Increasing Information Capacity in Ultra-High-Speed Optical Networks

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Abstract— High spectral efficiency of optical transmission links is essential for the overall throughput increase in optical networks. In this paper, we discuss multidimensional structure and parallel signal processing applied on advanced modulation, coding, and detection schemes and introduce an optimized design scenario for future 4 Tb/s and 10Tb/s Ethernet channels.

Keywords-optical networks; information capacity; modulation.

I. INTRODUCTION

It is well known that he Internet traffic has been growing exponentially and it is projected that the zettabyte level in data exchange will be exceeded in year 2017. It is also projected that the traffic from video services and peer-to-peer file sharing will comprise the majority of the Internet traffic. The wireless connectivity through (4/5G+) mobile networks and widespread use of mobile traffic for social networking has also become an integral part of the overall networking picture since it provides a large contribution to the never ending bandwidth demand in optical networks.

All applications mentioned above will demand an extremely large throughput in different optical networking segments (i. e., in access, metro and core), which means that high aggregate information capacity of optical links will be required. It is envisioned that current 100 Gb/s Ethernet (100 GbE) in converged optical packet networks will be eventually overlaid with 400 Gb/s Ethernet (400 GbE) and 1 Tb/s Ethernet (TbE). Down the road, 1+TbE (specifically 4 TbE) and even 10+ TbE) will become a relevant topic when talking about Terabit optical networking [2]. We should also mention that the total data traffic in aggregation (metro and regional) networking segment just recently exceeded the data traffic carried over by core optical networks.

Demand for higher information capacity is closely related to request that the information bandwidth in next generation networks is more flexible and highly dynamic and elastic in nature. The elastic and dynamic behavior requires that the data bit rate and signal spectral efficiency can be changed dynamically based on the traffic conditions and/or signal quality along specified lightpath (which is commonly related to the optical signal to noise ratio (OSNR). The point is that an automated action should be taken to adjust the bit rate/spectral efficiency, which is done by change in modulation/multiplexing scheme or in coding strength. This adjustment becomes necessity for aggregation networks, since their dominance in terms of the overall data traffic [1]. Accordingly, we can say that a higher attention should be given to the metro networking in order to satisfy both high information capacity and dynamic connectivity requests. However, the logic about capacity and connectivity applies also to other networking segments (optical access networks and data center networks, and core networks), which are all connected to the metro networks [3] [4].

In this paper, we will discuss the advanced schemes enabling high information capacity of optical channels and develop scenario for design of future superchannels by using parallelism and multidimensional structure. The paper is organized as follows. In next section, we will analyze spectral efficiency of optical channels through employed basis functions and identify multidimensional modulation and multiplexing schemes that contribute to information capacity increase. In Section III, we will apply optimized channel design to scenarios related to aggregate and core optical networks. Finally, in Section IV, we will make the relevant conclusions.

II. SPECTRAL EFFICIENCY INCREASE IN NEXT-GEN NETWORKS

It is interesting to observe that the IP traffic growth has the same dynamics as the speed of processors (Moore's law), which we illustrated in Figure 1. Having in mind the past connection between data rates of IP routers ports and speed of processors related to that, we can envision connection between projected dynamics of the speed (or bit rates) of serial optical interfaces carrying IP traffic and speed of processors, which is also illustrated in Figure 1. The key point is that both the driving forces and key enabling components are subjects of an exponential dynamics, which means that the speed of optical line interfaces (channels) should advance with the same pace as speed of processors. Since we will be dealing with ultra-high processor speeds and line bit rates, we can expect that both objectives will be achieved only if parallel approach is applied. The parallelism in design means that

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multidimensional approach in signal processing is underlining factor for information capacity increase. The parallelism/multidimensionality in optical networks can be imposed through modulation and multiplexing schemes, which is not a trivial task since there are a number of parameters that can be incorporated in an optimum high-speed optical channel design.

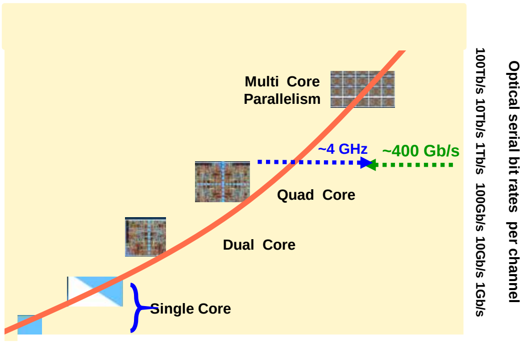

Figure 1. Envisioned parallelization of processors and speed of high-speed in optical channels

The increase in spectral efficiency of optical channels is precondition for overall throughput in high-speed optical networks. Optical channel construction can be done by fully utilizing all available basis function (amplitude, phase, time, frequency, space, and polarization) through parallelization and arrangement that would maximize information capacity of fiber links. Generally, any set of real-valued energy signals $\{s_i(t)\}$ can be expressed as a linear combination of D orthonormal basis functions $\{\Phi_j\}$, as [5]

$$s_i(t) = \sum_{j=1}^{D} s_{ij}\Phi_j(t), \begin{cases} 0 \le t \le T_s \\ i = 1,2,\ldots, M \end{cases} \tag{1a}$$

$$s_{ij} = \int_0^{T_s} s_i(t)\Phi_j dt, \begin{cases} i = 1,2,\ldots, M \\ j = 1,2,\ldots, D \end{cases} \tag{1b}$$

where M relates to well-known amplitude-phase constellation diagrams containing M states where symbols can reside, while T_s specifies symbol interval. The parallelism in signal representation in (1a,b), should be translated to modulation format design. The illustration of basis functions commonly considered for channel construction is presented in Figure 2.

When talking about increased spectral efficiency of amplitude-phase modulation formats with the constellation diagram of size M, it is possible to design some other structure different than conventional M-QAM formats. The design of these formats, also known as two-dimensional ones, can be done with respect to established constraints and optimization criteria (such as minimum mean square error (MMSE), minimum bit error rate (BER), minimum energy consumption, minimum latency, etc., as presented in [5] [6] [7]. We should outline that construction of advanced modulation formats based on specified criteria is still widely open research process.

Two-dimensional modulation formats with amplitude and phase as basis functions is commonly extended to more complex four-dimensional form if polarization state is used as additional basis. New format is different than polarization division multiplexing scheme since in four-dimensional signaling scheme only one mapper is used with four coordinates (amplitude, phase, x-polarization and y-polarization), which serve as inputs to corresponding I/Q modulators. With this approach, we can increase the Euclidean distance among neighboring points in constellation diagram and thus improve the OSNR, which can be essential in scenario with expected high impact of nonlinearities [5] [8].

The further parallelization in optical channel construction can be achieved by including the frequency as the signaling basis function, while keeping the Nyquist orthogonality criterion represented by raised cosine function spectral shape. In this format, known as the orthogonal frequency division multiplexing (OFDM) [5] [8] [9], the total spectrum is arranged with multiple overlapping optical (sub)-carriers that form a single channel, commonly recognized as superchannel. It has been proven that, with an arbitrary number of optical subcarriers per superchannel, a multiterabit capacity per channel can be realized [10] [11]. The OFDM subcarriers in superchannel are spaced apart by Δf_{SC} , which is equal to the symbol rate R_{SC} of the signal applied to them leading to an aggregate bit rate of an OFDM based channel equal to $R_S = R_{SC} N_{SC}$, where N_{SC} is number of subcarriers (assuming the same rate for each subcarrier). The Nyquist based overlapping can be also achieved in time domain by applying Nyquist WDM scheme, which produces the most efficient way of the signal multiplexing in time domain [10].

The orthogonal polynomials or orthogonal prolate spheroidal wave (OPSW) functions can be considered instead of orthogonal subcarrier [9], which is a promising way of introduction of the time basis function. If OPSW functions are used as orthonormal basis $\{\Phi_j\}$ in Eqn. (1), the pulse duration and the bandwidth of the OPSW functions will stay almost unchanged regardless of the associated order value. The OPSW functions are simultaneously time-limited to symbol duration T_s and bandwidth-limited to bandwidth Ω, which is essential property while considering spectral efficiency increase. They can be obtained as solutions of the following integral equation [9]

$$\int_{-T_s/2}^{T_s/2} \Phi_j(u)\frac{\sin[\Omega(t-u)]}{\pi(t-u)}du = \xi_j\Phi_j(t) \tag{2}$$

where the coefficient ξ_j *is* related to the energy concentration in the interval [-T_s/2, T_s/2]. The use of orthogonal polynomials/OPSW means that two basis functions (in-phase and quadrature components associated with amplitude/phase arrangement) are replaced with the set of 2M basis, thus producing arbitrary multidimensional schemes that can be eventually combined with polarization as a basis function.

The next dimension in parallel multidimensional approach aimed to increase the spectral efficiency is the space basis function employed through spatial multiplexing technique applied within the same optical fiber [13] [14]. By using a novel class of optical fibers known as few-mode fibers (FMF) and few-core fibers (FCF), a number of orthogonal spatial modes can be supported. Since each spatial mode can be independently modulated with signals already employing other basis function mentioned above while essentially occupying the same spectral bands, the total spectral efficiency will be increased in proportion with the number N_{mode} of spatial modes. As an example, the MCF fiber with 7 cores is shown in Fig 2c, in which the central core is FMF supporting 4 modes.

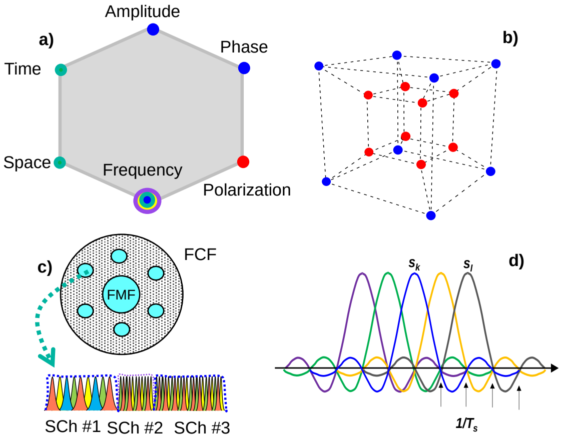

Figure 2. (a) Basis function of an optical channel; (b) coded modulation with amplitude-phase and polarization basis functions; (c) spatial modes with superchannel structure per mode; (d) OFDM spectral arrangement for superchannels

The sophisticated forward error correction (FEC) coding applied on advanced multidimensional modulation and multiplexing schemes is an essential component that contributes to the information capacity increase. The FEC process means that some number of redundant symbols (which is inversely proportional to the code rate R<1; R is the ratio between input information bits/symbols and output coded bits/symbols) have been introduced [5]. They are inserted into data stream in accordance with the specific mathematical algorithms in order to verify the signal health and to make a correction of wrongly detected symbols. With FEC in place, the OSNR requirements for a specific information bit rate and modulation format are relaxed, which means that the channel capacity over specified distance is brought to be closer to the Shannon's limit [15].

Although coding, modulation, and multiplexing are commonly considered as separate serial functions, they can also be performed in parallel manner through coded modulation approach. In such a way, the main functions that involve intense digital signal processing are effectively performed at much lower symbol rates [16]. Also, the coded modulation schemes are inherently adaptive in nature, which is highly desirable for applications in elastic network scenarios when dealing with changing network conditions (dynamic traffic flow and variable impact of impairments). In an adaptive coded modulation scheme, the appropriate code rate (error correction strength) can be selected based on information about the destination and link conditions to match to the required OSNR. Design of advanced coding schemes is still widely open research area, and there is expectation that the coding gain for more advanced FEC schemes will exceed 12 dB with coding rate R≥ 0.8, [17] [18]. It appears that a nonbinary low density parity coding LDPC-coded modulation is an approach for achieving a high coding gain. In an adaptive scheme, both the appropriate code rate (error correction strength) and modulation/multiplexing scheme are subject to adjustment based on information about the required data flow and transmission link conditions to match to the required OSNR [19].

III. MULTIDIMENSIONAL ASPECTS IN AGGREGATION AND CORE OPTICAL NETWORKS

Currently, the standardized dual polarization (DP-QPSK) modulation in predominant format used for creation of 100 GbE lightpaths in metro and core optical network segments. However, the need for 400 GbE and 1TbE line transport has become highly evident, thus requiring the most appropriate solutions in design of optical superchannels with an intention to reduce the number of subcarriers by increasing the size of constellation diagram. By using optimized multidimensional structure, we have developed implementation scenarios for future high-speed optical superchannels, with several options presented in Table 1. It quite realistic that practical solution will be based on 400Gb/s rate per carrier in superchannel structure, while the number of amplitude-phase constellation points can vary depending on network conditions and transmission length, with possible interchange between formats. We envision that 32 constellation points are quite realistic in near future, which means that achieved spectral efficiency will be ~6.9 b/s/Hz, while required OSNR will be ~23 dB. As for 1 TbE channels, if faster electronics is used for sampling and only a single carrier modulated with DP-32-QAM is employed, achieved spectral efficiency will be ~6.8 b/s/Hz with the required OSNR of ~27 dB. Some other options for bit rates of various Ethernet interfaces (including futuristic version of 4 TbE and 10 TbE) are also shown in Table 1.

If DP-32-QAM format is applied with the coding rate of 0.8, the required sampling rate would be ~295 GSamples/s, while required OSNR value will be ~27 dB. In such a case, achieved spectral efficiency will be ~6.8 b/s/Hz. If multicarrier superchannel is constructed for 4 TbE and 10 TbE rates bit rates, the required sampling rate can be reduced to be approximately (295 GSamples)/N_{mode}, where N_{mode} is the number of spatial modes that is used. This will also relax the OSNR requirements for at least 3 dB, if two spatial modes are used.

TABLE1: POSSIBLE DESIGN OF HIGH-SPEED SUPERCHANNELS

M (Number of constalation points DP-QAM format)	16	32	64	32	32	32
Bit rate [Gb/s]	400	400	400	1000	4000	10000
FEC Coding Rate; R	0.8	0.8	0.8	0.8	0.8	0.8
Spectral Bandwidth without FEC, Single Carrier; [GHz]	56	47	37	118	N/A	N/A
Spectral Bandwidth with FEC, Single Carrier; [GHz]	70	58.1	46.3	147.5	N/A	N/A
Sampling Rate per Carrier; Gsamples/s	140	116	93	295	116	116
Spatial Modes	1	1	1	1	2	3
Spectral Efficiency, Single Carrierr; [b/s/Hz]	5.7	6.9	8.6	6.8	N/A	N/A
Spectral Eff. (w. spacial mux), Multicarrier; [b/s/Hz]				6.0	11.9	15.1
OSNR per Single Carrier [dB]	~21	~23	~25	~27	~20*	~23**
***400 Gb/s per carrier**						

IV. CONCLUSION

Design of future high-speed optical networks is a challenging task. Optical channel design is essential and there is a number of possible options to maximize network performance while satisfying both the need for higher information capacity of optical links and the need for dynamic adjustment of data flows along the selected optical lightpaths. In this paper we presented methodology for a multidimensional channel design, which includes and intense signal processing in both time and frequency domains, and applied it to metro/core networking scenarios. We presented multidimensional design of future ultra-high speed 4TbE and 10 TbE interfaces and identified key parameters that would enable not only the highest information capacity, but a dynamic adjustment of date flows as well.

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