–detection decision points.

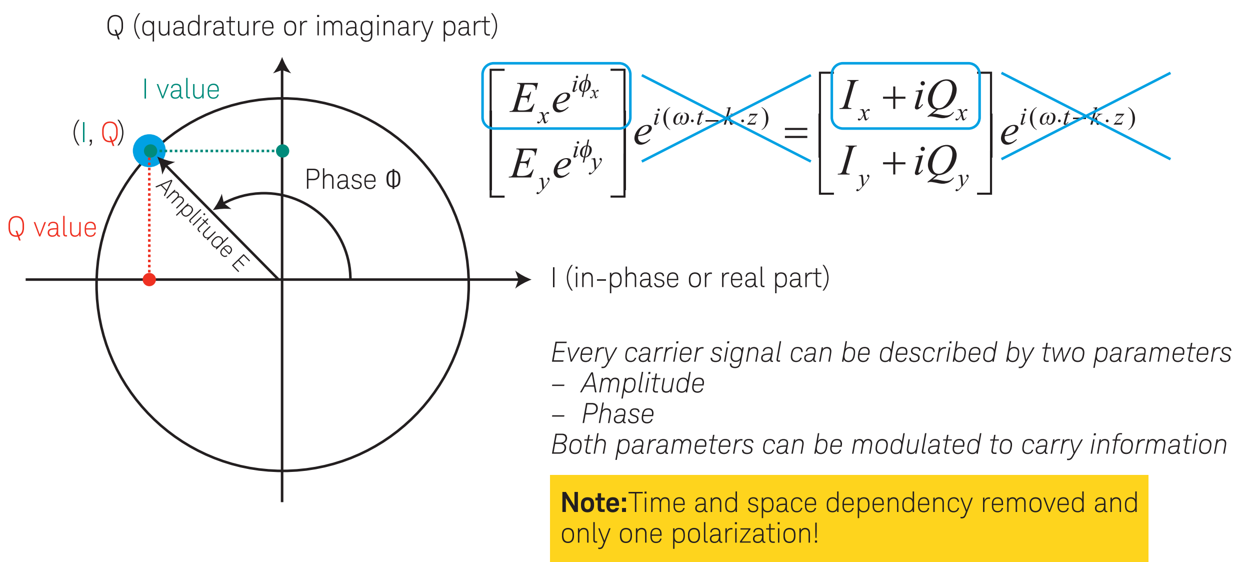



Figure 4. I/Q representation of a symbol

# How does this happen in practice? (continued)

Figure 5 shows the constellation points for the 4 symbols in quadrature phase shift keying (QPSK), a complex modulation type where the 4 symbols encode 2 bits each. The constellation points are situated on a circle with radius E. This means that the symbols only differ in phase (always π/2 between the neighboring points) not in amplitude. In the time domain, the 4 symbols are reflected by a combination of 2 waves of same amplitude and different phase.

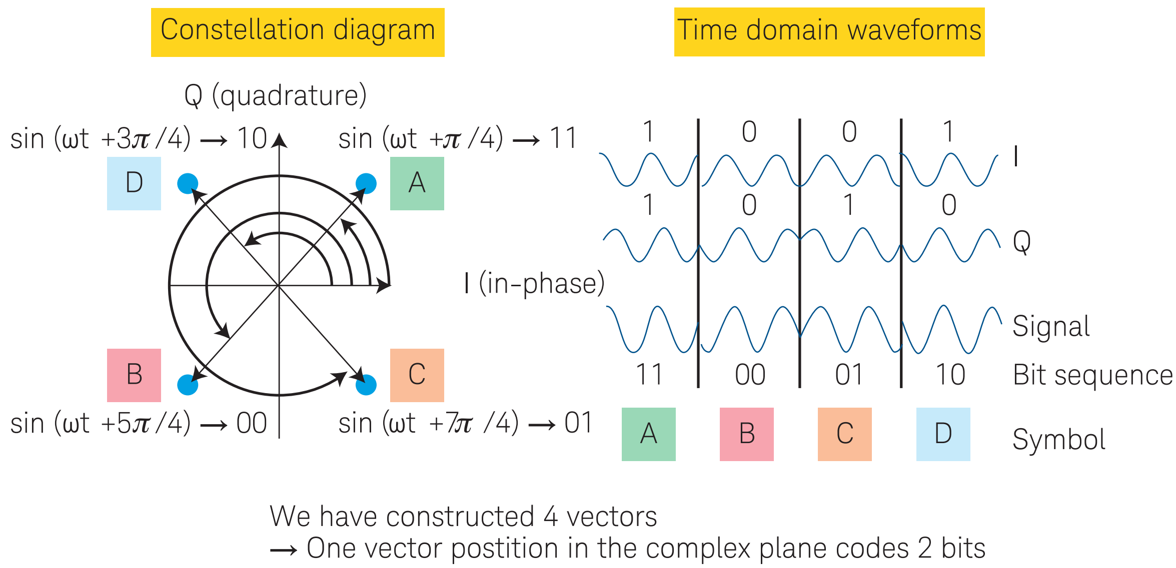



Figure 5. 4 symbols/constellation points for 2 bits encoded in one symbol (here quadrature phase shift keying (QPSK))

Conventional OOK can also be represented by a constellation diagram. As information is in amplitude only, the bit value 1 can be anywhere on a circle with radius (= amplitude) E (see Figure 6).

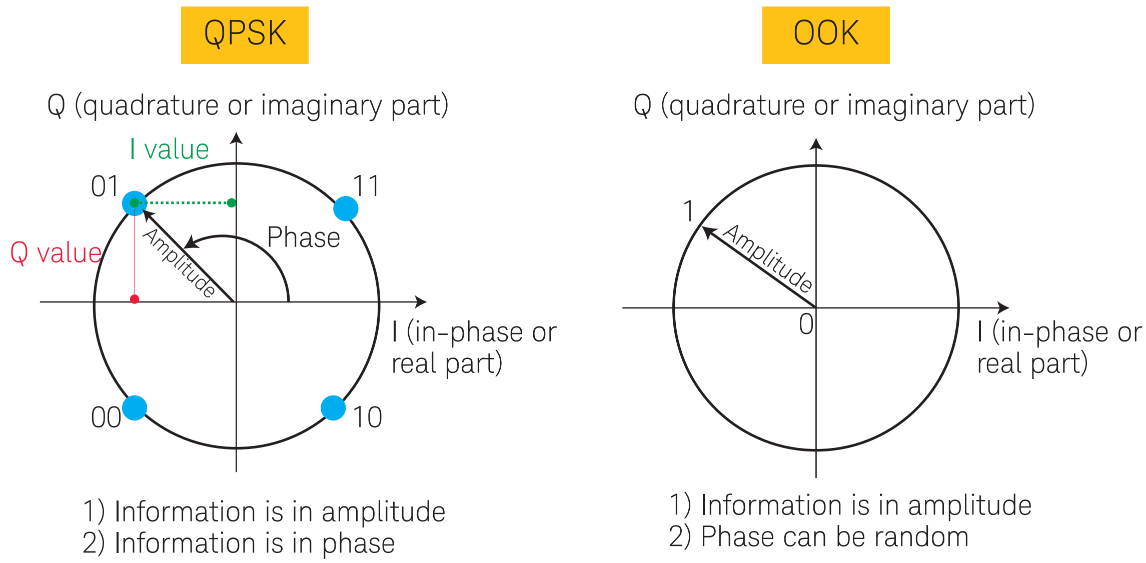



Figure 6. Constellation diagram of QPSK modulation versus OOK; in OOK phase is random

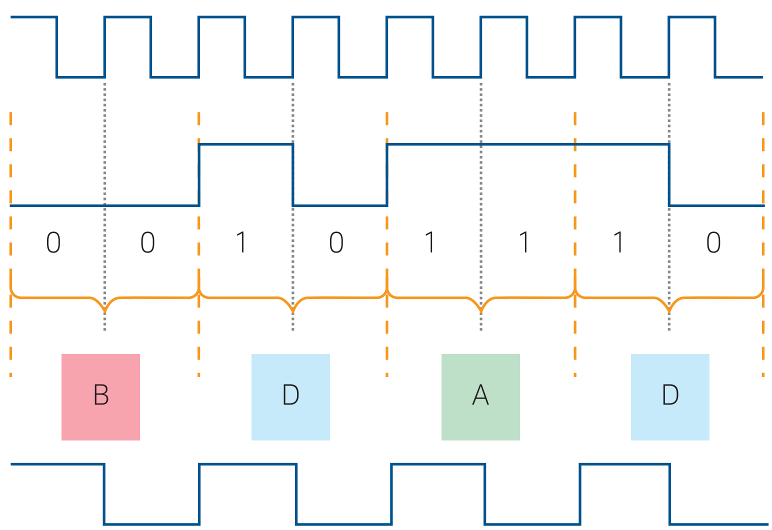
# New speed for the signal

We claimed that by using complex modulation schemes, the spectral efficiency of an optical data signal can be increased. To understand this in detail, we need to see that we now deal with 2 different definitions of speed: there is the bit rate $f_{tx}$, measured in bit/s which is also referred to as transmission rate. Furthermore, we now have the symbol rate S that quantifies the number of symbols transmitted per second, measured in Baud and therefore often called Baud rate.

With the coding efficiency in bits/ symbol: e = $\log_2$ (number of symbols in alphabet).

The symbol rate calculates:

$$S = \frac{f_{tx}}{e}$$




Data rate: [bit/s] or transmission rate

Original data → 8 bits

Symbols coded and transmitted as vectors → here 4 symbols

- Symbol rate: [# of symbols transmitted/s]
- Unit is [Baud], often called Baud rate

Figure 7. Symbol rate versus data rate on the example of QPSK

## New speed for the signal (continued)

The minimum optical bandwidth required by the signal (in Hz) is determined by dividing the symbol rate by 2. If the signal is also polarization multiplexed, divide the result by 2.

For a 100 Gbit/s QPSK signal this means for example that the symbol rate S = (100 Gbit/s) / (2 bits/symbol) = 50 GBaud. The occupied optical bandwidth is then 25 GHz.

Therefore, the optical bandwidth required by complex modulated signals does not depend on the data rate but only on the symbol rate (see Figure 8).

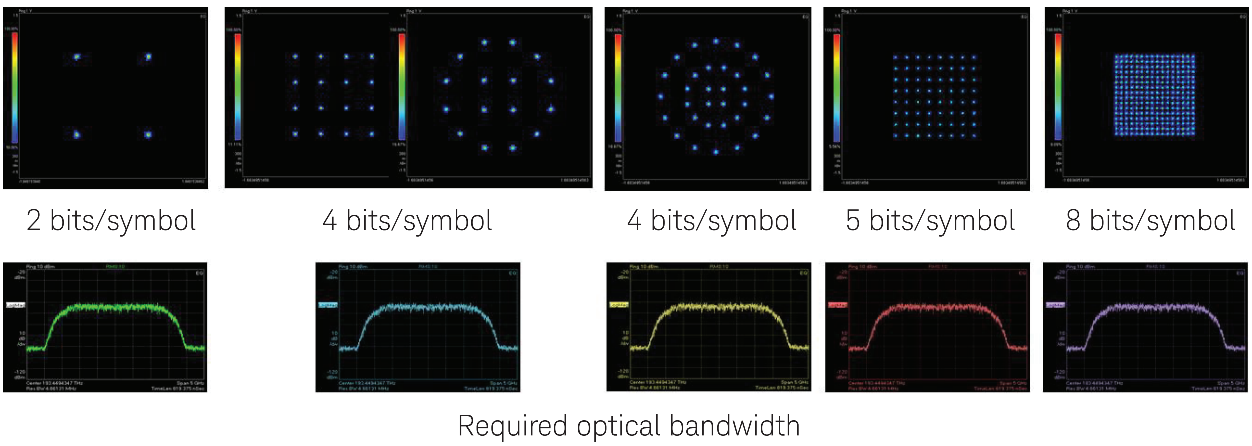



Figure 8. The data rate can be increased by increasing the number of bits encoded in one symbol. The required optical bandwidth stays the same for constant symbol rate. Signal analysis performed with an N4392A Integrated Optical Modulation Analyzer.

This means as well that the more bits are encoded into one symbol at a given data rate, the more the occupied optical bandwidth is reduced. With an N4392A Integrated Optical Modulation Analyzer, this can be examined in detail with the help of I/Q diagrams and frequency spectra.

It would be taking too narrow a view though to conclude that in any case, a modulation scheme with a higher number of bits encoded to one symbol is the right choice. Apart from the occupied bandwidth, considerations on reach, technical feasibility, existing infrastructure etc. have to be taken into account.

## A solution to dispersion problems

These new concepts also allow compensation for chromatic dispersion (CD) and polarization mode dispersion (PMD) in signal processing, since coherent detection provides the complete optical field information.

Dispersion – the effect that light waves travel at different speeds depending on their frequency and polarization – leads to pulse broadening that degrade the signal if not compensated. That is especially an issue for long fiber spans.

This means in turn that complex optical modulation releases us from the usage of PMD compensators or dispersion compensating fibers (DCF) and as well from the increase in latency induced by these modules.

## Multiplexing  for additional capacity

Besides the complex modulation approach, there are other methods that can be used additionally for transmitting a data signal more efficiently over a fiber link; in above mentioned PDM, a second light-wave signal, which is polarized orthogonally to the first, carries independent information and is transmitted over the same fiber (Figure 9). This is like adding a second channel and doubles the transmission capacity without the need of a second fiber.

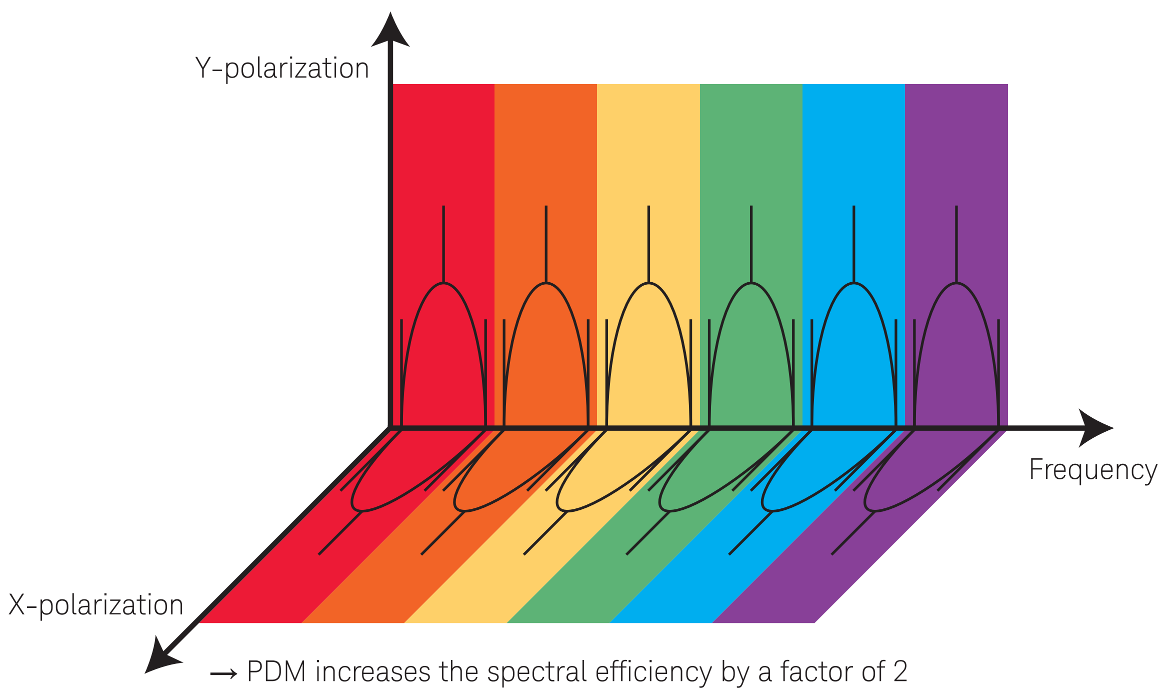



Figure 9. Polarization division multiplexing

# Multiplexing for additional capacity (continued)

Other types of multiplexing like WDM continue to be used; they have all in common that several independent data streams are bundled to be transferred over the same fiber. The use of pulse shaping filters, which reduce the bandwidth occupied by the signal, completes the tool set.

Figure 10 gives an idea of how a combination of these different techniques can improve spectral efficiency. At the bottom, we have the simplest scheme: on-off-keying. Using quadrature phase shift keying (QPSK) instead, you can double the transfer rate at the same symbol rate as in OOK, because in QPSK two bits are encoded in one symbol. Another factor of 2 can be gained through polarization division multiplexing. QPSK plus PDM allows you to transfer 2 x 2 = 4 times more bits at the same time which means at the same clock rate. In the end, after further narrowing the occupied spectrum with a pulse shaping filter, you can transmit 100 Gb/s in a 50 GHz wide channel.

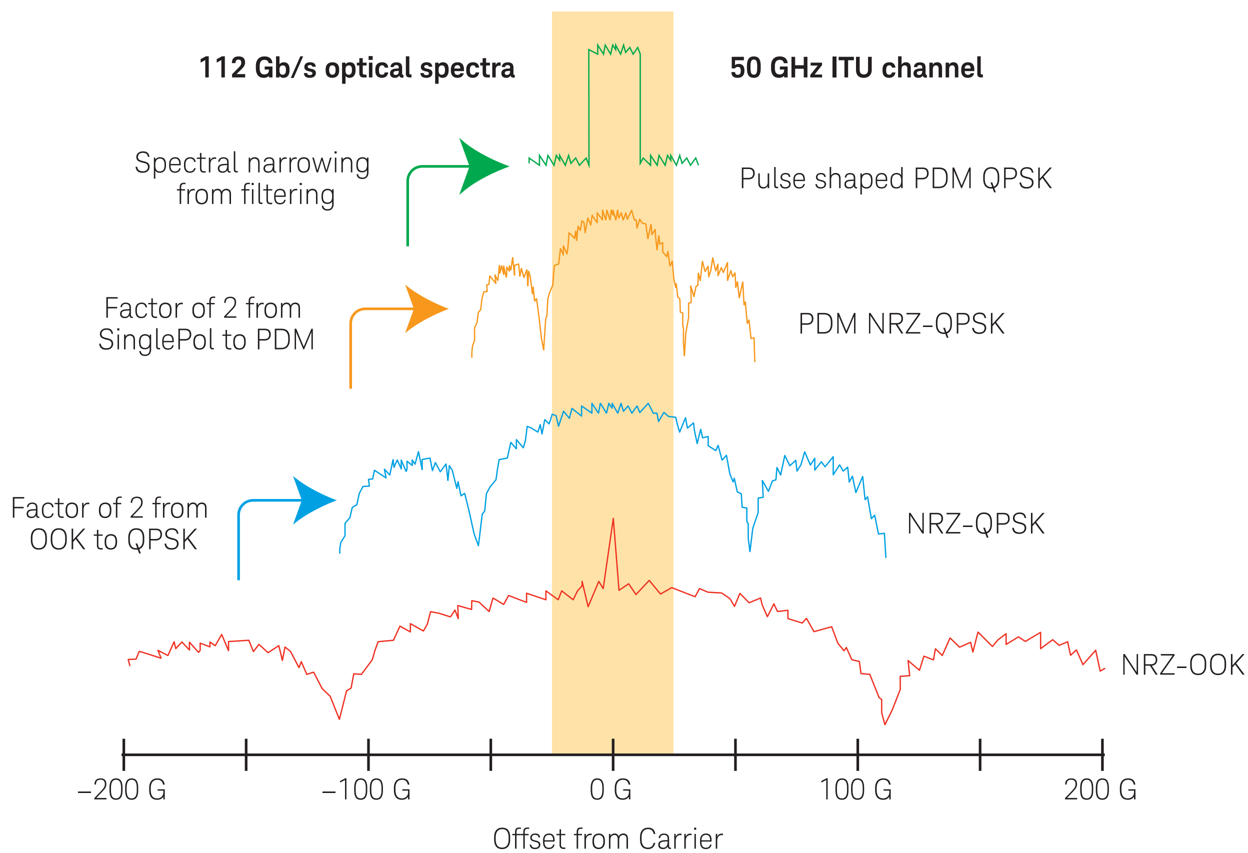



Figure 10. Increasing spectral efficiency by combining different modulation techniques

# No more limits to spectral efficiency?

There is a natural limit to the growth of data throughput:

Already in the 1940s, the American mathematician and electronics engineer Claude Shannon, the 'father of Information Theory', found, that in any communication channel the maximum speed at which data can be transferred without errors can be described in dependence of noise and bandwidth. He called this maximum bit rate 'channel capacity' which is largely known as 'Shannon limit'.

## Shannon–Hartley-theorem:

Channel-capacity: $C = B \log\left(1 + \frac{S}{N}\right)$

Where B is the bandwidth measured in Hz, S the average received signal power in W and N the average noise power in W.

The channel capacity can be increased by either increasing bandwidth or by optimizing the signal-to-noise-ratio (SNR = S/N).

In fact, the theorem provides a theoretical maximum without giving any information about which signal concept gets you closest to this limit.

In practice, the SNR is the fundamentally limiting factor. It is and will also in the future be the subject of ongoing optimization efforts because for data rates beyond 100 Gb/s, a better SNR performance is needed for long distances to reach the Shannon limit at a given bandwidth.

# No more limits to spectral efficiency? (continued)

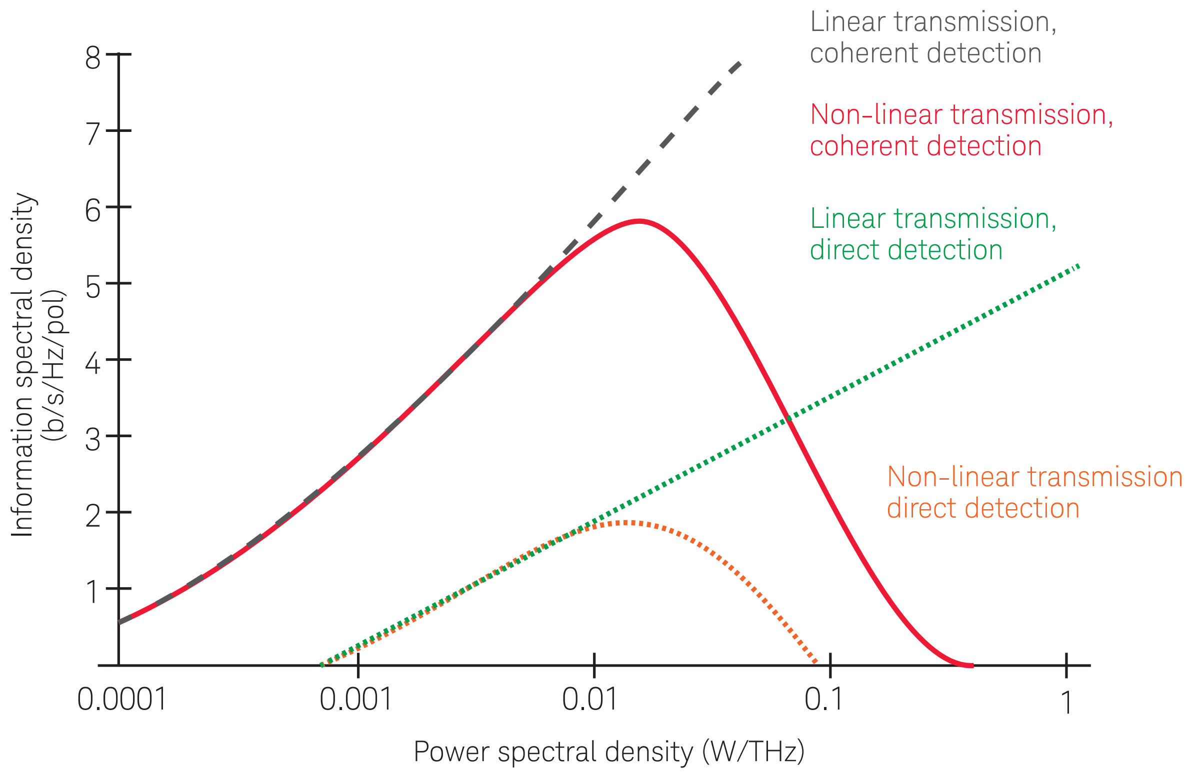



Figure 11. Examples of expected information spectral density limits per polarization by A. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear Shannon limit," JLT 28(4), 423-433

Ellis, Zhao and Cotter took example parameters to simulate the information spectral density C/B in dependence of transmission and detection type (Figure 11). For non-linear transmission, the information spectral density does not grow infinitely with launch power spectral density. Due to saturation effects of the power amplifier and non-linear effects in the fiber itself, there is a maximum value of information spectral density. This would not be the case if the transmission media were completely linear.

In this graphic, you can clearly see that direct detection as used in OOK – where information is extracted from amplitude only – cannot compete with coherent detection of complex modulated signals regarding information spectral density.

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## Literature

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