Orthogonal Frequency Division Multiplexing (OFDM) and other Advanced Options to achieve 100Gb/s Ethernet Transmission

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ABSTRACT
Based on the demand for transmission technologies offering high ratio of bits per symbol, two promising candidates to achieve a data rate of 100 Gb/s per optical carrier are discussed, namely optical orthogonal frequency division multiplexing and 16-ary multilevel modulation.
Keywords: 100 Gb/s Ethernet, optical modulation formats, multilevel transmission, orthogonal frequency division multiplexing.

1. INTRODUCTION

Numerous technologies have been introduced in recent years to cope with the ever-growing demand for transmission capacity in optical communications. Although the optical single-mode fiber offers enormous bandwidth in the order of magnitude of 10 THz, efficient exploitation of bandwidth has started to become an issue a couple of years ago. Moreover, limited speed of electronics and electro-optic devices such as modulators and photo receivers are considered as bottleneck for further increase of data rate based on binary modulation.

For all these reasons, optical modulation formats offering a high ratio of bits per symbol are an essential technology for next generation's high-speed data transmission. This way, data throughput can be increased while required bandwidth in the optical domain as well as for electronics is kept on a lower level.

In this paper, two promising candidates, namely optical orthogonal frequency division multiplexing (section 2) and 16-ary multilevel modulation (section 3) are introduced. Performance is analyzed by means of numerical simulation and by experiment.

2. OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OOFDM)

2.1 Basic Idea of OFDM

Orthogonal frequency division multiplexing (OFDM) is a transmission technology that is primarily known from wireless communications and wired transmission over copper cables [1]. It is a special case of the widely known frequency division multiplexing (FDM) technique for which digital or analog data is modulated onto a certain number of carriers and transmitted in parallel over the same transmission medium.

The main motivation for using FDM is the fact that due to parallel data transmission in frequency domain, each channel occupies only a small frequency band. Signal distortions originating from frequency-selective transmission channels (i.e. fiber dispersion for optical communications) are minimized.

The special property of OFDM is characterized by its very high spectral efficiency. While for conventional FDM, the spectral efficiency is limited by the selectivity of the bandpass filters required for demodulation, OFDM is designed such that the different carriers are pair wise orthogonal. This way, for the sampling point the inter-carrier interference (ICI) is suppressed although the channels are allowed to overlap spectrally.

Orthogonality is achieved by placing the different RF-carriers onto a fixed frequency grid and assuming rectangular pulse shaping. It can be shown that in this special case the OFDM signal can be described as the output of a discrete inverse Fourier transform with the parallel complex data symbols as input. This property has been one of the main driving aspects for OFDM in the past since modulation and demodulation of a high number of carriers can be realized by simple digital signal processing instead of using many local oscillators in transmitter and receiver.

2.2 Optical OFDM (OOFDM)

Very recently, OFDM has become a hot topic for digital optical communications [2-4]. It is just another example of the current tendency in optical communications to consider technologies that are originally known from classical digital communications. Using OFDM appears to be very attractive since the low bandwidth occupied by a single OFDM channel increases the robustness towards fiber dispersion drastically allowing the transmission of high data rates of 40 Gb/s and more over hundreds of kilometers without the need for dispersion compensation [2]. In the same way as for modulation formats like DPSK or DQPSK that were introduced in recent years, also for OFDM the challenge for optical system engineers is to adapt a classical technology to the special properties of the optical channel and the requirements of optical transmitters and receivers.

Thus, two approaches were published recently. An intuitive approach introduced by Llorente et al. [5] makes use of the fact that the famous wavelength-division multiplexing (WDM) technique itself already realizes data transmission over a certain number of different carriers. By means of special pulse shaping and carrier wavelength selection, orthogonality between the different wavelength channels is achieved resulting in the so-called orthogonal WDM technique (OWDM). However, this way the option of simple modulation and demodulation by means of discrete Fourier transforms cannot be utilized as this kind of digital signal processing is not available in the optical domain.

As an alternative, generation of an electrical OFDM signal by means of electrical signal processing followed by modulation onto a single optical carrier is the approach that is followed by the majority of research groups [2-4]. This approach is known as optical OFDM (OOFDM). Here, the modulation is a two-step process: The electrical OFDM signal already is a broadband bandpass signal which is then modulated onto the optical carrier. To increase data throughput, OOFDM can be combined with WDM resulting in multi-Tb/s transmission.

Nevertheless, OOFDM itself offers different options for implementation. An important issue is optical demodulation that can be realized either by means of direct detection (DD) or coherent detection (CD) using a local oscillator. From point of view of effort, DD is preferable. However, for DD the optical intensity has to be modulated. Due to the fact that the electrical OFDM signal is quasi-analog with zero mean and high peak-to-average ratio, the majority of the optical power has to be wasted for the optical carrier (i.e. an additional DC-value of the complex baseband signal) resulting in low receiver sensitivity.

For CD, in addition the bandwidth efficiency is twice as high as for DD since for pure intensity modulation inherently a double-sideband signal is generated. For CD, a complex optical I-Q modulator composed of two real modulators in parallel followed by superposition with 90 degrees phase shift allows for transmission of twice as much data within the same bandwidth. For intensity modulation, the bandwidth efficiency may be increased by suppressing one of the redundant sidebands resulting in OOFDM with single-sideband (SSB) transmission.

2.3 Simulation Results

In order to show the robustness of OOFDM towards fiber dispersion and also fiber nonlinearity, numerical simulations were carried out for a data stream of 42.7 Gb/s data rate. The number of OFDM channels was varied between N_{min}=256 and N_{max}=2048. A Guard interval of 12 ns was added, a strategy belonging inherently to OFDM technology that ensures orthogonality of the different channels in case of a transmission channel with memory.

For the optical modulation, intensity modulation using a single Mach-Zehnder modulator in conjunction with SSB filtering and direct detection was implemented. The nonlinear optical transmission channel consisted of eight spans of standard single-mode fiber with a length of 80 km each. No dispersion compensation was inserted along the whole link. As a criterion for performance, required OSNR for a BER of 10^{-3} was measured. Using FEC, after decoding this is transferred into a BER below 10^{-9} depending on the specific code.

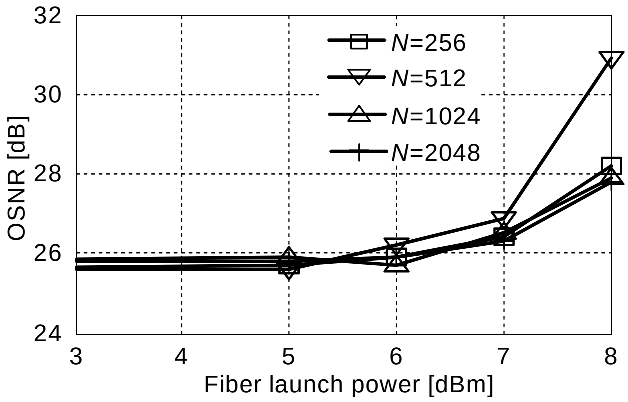

Figure 1. Simulation result for 42.7 Gb/s OOFDM transmission over 640 km of standard single-mode fiber; OSNR required for BER=10^{-3} as function of fiber launch power

Figure 1 shows the required OSNR as function of fiber launch power for different values of *N*. The most important result is that transmission is possible over 640 km over SSMF without any dispersion compensation. It can be explained by the fact that even for the lowest value of N_{min}=256, each subchannel occupies a bandwidth of approximately 42.7 GHz/256=177 MHz resulting in high robustness towards fiber dispersion.

3. MULTILEVEL MODULATION

Optical modulation formats incorporating four or eight bits per symbol were investigated in numerous contributions in the last couple of years (e.g. DQPSK [6] and 8-DPSK [7]). However, to carry out the step from 10 Gb/s to 40 Gb/s data rate using devices designed for 10 Gsymb/s, a number of 16 bits are required per symbol. The main challenge is to find the most advantageous combination of amplitude-shift keying (ASK) and DPSK. Several approaches, which are reviewed in [8], are possible:

The most straightforward strategy is to extend 30 Gb/s 8-DPSK by an additional phase modulator resulting in 40 Gb/s 16-DPSK, i.e. in the complex plane 16 symbols are placed onto the unit circle [figure 2a)]. Depending on the current bit at the data input of the additional phase modulator, the 8-DPSK symbol is shifted by $\pi/8$ in case of a ‘1’, while in case of a ‘0’ the incoming phase of the symbol is preserved. Although in theory the idea is simple, experiments have shown that the phase stability of the modulators and the corresponding demodulators is very critical resulting in an experimental setup that is very hard to run for more than a couple of seconds. Moreover, 16-DPSK is sub-optimum regarding exploitation of the full area that the complex plane offers, i.e. the ratio of symbol distance and signal power is low resulting in poor receiver sensitivity.

Similar behavior is found for the other extreme case of 16-ASK [figure 2b)]. Here, 16 symbols are placed onto the positive real axis. The symbol distance is extremely low resulting in poor sensitivity as well.

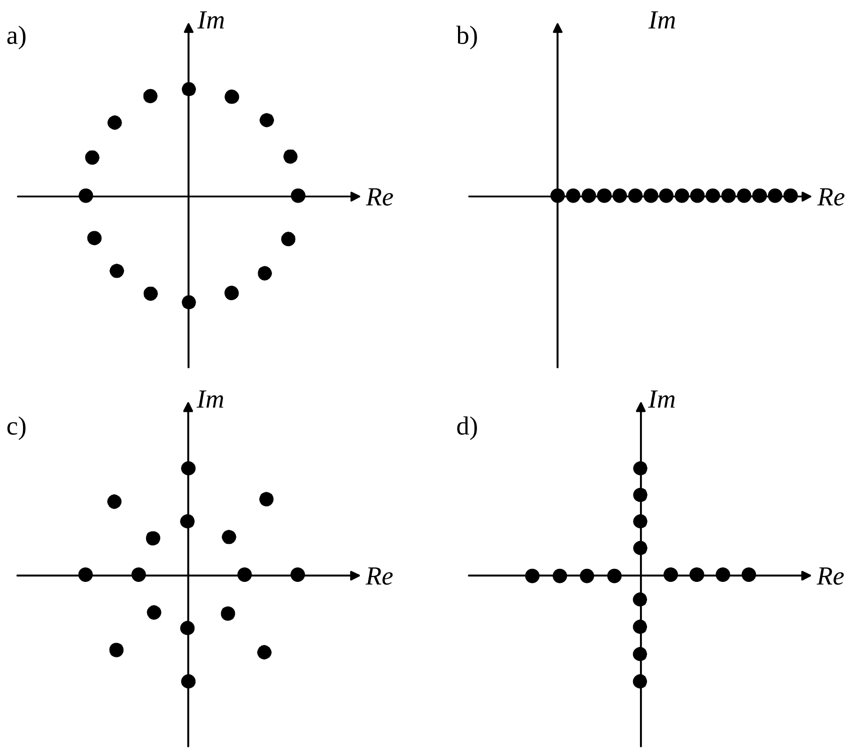

Figure 2. Constellation of symbols in the complex plane for a) 16-DPSK; b) 16-ASK; c) star 16-QAM; d) QASK-DQPSK

Much better performance is achieved for a combination of ASK and DPSK. One approach is to extend 8-DPSK by two-level ASK. The 16 symbols appear as two rings in the complex plane with 8 symbols per ring [figure 2c)]. Due to this topology, this method is called star-16 QAM. A second method is given by combination of DQPSK with four-level ASK (=QASK) resulting in four rings with four symbols each called QASK-DQPSK [figure 2d)]. Both methods utilize the area of the complex plane much more efficiently. However, it has turned out that for both methods from point of view of sensitivity the diameters of the rings have to be optimized to find a good compromise between performance of the DPSK part and the ASK part, respectively. Especially, the inner ring has to be of sufficient size to enable distinction of the different phases of the symbols on this ring.

A strategy to mitigate this trade-off was introduced in [9] by using a special pulse shaping called inverse return-to-zero (inverse RZ). For binary ASK it conjunction with inverse RZ, a ‘0’ is encoded as temporary breakdown of the optical power, while for a ‘1’ the optical power remains at high level. Using this pulse shaping, for the QASK-DQPSK format the four levels of the QASK part are transmitted by means of four different values for temporary decay of optical power. The DQPSK part, however, is transmitted by modulating the phase of the signal in the time slot between, i.e. in the transmitter the phase of the signal can be detected while signal has maximum power.

Measurement results for this modulation format are depicted in figure 3, where the BER is plotted as function of the optical signal-to-noise ratio measured within 0.1 nm bandwidth. The main outcome is the fact that the DQPSK-part is disturbed by the additional QASK part only very little. Moreover, even after transmission over 75 km of standard single-mode fiber the DPSK part shows only a very low penalty. In contrast, the QASK part inherently shows low performance which is attributed to low symbol distance. Improvement might be achievable by optimizing the duty cycle of inverse RZ and the ring ratio.

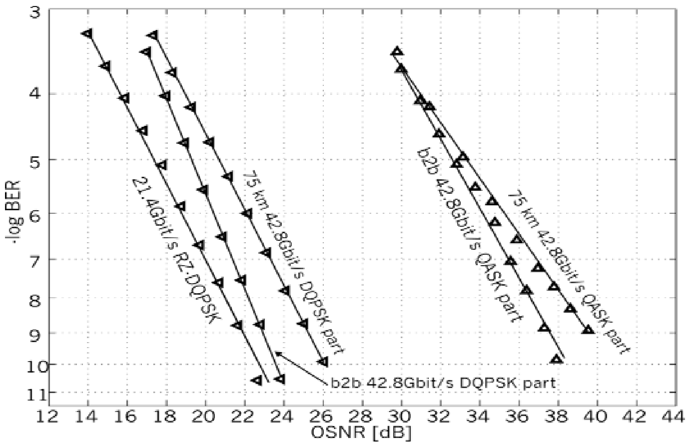

Figure 3. Measurement results for 16-ary inverse RZ QASK-DPSK modulation.

4. CONCLUSIONS

Two interesting approaches to achieve data transmission of 40 Gb/s and beyond (e.g. 100 Gb/s Ethernet) based on low symbol rate are discussed. On one hand, optical orthogonal frequency division multiplexing can combine a large number of parallel data streams into one broadband data stream with high spectral efficiency. Simulation results are shown for different values of the number of parallel data streams in nonlinear environment. On the other hand, 16-ary modulation formats enable 40 Gb/s transmission with 10 Gsymb/s (i.e. 100 Gb/s with 25 Gsymb/s). For a special case, namely inverse RZ QASK-DQPSK, measurement results are shown.

REFERENCES

[1] L.Hanzo, M. Münster, B.J. Choi, T. Keller: *OFDM and MC-CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*, Wiley, 2003.

[2] A.J. Lowery, L. Du, J. Armstrong: Orthogonal frequency division multiplexing for adaptive dispersion compensation in long haul WDM systems, *in Proc. OFC 2006, Anaheim, USA, March 2006, paper PDP39*.

[3] W. Shieh and C. Athaudage: Coherent optical orthogonal frequency division multiplexing, *El. Lett., vol. 42. pp. 587-589, May 2006*.

[4] S.L. Jansen, I. Morita, N. Takeda, H. Tanaka: 20-Gb/s OFDM transmission over 4160-km SSMF enabled by RF-pilot tone phase noise compensation, *in Proc. OFC 2007, Anaheim, USA, March 2007, paper PDP15*.

[5] R. Llorente, J.H. Lee, R. Clavero, M. Ibsen, J. Martí: Orthogonal wavelength-division-multiplexing technique feasibility evaluation, *J. Lightw. Technol., vol. 23. pp. 1145-1151, March 2005*.

[6] C. Wree, J. Leibrich, W. Rosenkranz: RZ-DQPSK format with high spectral efficiency and high robustness towards fiber nonlinearities, *in Proc. ECOC 2002, Copenhagen, Denmark, September 2002, paper 9.6.6*.

[7] M. Serbay, C. Wree, W. Rosenkranz: Experimental Investigation of RZ-8DPSK at 3x 10.7Gb/s, *in Proc. LEOS 2005, Sydney, Australia, October 2005, paper WE3*.

[8] N. Kikuchi: Amplitude and Phase Modulated 8-ary and 16-ary Multilevel Signaling Technologies for High-speed Optical Fiber Communication *in Proc. APOC 2005, Shanghai, China, October 2005, paper 602127*.

[9] M. Serbay, T. Tokle, P. Jeppesen, W. Rosenkranz: 42.8 Gbit/s, 4 Bits per Symbol 16-ary Inverse-RZ-QASK-DQPSK Transmission Experiment without Polmux, *in Proc. OFC 2007, Anaheim, USA, March 2007, paper OThL2*.