The Influence of Digital Modulations on 320 Gbit/s Optical Time Division Multiplexing

Lukas Koci, Petr Munster, Tomas Horvath, Milan Cucka, and Miloslav Filka

Original scientific paper

***Abstract*—In this article the optical time division multiplexing technique for high speed point-to-point optical networks is discussed. We performed test of influence of selected types modulation formats in the optical time division multiplexing simulation model with a distance of 30 km. Additionally, this paper focuses on maximum bandwidth usage, improvement of bit error rate and the another goal is to achieve the maximal transmission distance by using of special compensation optical fiber. Optimal length of compensation optical fiber was found and used during simulations. We demonstrated positive influence compensation optical fiber on bit error rate. For comparison of modulation formats such as return-to-zero, non-return-to-zero, chirped-return-to-zero, carrier-suppressed-return-to-zero, and m-ary quadrature amplitude modulation were tested. Our results confirm that it is possible to achieve better bit error rate for selected modulation formats.**

***Index Terms*—OTDM, RZ, NRZ, CRZ, m-QAM, modulation, BER.**

I. Introduction

THE bandwidth grows every year between 25 and 30 % due to the increasing requirements from users and new internet services [1]. The Optical Time Division Multiplexing (OTDM) is a very attractive way for increasing bandwidth in an optical fiber.

Copper wirings have many limitations and low bandwidth. The current trend is to install optical fibers in backbone and access networks. It is necessary to deal with multiple access of users to shared optical fiber. The OTDM together with the Wavelength Division Multiplexing (WDM) are basic technologies allowing merging of optical communication channels and increasing bandwidth. The Time Division Multiplexing (TDM) development in backbone and access networks is shown in Fig. 1.

The TDM can be realized optically (OTDM) or electrically (ETDM). The OTDM (multiplexer, distribution part, and demultiplexer) consists only of optical elements. This means, the OTDM does not require electro-optical and opto-electrical conversion.

For 320 Gbit/s OTDM bit interval is 3.13 ps and pulse width 1.0 ps. This is acceptable range for the lasers used in the OTDM. Transmission rate exceeding 1 Tbit/s requires

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Authors are with the Department of Telecommunications, Brno University of Technology, Brno, Czech Republic (E-mails: lukas.koci@phd.feec.vutbr.cz, munster@feec.vutbr.cz, horvath@feec.vutbr.cz, xcucka00@stud.feec.vutbr.cz, and filka@feec.vutbr.cz).

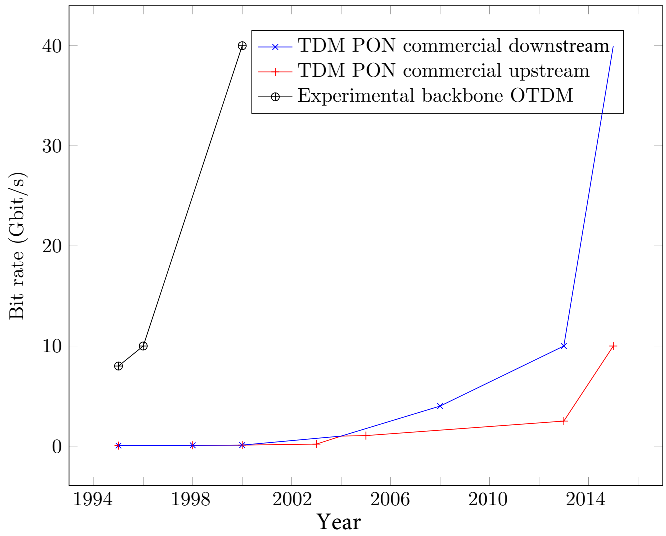

Fig. 1. Evolution roadmap for commercial TDM PON (Passive Optical Network) and OTDM backbone systems [2], [13].

bit interval and pulse width at level of femtoseconds. Currently there are the simulation models having transmission rate ≤ 5 Tbit/s [2]. There are more examples of possible solutions or new development trends. For the real application it is necessary to search new solutions for the OTDM, which have transmission rate < 1 Tbit/s.

In the context of OTDM the Inversion Dispersion Fiber (IDF) is often used. The dispersion compensation is done by using negative dispersion slope. By using specific length of transmission part it is possible to determine accurate length of the IDF and provide optimal compensation quality [3]. This solution is very important and helps to increase length transmission path, increase transmission rate and improve Bit-Error-Rate (BER).

The main contribution of this paper is construction of basic 320 Gbit/s OTDM simulation model including optimal length of the IDF and different modulation formats. Application optimal length of the IDF at the end of the transmission path considerably improved transmission quality and the BER. Especially use the different modulations formats, it has been proven improving the BER and Q-factor.

The remaining part of the article is organized as follows, Section II overviews other associated articles. Section III describes the modulation formats used in these simulation models. Section IV describes the relationship between tem-

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poral Full Width Half Maximum (FWHM) and spectrum FWHM and their limit values. Section V shows block scheme of the 320 Gbit/s OTDM network and description of simulation set-up. Section VI gives simulation results for different modulation formats and also influence of IDF on transmission quality. In Section VII the final summary of the article is presented.

II. State of Art

Recently, many works related to high speed OTDM have been published. Experimental set-up was demonstrated for a generation of 10 GHz clock signal and 1.28 Tbit/s data signal over 70 km [2]. Bandwidth exceeding 1 Tbit/s was used but on the other hand influence of different modulation formats was not demonstrated. Furthermore, the publication deals with 40 GHz MLFL, Dispersion Decreasing Fiber (DDF), IDF, optical demultiplexing using methods, and new modulation trends in optical communication. However, this article enables a direct comparison of modulation formats in 320 Gbit/s OTDM simulation model including using IDF.

The authors [4] describe the 40 Gbit/s OTDM link over a distance of 343 km. In this solution 4×10 Gbit/s and two basic modulation formats are used. This article offers an extension of other basic modulation formats, multi-level modulation format and increase bandwidth to 320 Gbit/s.

The publication [5] presents 160 Gbit/s OTDM transmission and compares the basic modulation formats. However, in this article it is possible to make a direct comparison between basic modulation formats and multi-level modulation. The other works published up to date are aimed at the single modulations (single or multi-level). It is not possible compare the results of various digital modulation (in one simulation model).

In the articles [6], [7], and [8] the authors deal with 320 Gbit/s OTDM transmission over 80 km and longer. They used only basic modulation and do not compare various modulation formats and their influence on the transmission system.

III. The modulation formats

The choice of optimal modulation format may have a positive influence on a maximal achievable distance, bandwidth and also BER. The basic modulation formats are Return-to-Zero (RZ), Non-Return-to-Zero (NRZ), Chirped-Return-to-Zero (CRZ) and Carrier-Suppressed-Return-to-Zero (CSRZ). In this paper all these basic modulation formats and also the m-ary Quadrature Amplitude Modulation (m-QAM) format were tested.

The first basic modulation format used in optical networks is NRZ. For duration of logical 1 signal, signal level does not return to zero and the phase value is π. When there is a change to logical 0, phase is 0. NRZ has narrower spectrum of the central lobe than other modulation formats [9].

RZ is a second basic modulation format for optical data transmissions. Basically a signal returns to logic 0 after duration of logical 1. There are three variants of RZ modulations, defined by a size of the duty cycle of 33% RZ, 50 % RZ, and 67 % RZ (CSRZ). The CRZ and CSRZ modulations are superstructure of RZ. In ideal, they are identical to RZ pulses and chirp-free [9].

CRZ contains non-zero chirp factor, which varies between ± 1. The chirp is added to RZ by applying a phase modulation. Due to that, the central lobe is wide.

The next modulation tested in our simulation model is the CSRZ. At first, the RZ signal is modulated by Mach-Zehnder modulator. Subsequently, a signal passes through a phase modulator driven by analogue sine wave generator at a frequency equal to half of the bit rate. The central peak is suppressed.

The m-QAM is the last modulation format tested in our simulation model. It is based on Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK) modulations. There are multiple variants of QAM modulations, which differ in a number of states. In this work a four-state modulation 4-QAM is tested. Position of each symbol (state) can be depicted into the Constellation diagram. The QAM modulator is composed of an imaginary and a quadrature part. Each part has half of the data rate and both parts are modulated onto two carriers. A phase shift between them is 90^o. Demodulation of the QAM signal is a reverse process.

IV. Transform-Limited Optical Pulses

Optical pulses generated by MLFL have a specific temporal FWHM. For 320 Gbit/s OTDM it is 3.13 ps or lower. The pulse width is measured in FWHM.

In OTDM it is preferred to operate with pulses of very short duration. When Optical Bandpass Filter (BPF) is used, the optical pulses can be shortened. Dependence of temporal FWHM and spectrum FWHM is depicted in Fig. 2. If the limit value is exceeded (time width or spectrum FWHM), the second parameter is increased.

The spectrum FWHM is calculated according to the equation:

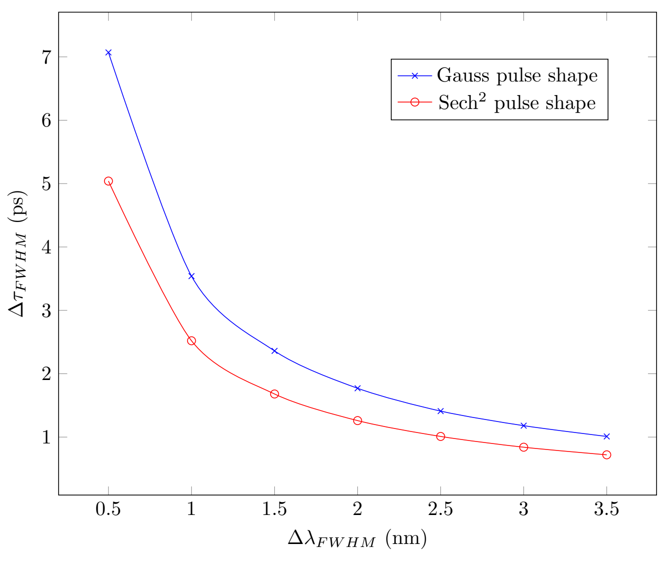

Fig. 2. Transformation limits for Sech^2 and Gauss pulses.

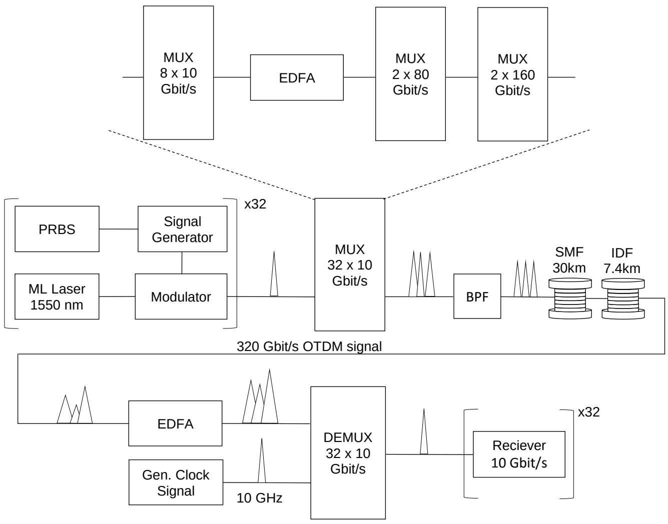

Fig. 3. Block scheme of the 320 Gbit/s OTDM network.

$$\Delta\lambda = \frac{\lambda^2 \times K}{\Delta t \times c_0}. \quad (1)$$

where $\Delta\lambda$ is the spectrum FWHM of a signal, Δt is the temporal FWHM of investigated signal, c_0 represents the speed of the light in vacuum, λ is the wavelength and K is Time-Bandwidth-Product [10]:

$$K = \Delta\lambda \times \Delta t \quad (2)$$

when $K = 0.4413$ for the Gauss pulse shape and $K = 0.3148$ for the Sech pulse shape.

V. Simulation set-up

The experimental set-up is shown in Fig. 3. A block scheme of the simulation model can be divided into three parts (transmitter, distribution part and receiver). To make simulation model realistic attenuaters and Erbium Doped Fiber Amplifiers (EDFAs) are installed. The simulation was performed in the OptSim software from RSoft Design Group [14].

The transmitter includes a 10 GHz MLFL laser as a source of 3.13 ps very short pulses at 1550 nm. The short pulses are modulated by a Mach-Zehnder Modulator (MZM) with a PRBS word length of $2^7 - 1$. The 10 Gbit/s modulated signal is multiplexed to 320 Gbit/s by the OTDM fiber-delay multiplexer. The 320 Gbit/s modulated signal passes through the BPF, which is set to 4 nm.

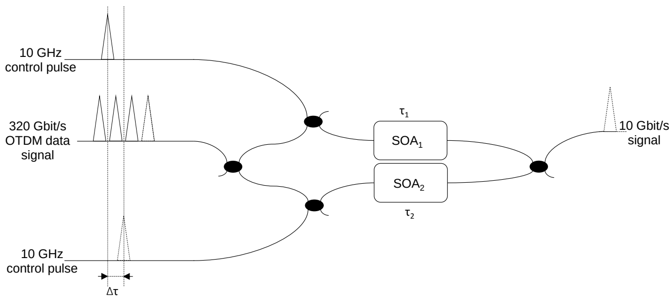

Fig. 5. The principle of the TOAD based on SMZ.

The distribution part consists of a 30 km Single Mode Fiber (SMF), compensated by 7.4 km of the IDF. A total dispersion slope of SMF is 0.9×10^3 s/m^3 and of IDF is -0.359×10^3 s/m^3.

In the receiver part, the 320 Gbit/s signal is first amplified in EDFA and then demultiplexed to 10 Gbit/s by Symmetric Mach-Zehnder (SMZ) interferometer using Semiconductor Optical Amplifier (SOA). The most important part of SMZ is the 10 GHz control signal demarcation which is after for of the data signal. Time delay between two control pulses is realized by an optical splitter 1:2, and by two time-delay units realized in the simulation model.

The principle description of the Terahertz Optical Asymmetric Demultiplexer (TOAD) based on SMZ is in literature [2], [11], [12] and is shown in Fig. 5. The 10 Gbit/s demultiplexed signal passes through a polarization filter and is analyzed by the BER analyser.

VI. Results

A. The modulation formats simulation

Fig. 4 a), b), and c) show the wavelength spectrum of NRZ, CSRZ and 4-QAM with a bitrate of 320 Gbit/s multiplexed OTDM signals. Measurements were performed after pass through BPF. BPF must be used before the signal passes through the 30 km optical line and the 7.4 km IDF. This ensures the better results of transmission, especially reduction the BER.

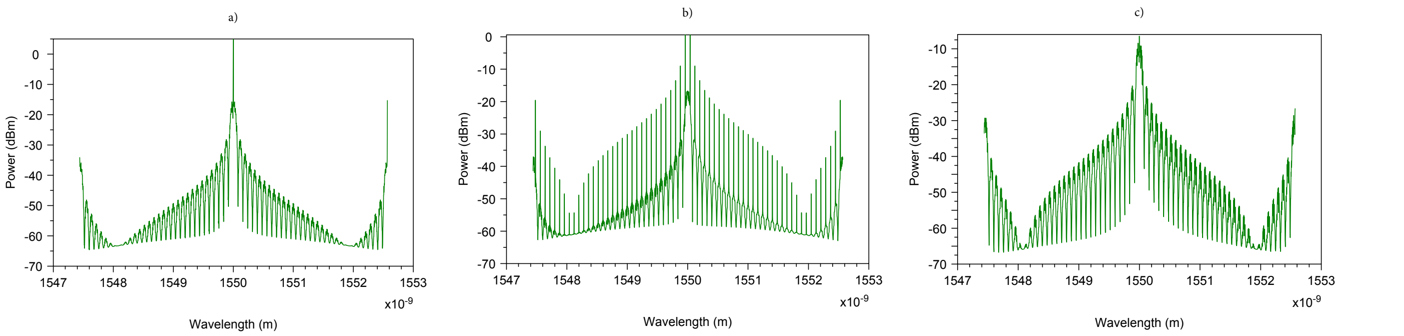

Fig. 4. The wavelength spectrum of a 320 Gbit/s OTDM signals for the a) NRZ, b) CSRZ, and c) 4-QAM formats.

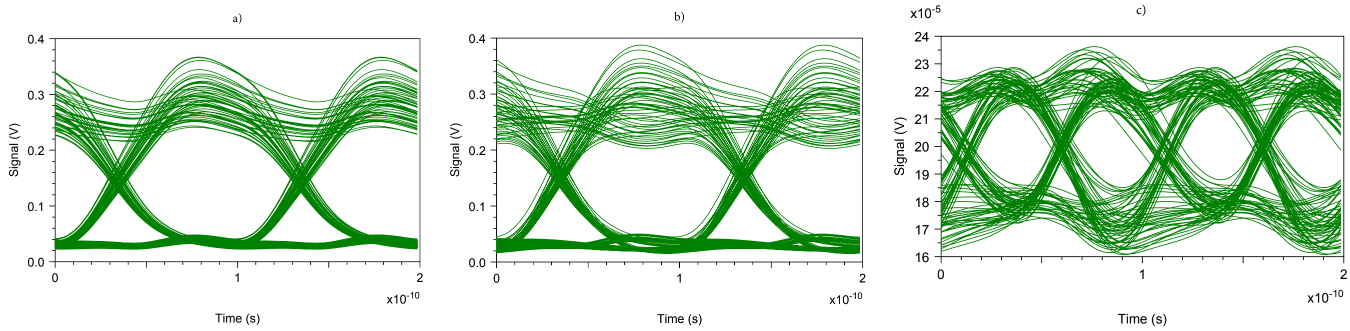

Fig. 6. Eye diagrams for a) NRZ, b) CSRZ, and c) 4-QAM

In Fig. 6 we can see eye diagrams at the end of SMZ TOAD. Different shapes of the eye diagrams demonstrate the differences between basic modulation formats and the 4-QAM modulation. It is caused by a number of transmitted states in individual modulations.

For all 320 Gbit/s OTDM systems except the CSRZ, BER of less than 10^{-9} was obtained. The RZ, NRZ, and CRZ modulation formats have narrower central lobe. It is a prerequisite for using in high transmission OTDM systems.

The BER values of all tested modulations are presented in Fig. 7. From Fig. 7 we can see they acceptable results are for the RZ, NRZ, and CRZ modulation formats having BER exceeding 2.00×10^{-13}, eventually 4-QAM having BER 2.10×10^{-10}.

B. The IDF simulation

The IDF has a positive influence on the total BER. Optimal length of IDF was selected based on BER, the results are shown in Fig. 8. Distribution path has the best parameters while using IDF of a length between 7.2 and 7.4 km. When IDF of a length 7.6 km is used, the value of BER is improvement of $> 30\,\%$.

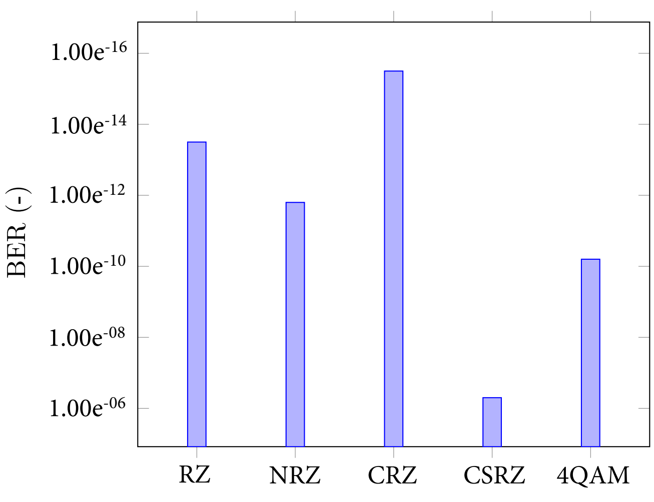

Fig. 7. Comparison of all modulation formats used in the simulation.

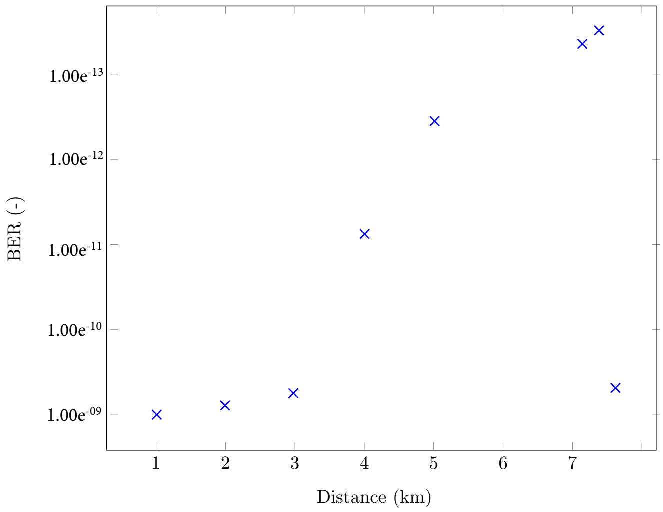

Fig. 8. The effect of size BER on the length of the IDF, while using the RZ modulation format.

VII. Conclusion

In this article we demonstrated influence of modulation formats on the 320 Gbit/s OTDM transmission system over 30 km of SMF and 7.4 km of IDF. From our results it is evident that CRZ modulation format is a suitable choice for using in the 320 Gbit/s OTDM optical communications. On the other hand, the CSRZ modulation format is not suitable for the OTDM systems. In the simulation models Forward Error Correction (FEC) is not used. In addition using IDF may have a huge impact on the OTDM system. The future research would focus on an application of multitone modulation formats, application of FEC, extension of distribution path, and increasing the of bit rate to 640 Gbit/s and higher.

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Lukas Koci was born on the 29 of September 1990 in Brno, Czech Republic. He graduated at the University of Technology in Brno and received academic title Ing at the Department of Telecommunications. Currently, he is studying Doctoral program at Brno University of Technology, Department of Telecommunications. His research is focused on optical communication networks, optical time division multiplexing, wavelength division multiplexing, passive optical networks, and especially software defined optical networks.

Petr Munster (MSc, PhD.) was born in 1984, in Zln (Czech Republic). He received his PhD at the Brno University of Technology, Department of Telecommunications in 2014 on the thesis entitled Parameters of the FTTx networks. His current research themes focuses on fiber-optic sensors, especially distributed fiber-optic sensors, and also on fiber-optic telecommunications. He has about 50 scientific publications in journals and conferences in last 5 years.

Tomas Horvath was born in Havirov, Czech Republic on March 7, 1989. He received his M.Sc. degrees in Telecommunications from the Brno University of Technology, Brno, in 2013. His research interests include passive optical networks (xPON), optoelectronics, and BitTorrent protocol. Currently, he has been actually post graduate student at Brno University of Technology, Department of Telecommunications and his topic of dissertation thesis is Optimization services in FTTx optical access networks.

Milan Cucka was born in Vykov, Czech Republic on January 20, 1989. He received his M.Sc. degrees in Telecommunications from the Brno University of Technology, Brno, in 2014. His research interests include distributed optical sensors, optoelectronics, and fiber bragg gratings. Currently, he has been actually post graduate student at Brno University of Technology, Department of Telecommunications and his topic of dissertation thesis are distributed fiber optics systems.

Miloslav Filka (prof.) was born in 1946 in Brno, Czech Republic. Since 2010 he is a professor at the Department of Telecommunications at Brno University of Technology. Hi is a leader of the optical group OptoLab and also head of the Laboratory of transmission media and optical networks. He is a member of a several institutes (e.g. Institute of Electrical & Electronics Engineeres) and is also committee of many conferences (International Conference Telecommunications and Signal Processing, International Conference New Information and Multimedia Technologies). His current research themes focuses on fiber-optic telecommunications, especially FTTx technologies.