Chapter

Research of M-PAM and Duobinary Modulation Formats for Use in High-Speed WDM-PON Systems

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Abstract

The exponential growth of Internet data traffic and progress of Information and Communication Technology (ICT) sector pushes hard the telecommunication infrastructure for upgrading the transmission data rate. Wavelength division multiplexed passive optical networks (WDM-PONs) can be the next generation solution for nowadays problems which are related to transmission capacity. Next-generation WDM-PON systems based on mixed wavelength transmitters are expected to become more cost-efficient at high per user data rates, e.g., over 10 Gbit/s per channel. Important advantage of this technology is to set various channel spacing and use different modulation formats to increase spectral efficiency in the same time and provide different transmission speeds for end user, based on pay-as-you-grow approach. Therefore, several modulation formats like non-return to zero (NRZ) also called 2-level pulse-amplitude modulation (PAM-2), four level PAM or PAM-4 and Duobinary (DB) are investigated to understand their limitations, advantages and disadvantages to be further used in next generation PON systems to increase its capacity and spectral efficiency.

Keywords: wavelength division multiplexed passive optical network (WDM-PON), non-return to zero (NRZ), four level pulse-amplitude modulation (PAM-4), duobinary (DB), capacity, spectral efficiency

1. Introduction

The exponential growth of Internet data traffic and progress of Information and Communication Technology (ICT) sector pushes hard the telecommunication infrastructure for upgrading the transmission data rate [1]. Power and cost-efficient fiber optical access networks, like passive optical network (PON) and short-range fiber optical links are one of the key technologies enabling bandwidth hungry services like video on demand (VoD), high definition TV, and cloud computing supported by large scale high-performance computers and data centers. Such optical links typically use direct detection and on-off keying modulation (OOK) with NRZ line code. Today's challenge for optical access networks and data centers is to increase the serial line rate of a NRZ link meeting the requirements to the physical bandwidth of the photonic and electronic components like optical signal modulators and photodiodes [2].

Solution for telecommunication infrastructure upgrade and alternative solution for increase of the serial line rate of the NRZ link is to use multi-level signaling formats such as pulse-amplitude modulation (PAM), abbreviated as PAM-M or M-PAM, where multiple digital bits per symbol are encoded into M different signal amplitude levels. The four-level PAM modulation format is receiving significant attention because of its relative ease of implementation in comparison to higher-order modulation formats like quadrature phase-shift keying (QPSK), and m-ary quadrature amplitude modulation (m-QAM). It is clear that M-PAM offers a good trade-off between performance and complexity. Usage of PAM-4 format is effective way to double the data rate of NRZ link. Previously PAM-4 modulation formats have been investigated for application with traditional electrical networks [3, 4], but now researchers are focused on investigation of PAM-4 and M-PAM modulation formats for utilization in optical access networks as well as data center interconnections [5]. Also, there are very limited number of studies which are focused on spectrum slicing and stitching back method, which deals with bandwidth bottleneck problem by slicing the broadband signal in lower-bandwidth signal slices. This spectrum slicing and stitching back method or technique allows transmission of wide bandwidth signals from the service provider to the end user over an optical distribution network via low bandwidth equipment [6, 7]. It is ideally suited for cost sensitive fiber optical access networks where variable bandwidth and scalability as well as flexibility are important. It must be noted that this method is investigated for intensity modulated direct detection NRZ-OOK and duobinary systems, but there are no investigations on its usage together with M-PAM systems [8, 9]. It must be noted that multi-level signaling also changes some rules, which were used in NRZ coded transmission systems. For M-PAM systems it is important to implement more complex and precise level threshold detection for signal inputs, also signal-to-noise (SNR) requirements are higher than in case of NRZ. Eye time skew, amplitude compression in lower eye diagram eyes, intersymbol interference for M-PAM systems also is an issue which must be investigated. So, we can say that PAM-4 links are new science—still learning what impairments create errors in receivers [10, 11]. Significant efforts have been put on investigation of PAM-4 format in fiber optical transmission networks, however there are following aspects, which have not been studied or have been studied insufficiently. High-level PAM modulation techniques, like PAM-4, can dramatically improve the spectral efficiency and available bitrate by using the bandwidth of already existing optical, electro-optical or electrical devices. Minimal available channel spacing (which has direct impact on the utilization of resources like optical spectrum), maximal available number of channels, by wavelength division multiplexing (WDM) technique, maximal transmission distance (network reach) in dispersion compensated and non-compensated M-PAM modulated WDM-PON optical access systems.

Another way to improve capacity of limited bandwidth is by using duobinary modulation format. Transmission capacity will be increased in comparison with NRZ, utilization of DB will increase the transmission capacity by improving the bandwidth efficiency and reducing channel spacing with this modulation format [12]. Duobinary modulation format is type of proficient pseudo-multilevel modulation format, and therefore is the area of interest due to its increased spectral efficiency. It has been already used to increase the channel capacity by improving the bandwidth utilization in commercial links. The most important feature of duobinary modulation format is its usage for longer transmission distances where it has high tolerance to the influence of chromatic dispersion (CD) [13].

At first, in the paper we investigate the performance and minimal channel interval of 10 Gbit/s per channel NRZ-OOK (which is basically PAM-2) modulated transmission system, then we investigate PAM-4 and raise the transmission speed up to 20 Gbit/s per wavelength and in the end compare it to NRZ and duobinary modulation formats.

2. Evaluation of various channel spacings for increasing spectral efficiency of WDM-PON transmission system

At the moment passive optical networks have been standardized to next-generation NG-PON2 accordingly to ITU-T G.989.2 recommendation standards and are widely investigated. Operators are widely deploying time-division multiplexing (TDM) based passive optical networks in urban areas with bitrates up to 10 Gbit/s, but WDM-PON's still are in stage of research [14, 15].

The ITU-T G.694.1 recommendation provides a frequency grid for (WDM) transmission systems and specifies inter-channel intervals. The same frequency grid or channel spacing is used for spectral effectiveness improvement of PON system in our research. Anchored to 193.1 THz (central channel frequency), it supports a variety of inter-mediate channel spacings ranging from narrowed 12.5 GHz to 100 GHz and wider. Depending on the selected step of the inter-channel interval are defined the following abbreviations and acronyms:

WDM—wavelength division multiplexing.
CWDM—coarse wavelength division multiplexing.
DWDM—dense wavelength division multiplexing.

There are two types of inter-channel interval definitions in (WDM) systems:

Fixed inter-channel interval (fixed grid).
Flexible inter-channel interval (flexible grid).

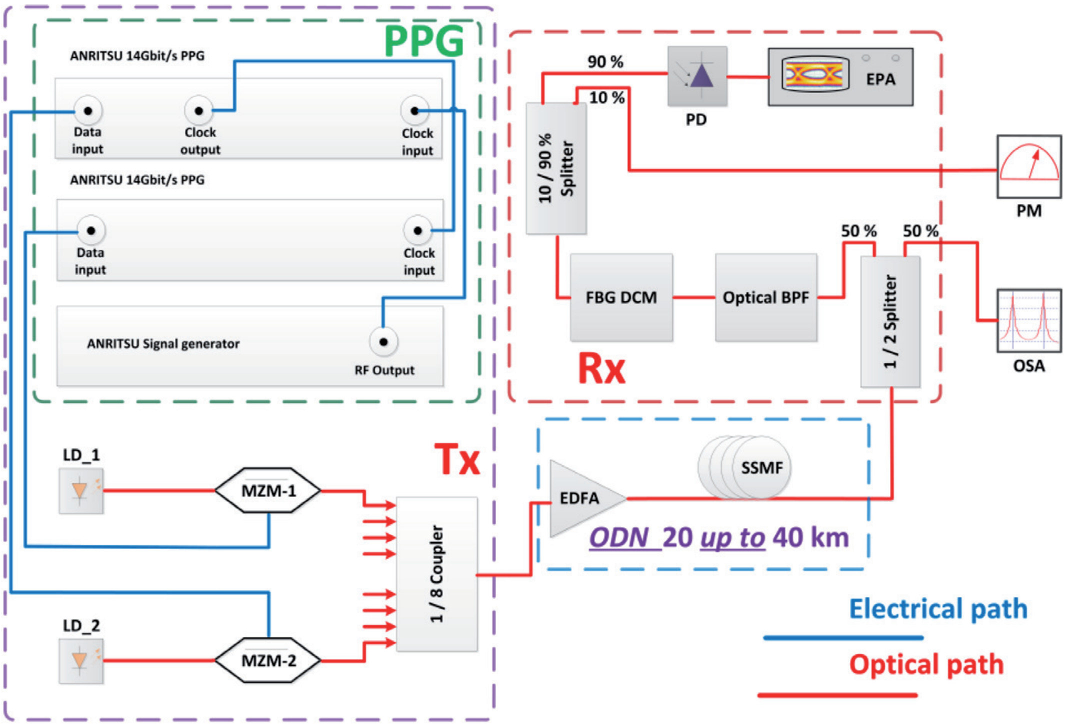
According to ITU-T G.694.1 rec. the minimum step of a fixed channel interval is 12.5 GHz (please see **Table 1**). The flexible channel step is half of the 12.5 GHz, that can be used for the inter-channel interval like 6.25 GHz. Reducing the inter-channel interval leads to increase of crosstalk and non-linear effects (NOE) of transmitted optical signal [16–18].

For research of spectral efficiency increasing, the experimental 2-channel NRZ-OOK modulated 10 Gbit/s bit rate per channel transmission system model was created for Next-generation WDM-PON systems based on tunable wavelength transmitters, please see in **Figure 1**. First step of the research is based on various channel spacing impact on the end user transmitted signal with following fixed 10 Gbit/s transmission speed per channel.

As one can see in **Figure 1**. transmitter (Tx) part of our investigated transmission system model consists of two continuous wave (CW) laser sources—Agilent 81949A, with fixed central frequency 193.1 THz or 1552.524 nm in wavelength, and COBRITE DX-1 laser with tunable central frequency, which can be set the necessary channel spacing. Agilent 81949A continuous wave laser source was connected

Nominal central frequencies (THz) for spacing				Nominal central wavelengths (λ, nm)
12.5 GHz	25 GHz	50 GHz	100 GHz	
193.9375	-	-	-	1530.0413
195.9250	195.925	-	-	1530.1389
195.9125	-	-	-	1530.2365
195.9000	195.900	195.90	195.9	1530.3341

Table 1.
Nominal central frequencies grid of the DWDM grid [17].



PPG: Pulse Pattern Generator, **Tx:** Transmitter, **Rx:** Receiver, **LD_1:** 1st CW Laser source, **LD_2:** 2nd CW Laser source, **MZM-1:** 10G MZM Mach-Zehnder-modulator, **MZM-2:** 40G MZM Mach-Zehnder-modulator, **EDFA:** EDFA amplifier, **SSMF:** ITU-T G.652 Single-mode-fiber, **OSA:** Optical Spectrum Analyzer, **Optical BPF:** Optical Tunable Filter, **DCM:** FBG Dispersion Compensation Module, **PD:** 10G Photodiode, **EPA:** Eye Pattern Analyzer.

Figure 1.
2-Channel NRZ-OOK modulated optical transmission system with 10 Gbit/s transmission speed per channel and flexible channel spacing.

to the 40G intensity Mach-Zehnder (MZM) modulator, COBRITE DX-1 laser light source was connected to the second MZM intensity modulator. Both laser sources were used with minimal output power +9 dBm for Agilent 81949A and +6 dBm for COBRITE DX-1. To provide the same level of optical power for both optical channels, after the PHOTLINE 40G MZM, an optical attenuator of 3.05 dB insertion loss was additionally attached to the modulator's optical output. Pulse Pattern Generator (PPG) with Pseudo random bit sequence (PRBS9) was used for generation of NRZ coded electrical signals. The external 10 GHz clock signal generator was used in this experiment for as a clock signal source for PPGs. Two electrical PPG non-inverted RF data signal outputs were connected to each of MZMs electrical signal inputs. The data rate for each of the PPGs was 10 Gbit/s throughout the experiment.

ITU-T G.652 standard single mode fiber (SSMF) with dispersion coefficient of 16 ps/(nm × km), and 0.2 dB/km attenuation coefficient was used in optical distribution network. Depending of SSMF fiber span length (20 or 40 km), an Erbium doped fiber amplifier (EDFA) with additional gain was used to provide sufficient optical power level before the PIN photoreceiver.

At the receiver part (Rx), the incoming optical signal was divided by 50% power splitter with 3.5 dB insertion loss. One output of optical power splitter was connected to the optical spectrum analyzer (OSA). Second output of power splitter was connected to the optical band pass filter (BPF) OTF-350 with a tuned 35 GHz 3-dB bandwidth. After BPF filter, fiber Bragg grating dispersion compensation module (FBG DCM), with 3 dB insertion loss was connected for post-compensation purposes of chromatic dispersion (CD). To avoid the maximum optical input optical power level rating of +3 dBm before the 10G PIN photoreceiver (PD) a monitoring power splitter with a power ratio of 10–90% and power meter was used. First channel was filtered out by using optical BPF. As one can see in **Figure 2(a)**, optical spectrum with central channel frequency 1552.560 nm (193.096 THz in frequency)

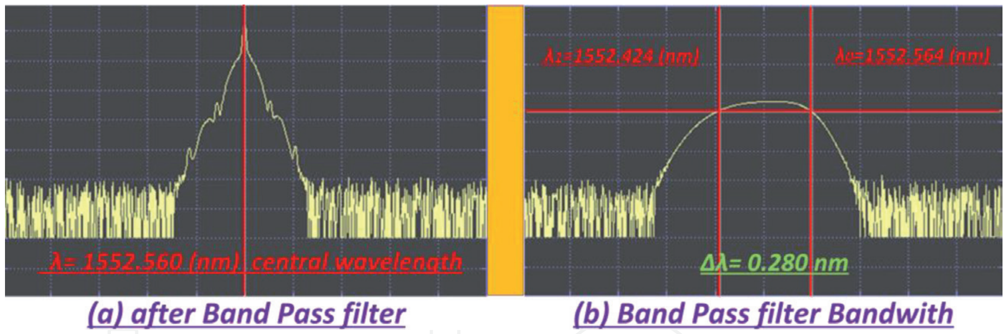


Figure 2.
Central channel spectrum of 2-channel NRZ-OOK modulated optical transmission system with 10 Gbit/s per channel: (a) after BPF and (b) measured amplited frequency response of BPF.

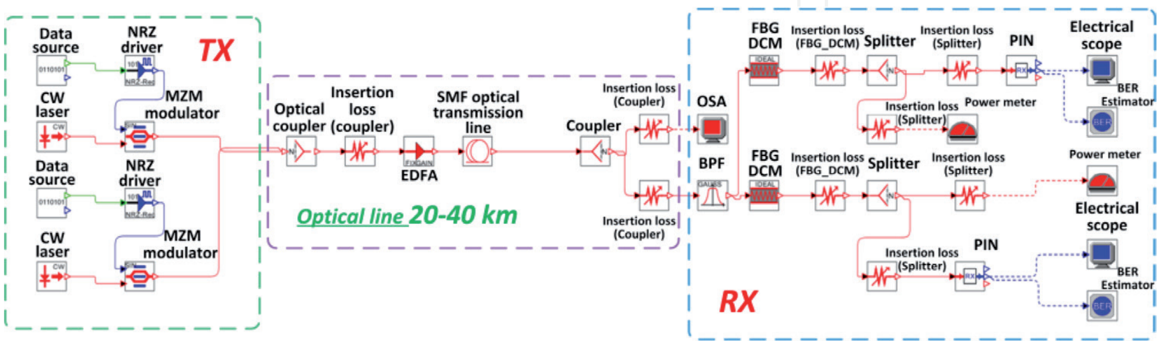


Figure 3.
Simulation scheme of 2-channel NRZ modulated optical transmission system with 10 Gbit/s transmission speed per channel with flexible channel interval.

is slightly shifted relative to ITU-T G.694.1 rec. Grid central frequency of 193.1 THz. By obtained results from the optical spectrum analyzer (OSA), the BPF pass band is $\Delta\lambda$ = 0.280 nm equal to 35 GHz, where λ_0 = 1552.564 nm and λ_1 = 1552.424 nm.

An eye analyzer was used for measurements of received electrical signal quality. The eyes of received signals for both channels were open, therefore leading to error free transmission. As the eye pattern analyzer for quality measurement use special masks to determine if the signal is above or below necessary quality. We continued our research in OptSim simulation environment by creating relevant simulation model and using the previously obtained experimental data.

For more precise expected Bit-error-rate (BER) values of received signal the simulation model was created in OptSim simulation software environment. The model used BER estimator based on statistical signal analysis. As one can see in **Figure 3**, simulation scheme implemented in OptSim simulation software for BER measurements has the same setup as experimental system. In the OptSim simulation environment, it is necessary to perform the assembly of used electrical-optical components in order to repeat the 2-channel NRZ-OOK modulated 10 Gbit/s per channel transmission system to research impact of various channel spacings.

According to ITU-T G.694.1 rec., see **Table 2**, during the experiment, the inter-channel interval for transmission system was changed from 100 GHz to 25 GHz. We started the experiment at a 20 km long fiber ODN distance with 100 GHz channel spacing. Firstly, the measurements was carried out without the chromatic dispersion (CD) post-compensation, at 20 km fiber link. For transmission over 20 km fiber span we observed negligible chromatic dispersion impact on 10 Gbit/s signal, received signal is mainly insignificant impact of dispersion [19].

The 12.5 GHz channel spacing interval was not obtained in this step of research. The reason for that was too wide filter pass-band, as a result photoreceiver captured

Frequency interval (THz)	100 GHz		50 GHz		25 GHz	
CW laser	Freq., (THz)	(λ, nm)	Freq., (THz)	(λ, nm)	Freq., (THz)	(λ, nm)
1st CH	193.1	1552.524	193.1	1552.524	193.1	1552.524
2nd CH	193.0	1553.328	193.05	1552.926	193.075	1552.725

Table 2.
Experimentally used channel interval according to ITU-T G.694.1 rec.

1st-CH, (THz)	2nd-CH, (THz)	2nd-CH, (nm)	Delta, (THz)	CH–interval, (GHz)
193.1	193.08125	1552.675	0.01875	18.750
193.1	193.07813	1552.700	0.02187	21.875
193.1	193.07500	1552.725	0.02500	25.000
193.1	193.07188	1552.751	0.02187	28.125
193.1	193.06875	1552.776	0.03125	31.250
193.1	193.06563	1552.801	0.02187	34.375
193.1	193.06250	1552.826	0.03750	37.500
193.1	193.05625	1552.876	0.04375	43.750
193.1	193.05000	1552.926	0.05000	50.000
193.1	193.00000	1553.329	0.10000	100.000

Table 3.
Channel spacing dependence on the channel interval.

both channels simultaneously. They did not appear on the Eye Analyzer because it was not possible to synchronize between the transmitter and receiver. After obtaining the results at fixed inter-channel intervals from 100 to 25 GHz, the smallest inter-channel interval at which transmission is possible was found. The step used to search for the inter-channel interval is 6.25 GHz and half of the found step 6.25/2 = 3.125 GHz. Result of channel spacing impact was obtained from channel with fixed central frequency of 193.1 THz = 1552.524 wavelength corresponding to the laser source used by Agilent 81949A. Our transmission system has only two channels, it is not possible to choose a central channel, both channels have mainly the same effect of crosstalk. The channel interval was changed by changing the central wavelength of the second CW laser source with 6.25 and 3.125 GHz step. Instead of experiment for 2-channel NRZ-OOK modulated optical transmission system with 10 Gbit/s transmission speed per channel previously calculated flexible channel interval was used in our research, please see **Table 3**.

Fiber optical transmission system made by the optical components affected by various factors caused by higher attenuation mentioned in specification insertion loss. To create same simulation model in OptSim simulation software environment, it was necessary to adapt model optical elements of the actual loss. In **Figure 4**. we can see BER estimated from the data obtained in OptSim simulation according to different channel intervals.

The BER threshold of 10^{-9} for our investigated transmission system was used to evaluate maximal crosstalk impact between the channels. According to the

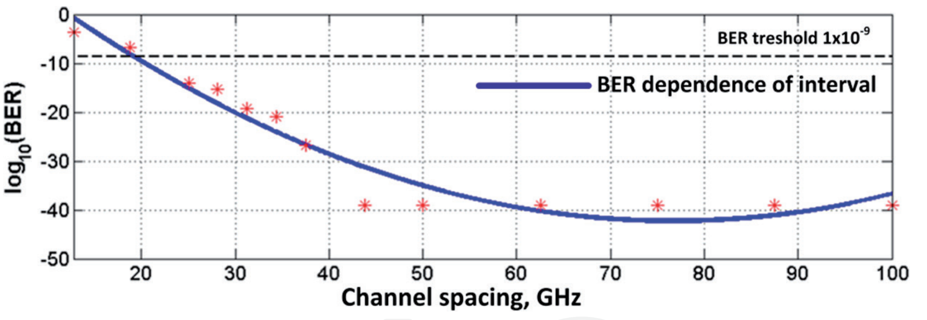


Figure 4.
BER dependence on the channel interval for a 20 km long 2-channel NRZ-OOK modulated optical transmission system with 10 Gbit/s transmission speed per channel.

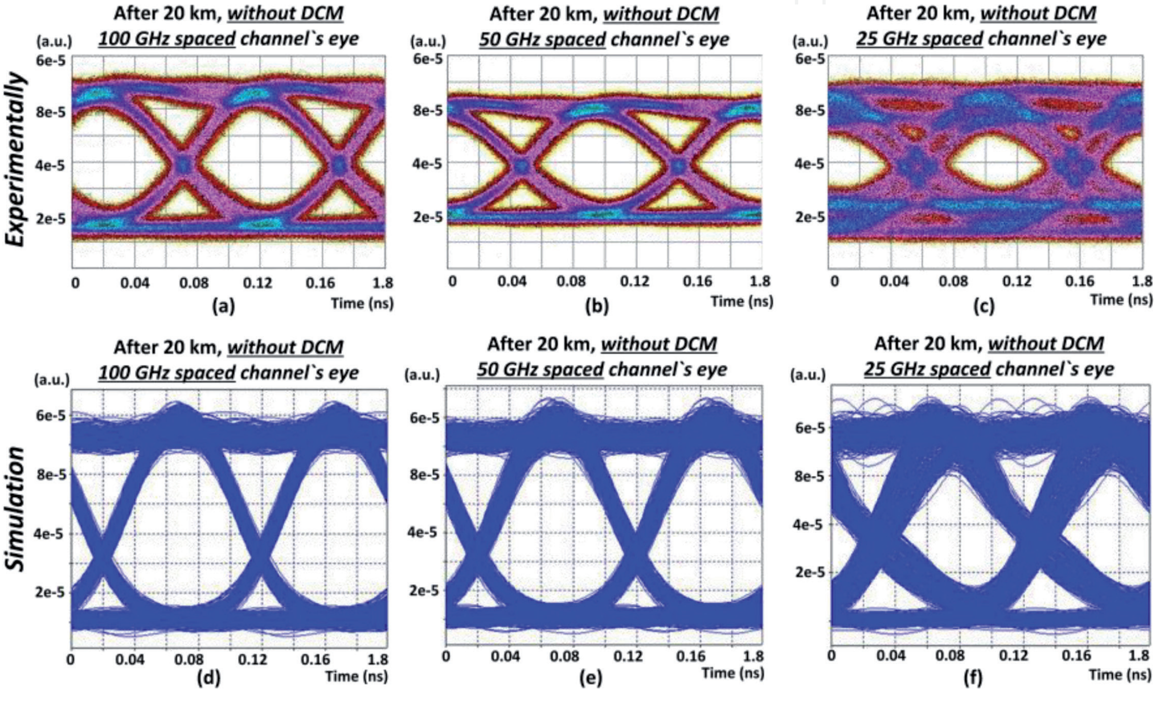


Figure 5.
Comparison of experimental and simulative results: eye diagrams of 20 km 2-channel NRZ-OOK modulated optical transmission system with 10 Gbit/s transmission speed per channel without CD post-compensation: (a) 100 GHz channel spacing, (b) 50 GHz channel spacing, (c) 25 GHz channel spacing, (d) 100 GHz channel spacing in the environment of OptSim, (e) 50 GHz channel spacing in the environment of OptSim, and (f) 25 GHz channel spacing in the environment of OptSim.

obtained results channel interval effect up to 30 GHz can be evaluated, higher than used value of BPF filter. Deterioration of the BER used for channel interval less than 30 GHz in our research, can be explained by adjacent channel overlapping. At 20 km long SSMF fiber optical link minimal channel spacing was achieved ensuring BER < 10^{-3} threshold at 25 GHz. In **Figure 5**, we can see experimental and theoretical (simulation data) eye diagrams of received signal for second channel with 100, 50 and 25 GHz channel spacing crosstalk impact, please see **Figure 5**.

In second part of our research the length of ODN was increased from 20 to 40 km, by adding 20 km SSMF fiber span. The effect of chromatic dispersion was observed in upgraded transmission system. Fiber Bragg grating dispersion compensation module (FBG DCM) with −640 ps/nm was used for dispersion compensation. The BER value exceeded our defined BER threshold of $1x10^{-9}$ at 31.25 GHz channel spacing according to the obtained results of OptSim simulation software. By performing experiment, the 31.25 GHz inter-channel spacing was the last interval at which mask testing with eye diagram analyzer for received eye diagrams was

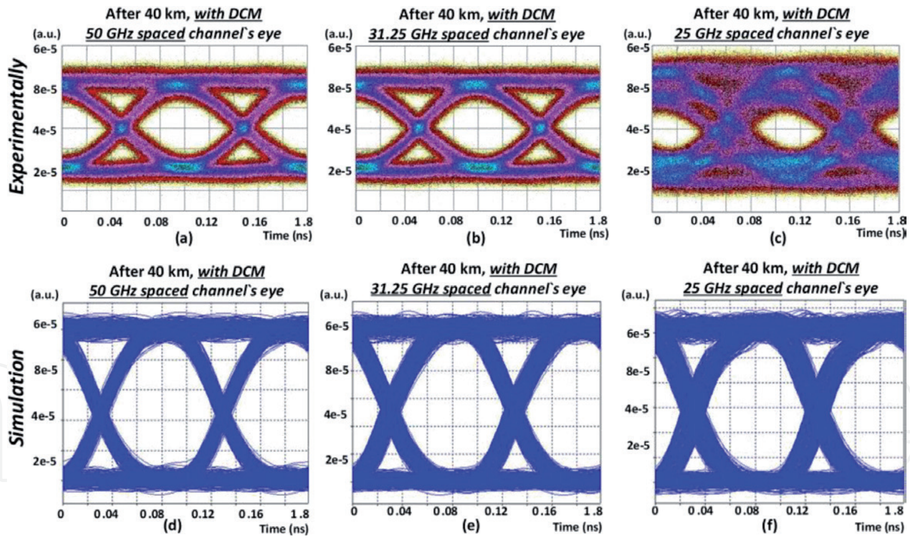


Figure 6.
Comparison of experimental and simulative results: eye diagrams of 40 km 2-channel NRZ modulated optical transmission system with 10 Gbit/s transmission speed per channel with CD post-compensation: (a) 50 GHz channel spacing, (b) 31.25 GHz channel spacing, (c) 25 GHz channel spacing, (d) 50 GHz channel spacing in the environment of OptSim, (e) 31.25 GHz channel spacing in the environment of OptSim, and (f) 25 GHz channel spacing in the environment of OptSim.

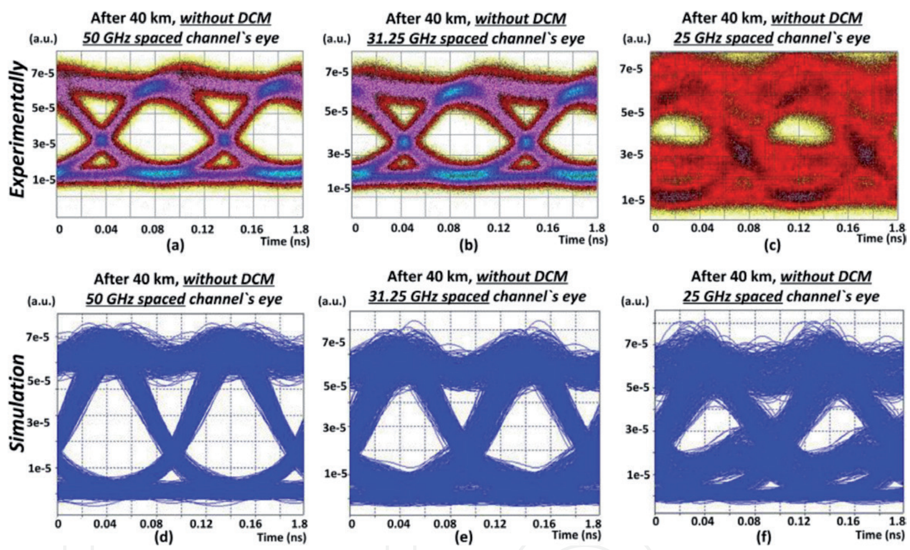


Figure 7.
Comparison of experimental and simulative results: eye diagrams of 40 km 2-channel NRZ modulated optical transmission system with 10 Gbit/s transmission speed per channel without CD post-compensation: (a) 50 GHz channel spacing, (b) 31.25 GHz channel spacing, (c) 25 GHz channel spacing, (d) 50 GHz channel spacing in the environment of OptSim, (e) 31.25 GHz channel spacing in the environment of OptSim, and (f) 25 GHz channel spacing in the environment of OptSim.

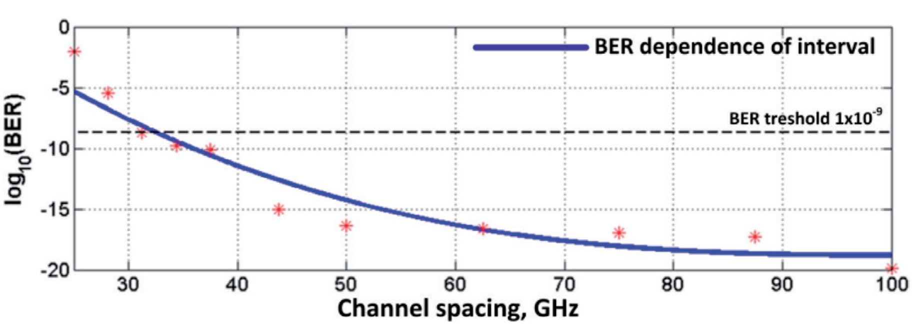


Figure 8.
BER dependence on channel interval for a 40 km 2-channel NRZ-OOK modulated optical transmission system with 10 Gbit/s transmission speed per channel.

possible [20]. By obtained experimental and simulation results it can be concluded that the model of optical transmission created in the simulation environment corresponds to the experimental fiber optic transmission system. Channel overlaps at 40 km long fiber section, with use of dispersion compensation, see **Figure 6** and without dispersion compensation see **Figure 7**. Results, with BER below our inter-channel interval, please see **Figure 8**.

Our defined BER threshold of 1×10^{-9} was exceeded at the 31.25 GHz channel interval where the BER of received signal was 7.4×10^{-11}.

3. Evaluation of PAM-4 modulation format use in WDM-PON systems

In our research we investigated the 4-channel 10 Gbaud/s (20 Gbit/s) per channel PAM-4modulated WDM-PON access system with minimal allowable channel spacing, which has a direct impact on the utilization of resources like optical spectrum. The research was made with and without fiber chromatic dispersion (CD) fiber Bragg grating compensation module (FBG DCM). We evaluate system performance and found the maximal transmission distance for multichannel PAM-4 modulated WDM-PON transmission system operating at 20 Gbit/s per channel. In OptSim simulation software we created transmission system model to evaluate the performance of 4-channel PAM-4 modulated WDM-PON transmission system operating at 10 Gbaud/s or 20 Gbit/s per channel under the condition with BER threshold of 10^{-3}, by use of Reed Solomon (RS 255,223) forward error correction (FEC) code for 10 Gbit/s PONs [21, 22]. The theoretical FEC relationship restores 1.1×10^{-3} pre-FEC BER to a 10^{-12} post-FEC in the PON standards. As it is shown in **Figure 9**, the PAM-4 modulated WDM-PON simulation scheme was created in OptSim simulation software environment. Here the Matlab software was used for BER estimation of received PAM-4 signals. WDM-PON simulation model consists of 4 channels, with central frequency 193.1 THz for second channel and chosen 50 or 100 GHz, according to the previously mentioned ITU G.694.1 rec. According to our previously channel interval research of flexible channel spacing like 37.5 and 25 GHz also was realized. However, the quality of received signal was low, with crosstalk impact and error-free transmission was not possible, performance was above our defined BER threshold 1×10^{-3}.

We evaluated the performance of WDM-PON architecture in terms of maximal transmission reach. Optical line terminal (OLT) is located in central office (CO) and consists of four transmitters (OLT_Tx). Each OLT_Tx transmitter consists of two pseudo-random bit sequence (PRBS) generators and NRZ drivers, as a result two

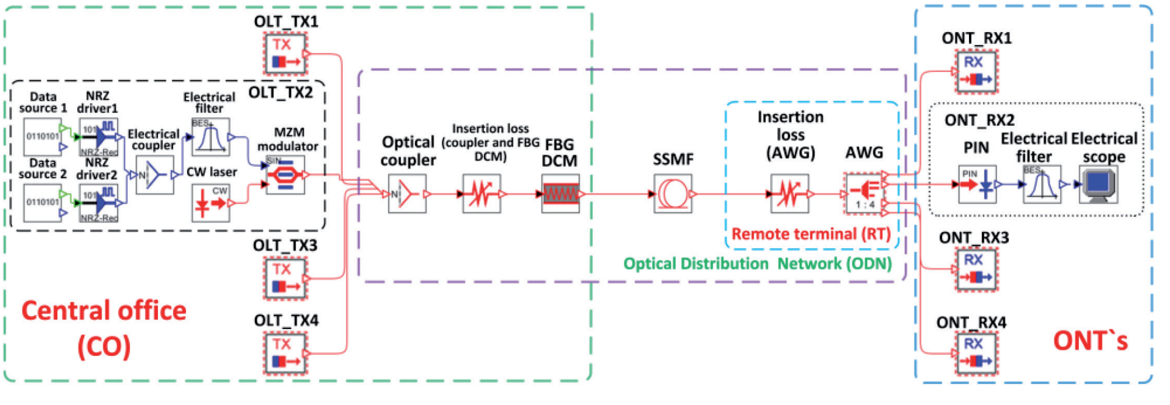


Figure 9.
Simulation scheme of 4-channel PAM-4 modulated WDM-PON transmission system operating at 10 Gbaud/s per wavelength.

electrical signals are generated where one of them has twice larger amplitude than other for each particular electrical signal. An electrical coupler is used to couple both electrical signals in such a way generating electrical PAM-4 signal. Afterwards, additional electrical filters were used for ensuring of optimal system performance. Generated PAM-4 signal was send to external MZM with 3 dB insertion loss and 20 dB extinction ratio. Continuous wavelength (CW) laser with linewidth of 50 MHz and output power of +3 dBm is used as the light source [23].

Optical signals from four transmitters are coupled together by using optical coupler with 1 dB insertion loss. Chromatic dispersion pre-compensation by FBG DCM, with additional 3 dB insertion loss is realized for all channels before launching optical signal in ITU-T G.652 single mode fiber (SMF), used for transmission in optical distribution network (ODN). After transmission in ODN, all channels are separated by arrayed waveguide grating (AWG) demultiplexer which insertion loss is 3.5 dB. Here we applied various channel spacings—50 or 100 GHz (3-dB bandwidth is 20 GHz) for research of the crosstalk impact. Each receiver of optical network terminal (ONT) consists of PIN photoreceiver (sensitivity is −19 dBm for BER of 10^{-12}). An optimal electrical Bessel low-pass filter (LPF) with bandwidth (3-dB bandwidth is 7.5 GHz), was adopted for more successful system performance. An electrical scope was used for evaluation of received signal bit patterns quality, accordingly, eye diagrams.

As it is shown in **Figure 10(a)** in B2B configuration for first investigated 100 GHz channel spacing, the signal quality is good, eye is open and error-free transmission can be provided. After 59 km transmission which was the maximum transmission distance without use of FBG DCM, the BER of received signal was 7.5×10^{-4}, please see **Figure 10(b)**. Dispersion compensation FBG DCM module was implemented to evaluate transmission distance in terms of maximal reach. As it is shown in **Figure 10(c)** by using this technique of FBG DCM, the maximum achievable transmission distance 74 km was reached, where BER of received signal was 9×10^{-4}. Extra 15 km or 25.4% of link length was gained.

Therefore, basis on our research data we can conclude that narrower channel spacing for 4-channel PAM-4 10 Gbaud/s WDM-PON system is 50 GHz. As it is shown in **Figure 11(a)** in B2B configuration for second investigated 50 GHz channel spacing, the signal quality is good, eye is open and error-free transmission can be provided. After 58 km transmission, which was the maximum transmission distance without use of FBG DCM, the BER of received signal was 8×10^{-4}, shown in **Figure 11(b)**. In our research we show the eye diagrams of received signal for the second channel, the drop in BER performance can be explained by the impact of crosstalk between channels. Dispersion compensation FBG DCM module was

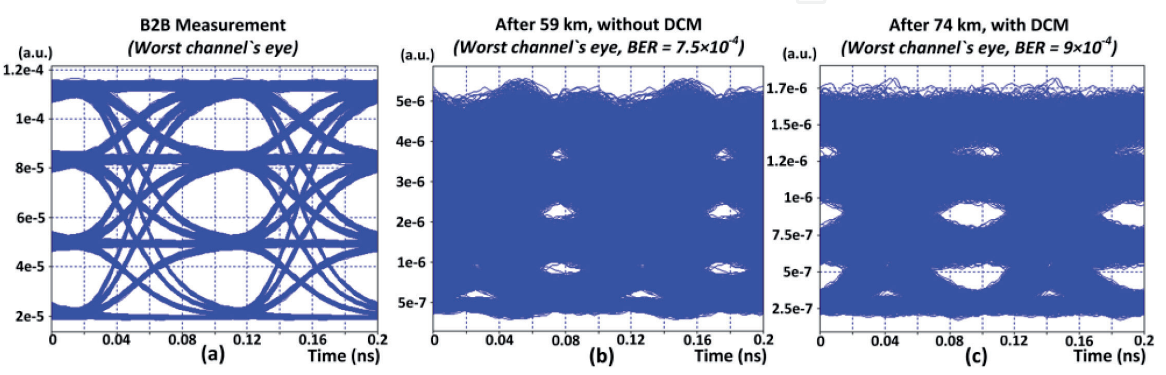


Figure 10.
Eye diagrams of received signal (a) after B2B transmission, (b) after 59 km transmission without use of CD pre-compensation, (c) after 74 km transmission with use of CD pre-compensation for 4-channel 20 Gbit/s per channel PAM-4100 GHz spaced WDM-PON transmission system.

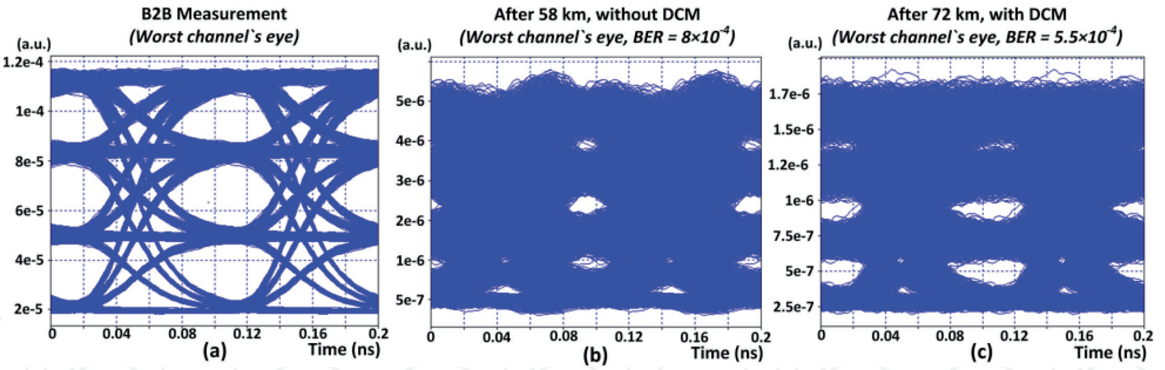


Figure 11.
Eye diagrams of received signal (a) after B2B transmission, (b) after 58 km transmission without use of CD pre-compensation (c) after 72 km transmission with use of CD pre-compensation for 4-channel 20 Gbit/s per channel PAM-4 50 GHz spaced WDM-PON transmission system.

implemented to evaluate transmission distance in terms of maximal reach. As it is shown in **Figure 11(c)**, by using this technique of FBG DCM, the maximum achievable transmission distance was 72 km, with BER of received signal 5.5×10^{-4}. Extra 14 km or 24% of link length was gained.

It was shown, that maximal transmission distance with BER below FEC limit of 10^{-3} for 100 GHz spaced 4-channel PAM-4 WDM-PON system can be increased by 15 km or 25.4% by use of implemented FBG DCM. In case of 50 GHz channel spacing, maximum transmission system reach can be increased by 14 km or 24% by use of FBG DCM.

4. Evaluation of PAM-4, NRZ and duobinary modulation formats performance in WDM-PON system architecture

In case of research we improve our previously made 4-channel PAM-4 WDM-PON system simulation model capacity by increasing number of multilevel channels and implement the use of different modulation formats in terms of system performance by maximal achievable reach. Several modulation formats have been proposed in the past and have become standards. In this research are investigated several modulation formats for use in WDM-PON architecture-based system, like NRZ, PAM-4 and duobinary (DB). Alternative solution instead widely used direct detection on-off keying modulation format NRZ-OOK with physical bandwidth limitations is to use more spectrally efficient multi-level formats such as PAM-4 [24, 25]. Another way to improve the bandwidth efficiency and reduce channel spacing is by using duobinary modulation format [12]. The most important feature of this multi-level modulation format duobinary is a viability of usage for longer transmission distances without regeneration with high tolerance to chromatic dispersion CD influence. As we know duobinary is used to increase the channel capacity by improving the bandwidth utilization [13].

The goal of our created 8-channel 20 Gbit/s per channel WDM-PON simulation model evaluate maximum transmission reach using different modulation formats, discussed previously in this paper like NRZ, PAM-4 and perspective duobinary modulation format. As it is shown in **Figure 12** the 8-channel WDM-PON simulation scheme with different optical transmitters (Tx) located in CO Optical Line Terminal (OLT_Tx) part for each modulation format realization are shown. According to ITU-T G.694.1 rec. Frequency with grid central frequency of 193.1 THz and channel spacing of 50 and 100 GHz are chosen for research of crosstalk impact on modulation formats under research [26].

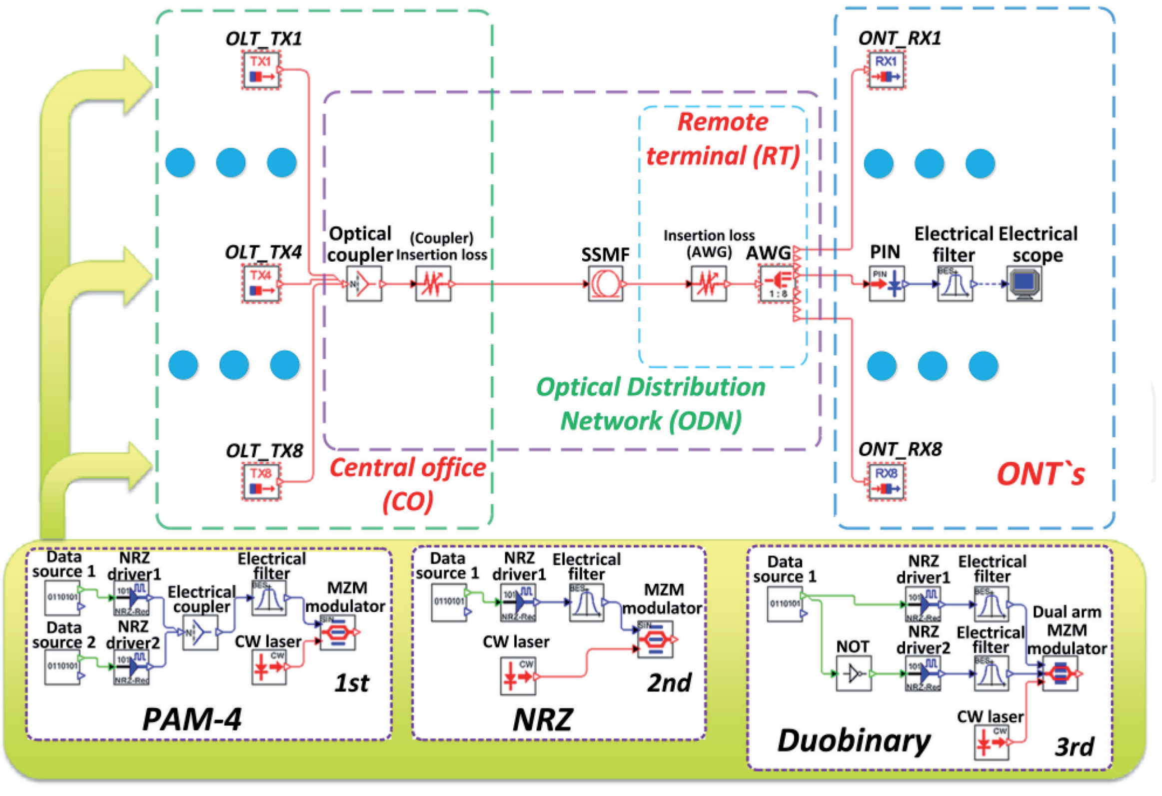


Figure 12.
Simulation scheme of 8-channel 20 Gbit/s transmission speed per channel PAM-4, DB and NRZ modulated WDM-PON optical transmission system.

In first simulation model PAM-4 transmitter is designed like previously, from two 10 Gbit/s NRZ coded electrical data signals (where one of them has twice larger amplitude), by coupled together with electrical coupler. Coupled PAM-4 electrical signal filtered with electrical Bessel low-pass filter (3-dB bandwidth is 10 GHz) and send to external MZM [21].

Second simulation model duobinary transmitter was realized with 20 Gbit/s bit rate per channel. Data source element with pseudo random bit sequence (PRBS) has only one logical output, where the output signal is divided in two signals. One of those signals is inverted by logical NOT element. Afterwards each data signal sent to NRZ drivers and filtered by Bessel low-pass filters (3-dB bandwidth is 5 GHz). Each NRZ coded electrical signal is passed to inputs of dual-arm MZM, at the end forming the DB transmitter [27].

Third simulation model NRZ transmitter consists of one NRZ driver with electrical signal input of data source with PRBS sequence. Afterwards NRZ coded data signal are directly connected to MZM RF signal input.

Following fixed parameters of optical and electrical elements was used: continuous wavelength (CW) laser output power + 6 dBm, extinction ratio 20 dB and 3 dB insertion loss of MZM, ITU-T G.652 SSMF with dispersion coefficient 17 ps/(nm × km), dispersion slope 0.056 ps/nm^2 × km and 0.2 dB/km attenuation coefficient [28]. Bandwidth of electrical LPF filters has been adjusted for optimal performance of each modulation format and have not been changed during research.

Each receiver consists of 40 GHz PIN photodiode with sensitivity equal to −19 dBm at 10 Gbit/s reference bit rate, dark current of 10 nA and responsivity of 0.8 A/W [29]. An electrical LPF filter bandwidth was adopted at receiver side for more successful system performance depending on the used modulation format. During the simulations LPF bandwidth of 15 GHz was chosen for PAM-4 modulated signals, and 10 and 17 GHz for DB and NRZ modulated electrical signals.

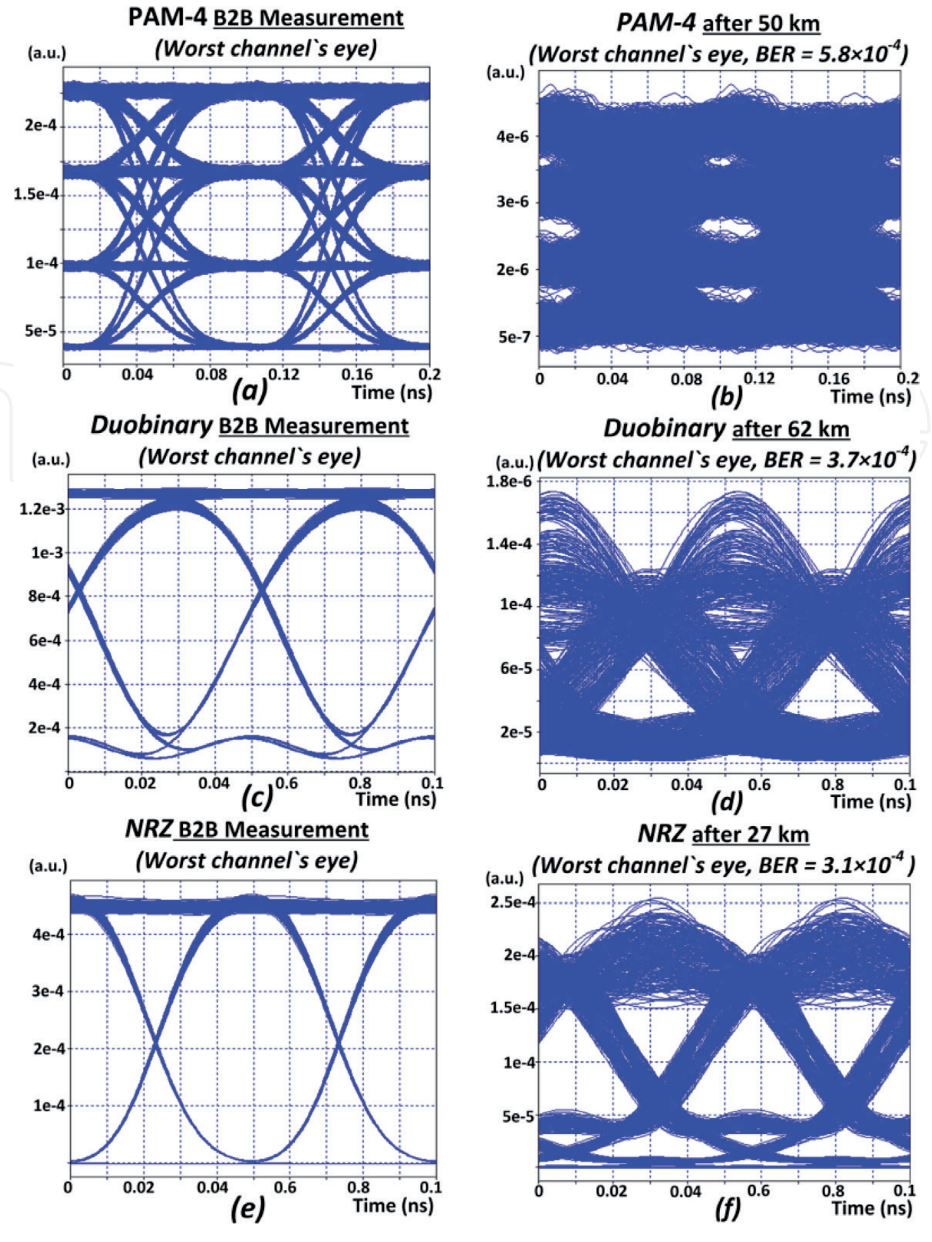


Figure 13.
Eye diagrams of received (a) PAM4, (c) DB and (e) NRZ signals after B2B transmission, and after maximal reached transmission distance: (b) 50 km with PAM-4, (d) 62 km with DB, (f) 27 km with NRZ modulated signals for 8-channel 20 Gbit/s per channel WDM -PON transmission system.

The BER threshold of 10^{-3} with additional FEC was used for our investigated WDM-PON transmission system to compare performance in terms of maximal network reach for PAM-4, DB, NRZ modulated optical signals. During the simulations it was observed that maximal achievable distance has minimal crosstalk impact on BER for all modulation formats, which was negligible, depending on our chosen channel spacing.

As it is shown in **Figure 13(a, c** and **e)** in B2B configuration for narrowest investigated 50 GHz channel spacing, the signal quality is good, eye is open and error-free transmission can be provided. After transmission the BER of received DB modulated signal with maximum reached distance of 62 km was 3.7×10^{-4}. PAM-4 and NRZ modulated signals shows 50 km and 27 km maximal reached transmission distance, where BER of received signal was 5.8×10^{-4} and 3.1×10^{-4}, please see **Figure 13(b, d** and **f)**. The largest network reach with BER below defined threshold, was provided by DB modulation format, extending the reach of 62 km.

5. Conclusions

Nowadays the WDM-PON systems rely on fixed wavelength transmitters and are expected to become more cost-efficient at high per user data rates. It was examined that different types of optical modulation formats are available for passive WDM fiber optical access networks. Implementation and research of multilevel modulation formats like PAM-4 and duobinary can dramatically improve the spectral efficiency and available bitrate by using the bandwidth of already existing optical, electro-optical or electrical devices. Theoretical simulations and experimental research methods showed possibility to double the available transmission speed in optical access networks by using the same bandwidth, e.g., instead of 10 Gbit/s transmit 20 Gbit/s signal by using 10 GHz electrical and electro-optical equipment, if PAM-4 modulation method is used. In our research we investigated existing optical modulation formats—widely used NRZ, DB and PAM-4 for optical access networks, by experimentally demonstrating and modeling system transmission in RSOFT OptSim simulation environment and Matlab software. As it shown by simulation results, narrowest channel spacing provides higher spectral efficiency. However, better signal quality and system performance are achieved with larger channel spacing interval, e.g., 100 GHz, mainly due to crosstalk between channels. From experimental data we can clearly see that the chromatic dispersion limits transmission capacity when bit rates increase. Implementation of the efficient compensation solution may sufficiently extend the reach of optical link and improve the transmission quality in our investigated WDM-PON systems.

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