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Modulation Formats for Beyond-100Gbps Ethernet Optical Links – A Review of Research

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Abstract: The current increase in data-centers traffic and cloud-based services presents a formidable challenge for optical interconnects. We examine these challenges, and review recent breakthroughs in advanced modulation formats formats for intensity modulation – direct detection.

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1. Introduction

In these years, a chasm is developing between the capacity of core networks and the capacity of optical Ethernet links inside data centers. At the same time, more and more Internet traffic takes place inside data centers due to the increase in use of cloud based services, high definition (HD) TV streaming, on-line gaming and sharing of photos, videos and other files. These two developments combined dictate an increased effort in the development of faster optical Ethernet links. In this paper, we present an overview of recent breakthroughs in advanced modulation of intensity modulated (IM) direct detection (DD) optical links, which potentially can provide the required increase in Ethernet link capacity while maintaining the bandwidth and form factor of existing links.

In the report "*IEEE Industry Connections Ethernet Bandwidth Assessment"* published by the IEEE 802.3 Ethernet Working Group [1], the Chairman, David Law states that *"…the bandwidth requirements for core networking and computing applications were growing at different rates, driving the need to develop the two new wireline Ethernet speeds..."* In fact, it is observed that core network bandwidth doubles every 18 months, whereas server and computing application bandwidth doubles every 24 months. This difference in bandwidth growth rates underpins the need for faster Ethernet links. Demand for 100 Gbps Ethernet is foreseen already in 2013 (indeed, the percentage of data center links operating at 100 Gbps has inecreased from below 10% in 2011 to above 20 % in 2013), and demand for 400 Gbps links is foreseen in 2015 [1]. In addition, there is an emerging need for increasing the reach up to 10 km, forcing future solutions to be robust to dispersion while keeping complexity low.

Current and upcoming standards for 100 Gbps, such as 100GBASE-SR10, 100GBASE-SR4, and 100GBASE-LR4 are based on the use of 10 lanes of 10 Gbps or 4 lanes at 25 Gbps each. Upgrading to 400 Gbps links using the same technology will require an increase in the number of lanes to e.g. 16 lanes operating at 25 Gbps each, thereby making it challenging to meet 400 Gbit/s form-factor pluggable (e.g. CFP4) requirements on power consumption and footprint [2].

As an alternative, advanced modulation formats capable of higher transmission speeds at reduced bandwidths have been researched in recent years. This paper provides an overview of this research, and presents some of the technological challenges involved with their deployment.

2. Overview of recent breakthroughs in spectrally efficient IM/DD modulation formats

Advanced modulation formats capable of transmitting more than one bit per optical symbol have been used and researched for core network applications in several years and today quadrature phase shift keying (QPSK) systems are available commercially. These, however, rely on combined modulation of the optical phase and amplitude, and are thus not suitable for IM/DD links. For data center interconnects, alternative solutions based solely on optical amplitude modulation must be developed.

One of the simplest methods of achieving high spectral efficiency in IM/DD links is to simply increase the number of amplitude levels in the signal. This modulation format is commonly referred to as M-level pulse amplitude modulation (M-PAM), where M refers to the number of levels in the signal. Each optical symbol will carry log_2(M) bits of information. In 2013, 4-PAM modulation of a vertical cavity surface emitting laser (VCSEL) at 50 Gbps was reported [3]. The 50 Gbps signal from the VSCEL is polarization multiplexed to a total capacity of 100 Gbps using a symbol rate of only 25 Gbaud. The signal is transmitted over 100 m of standard single mode fiber (SSMF). In order to receive the signal error free, custom forward error correction, where the two bit streams in the signal are encoded with different FEC codes, is employed. For the least significant bit, 20% overhead FEC is required to recover the signal. A slightly higher bit rate of 60 Gbps for 4-PAM VCSEL links was reported in 2013 [4], albeit only for 2 m transmission over multimode fiber. The signal is recovered error free without forward error correction. 4-PAM modulation at 25 Gbaud would enable 400 Gbps Ethernet links employing 8 lanes, and can thus be considered a stepping stone towards 4 lane solutions for 400 Gbps links, which would require 16 amplitude levels for M-PAN signaling; a result which at the moment must be considered very challenging due to the signal to noise ratio (SNR) it would require. On the other hand, M-PAM is comparable simpler to implement that the other modulation formats examined in the remainder of this paper. Additionally, VCSEL drivers for 4-PAM signaling have already been demonstrated [5].

From the M-PAM results described above, it can be concluded that achieving the goal of 4 bits per symbol, or 100 Gbps in less than 25 GHz bandwidth, employing modulation in only one dimension is very challenging. But as Ethernet links relies on IM/DD, we cannot employ the phase of the optical carrier as the second dimension to modulate. This has generated interest in subcarrier modulated quadrature amplitude modulation (QAM), where the laser is driven by a QAM modulated electrical radio frequency (RF) subcarrier. Conventionally, subcarrier QAM modulation requires that the frequency of the subcarrier is equal to or higher than the symbol rate of the data signal. This means that the required bandwidth corresponds to the bandwidth of the double sided signal spectrum so that in order to achieve 100 Gbps in a 25 GHz bandwidth, a 12.5 GHz subcarrier would have to be modulated with a 64 level QAM signal. An interesting alternative consisting of QAM modulation at RF frequencies below the symbol rate has been proposed and demonstrated [6]. The achieved bit rate is 10 Gbps employing 4-QAM modulation of a 5 GHz subcarrier, resulting in a signal bandwidth of 7.5 GHz. The sub-cycle QAM signal is generated by delaying and adding the two outputs of an electrical XOR gate whose inputs consists of a non-return-to-zero (NRZ) data signal at the baud rate and an RF carrier at the subcarrier frequency. This method is originally proposed in [7]. The signal is transmitted over 20 km of SSMF, and display transmission performance and dispersion tolerance performance similar to or better than on-off keying (OOK) at the same bit rate. This result shows the great promise and potential of sub-cycle QAM modulation. In order to achieve 100 Gbps, a 12.5 GHz subcarrier could be modulated with a 25 Gbaud 16-QAM signal resulting in a signal bandwidth of approximately 19 GHz, i.e. compatible with the requirements for a 4-lane 400 Gbps solution. This, however, has not yet been demonstrated.

Instead of employing a single subcarrier at a very high symbol rate, several subcarriers at a low symbol rate can be combined to form a single signal of high bit rate. Since the bandwidth of each subcarrier is very low, a high spectral efficiency can be maintained without resorting to sub-cycle modulation. Two flavors of this modulation have been demonstrated for IM/DD optical links, namely discrete multitone (DMT) and orthogonal frequency division multiplexing (OFDM). For the latter, it is a requirement that the individual subcarriers are orthogonal to each other. DMT has been demonstrated at 100 Gbps employing wavelength division multiplexing (WDM) of two channels, each operating at 50 Gbps [8]. The signal is generated employing directly modulated lasers with a 3 dB modulation bandwidth of 16 GHz. Transmission over 80 km of SSMF is achieved in the 1300 nm wavelength band as well as in the 1550 nm wavelength band. For the 1550 nm experiment, several of the subcarriers experience dispersion induced fading, and dispersion compensation is required to recover the signal. The target of 100 Gbps per lane can be realized by doubling the bandwidth of the signal. As the DMT signal is generated in the digital domain employing an arbitrary waveform generator (AWG) with a sampling rate of 34 GSa/s, an AWG or a digital to analog converter (DAC) with a 68 GSa/s would be required in order to realize 100 Gbps per lane.

DMT is currently the most used modulation format for digital subscriber lines (DSL). Before 1996, however, another modulation format dominated this field, namely *carrierless amplitude and phase modulation* (CAP). CAP is in many ways similar to QAM described above. It employs two orthogonal dimensions for the modulation of the signal. Contrary to QAM, however, CAP does not use carriers. The orthogonal signals are generated by transversal filters with orthogonal impulse responses. Most commonly, the filters consists of a square-root raised cosine shaping filter multiplied by a sine and a cosine respectively to generate the orthogonal waveforms. Compared to DMT, CAP has the advantage of the possibility of an analog implementation. This is demonstrated at 40 Gbps in [9]. In addition, it is shown that CAP is superior to DMT in terms of SNR requirements and robustness towards multipath interference [10].

A variation of CAP employing several sub bands and dubbed “MultiCAP” is proposed and demonstrated experimentally in [11]. The achieved bit rate is 102 Gbps in a 3 dB bandwidth of 14 GHz. The signal is transmitted over 15 km of SSMF. The introduction of multiple bands in the CAP signal overcomes the main challenge of CAP signaling: the requirement of a channel with flat frequency response across the signal’s frequency spectrum. With MultiCAP, it is straightforward to employ different modulation order in the different sub bands according to the frequency response of the channel. The MultiCAP signal is generated using a DAC operating at a sample rate of

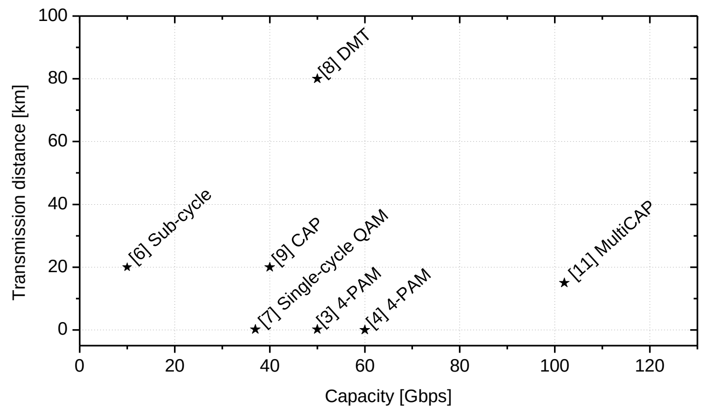

Fig. 1. Capacity and transmission distance achieved in the demonstrations discussed in the paper.

64 GSa/s, and thus employ a highly demanding digital implementation. Contrary to the DMT case, however, an analog implementation could be realized provided the appropriate transversal filters were designed.

The various examples mentioned above are collected in Fig. 1 in terms of capacity and achieved transmission distance.

3. Discussions and Conclusions

400 Gbps optical Ethernet links is expected to be in demand already in 2015. A 4-lane solution, which is compatible with current 100 Gbps 4-lane solutions is very attractive, and will require transmission of 100 Gbps in less than 25 GHz bandwidth. This has been achieved in one of the experimental demonstrations discussed here: The 102 Gbps MultiCAP experiment [11]. The demonstration is realized by employing state-of-the-art digital to analog converters (DACs) and off line digital signal processing. Recent development in the capabilities of DACs and field programmable gate arrays (FPGAs) is indicating that a real time solution could be realistic in just a few years [12]. In order to realize a low cost solution, a number of challenges remain, specifically regarding the development of high speed, cost efficient linear drivers for the laser and linear trans-impedance amplifiers (TIAs) for the photo detector. Additionally, more investigation in power consumption is required.

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