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Hierarchical modulation PAM4 with digital Nyquist pulse-shaped for flexible multi-ONU provisioning in NG-TDM PON

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ABSTRACT

In this paper, we study the performance of digital Nyquist-shaped and hierarchical modulation four-level pulse amplitude modulation (N-HM-PAM4), which is one of the most cost-effective modulations, in the context of the intensity-modulation and direct-detection (IM/DD) enabled the next generation time division multiplexed passive optical network (NG-TDM PON). In addition, by considering the power fading (which is incurred by the chromatic dispersion (CD)) and linear and nonlinear inter-symbol interference (ISI) (which is incurred by CD and square-law photo-detection) during the transmission, vestigial side band (VSB) optical equalization, overlap frequency-domain equalization (OFDE), and iterative nonlinear ISI digital domain compensation are applied in the system to improve both bandwidth efficiency and receiver sensitivity. Simulation results show how different parameters of the N-HM-PAM4 based NG-TDM PON (i.e., optical modulation index (OMI), iterative cancellation number, power ratio, and the distance between the optical line terminal (OLT) and its optical network units (ONUs)) affect the performance of the system, which is defined as the bit error ratio (BER) and received optical power (ROP) of the ONU.

1. Introduction

In order to cope with the ever-increasing data traffic demands in flexible and high speed next generation time division multiplexed passive optical networks (NG-TDM-PONs), various advance modulation formats and detection schemes have been proposed to increase the channel capacity without significantly increasing the cost of transceivers [1,2]. From the modulation formats perspective, various flexible modulation formats, such as discrete multi-tone modulation (DMT), Nyquist subcarrier modulation (SCM), carrier-less amplitude and phase modulation (CAP), and M-ary multiple level pulse amplitude modulation (PAM-M), have been investigated [3–5]. Among these modulations, PAM4 is a very attractive modulation scheme due to its low cost [5–7] and simple-to-deploy in the NG-TDM-PON system [6–12]. In order to increase the spectrum efficiency (SE), Nyquist PAM4 [13–17], which applies Nyquist shaping in the modulation scheme, was proposed and widely used in short-range communications. From the detection perspective, as compared to coherent detection, intensity modulation and direct detection (IM/DD) is considered as one of the most competitive candidates for the practical implementation in a high-speed and cost-effective PON system [18]. However, one major drawback of IM/DD is that the performance is significantly degraded owing to the power fading (which is incurred by the chromatic dispersion (CD)) and linear and nonlinear inter-symbol interference (ISI) (which is incurred by CD and square-law photo-detection) [19–23]. Those types of impairment may significantly distort the signal, thus reducing the channel capacity. To overcome the drack, advanced compensation techniques to mitigate impairments in IM/DD were designed for NG-TDM-PONs [10–15].

In addition, owing to different path loss characteristics, the signal-to-noise ratios (SNRs) from an optical line terminal (OLT) to its connected optical network units (ONUs) may vary in NG-TDM PON. The available channel capacities from the OLT to its connected ONUs are determined by the worst SNR among the SNRs between the OLT and its ONUs. This leads to the issue that some ONUs, which have the high SNRs, still incur low available channel capacities. Hierarchical modulation (HM) [24] is proposed to solve this issue. Basically, HM can dynamically adjust the modulation scheme based on the SNR value from the OLT to its ONU. Applying HM in NG-TDM PON has been demonstrated to significantly improve the link capacity and power budget [29–30]. The HM-PAM4 technique in [30] is similar with the basic principle of non-uniform PAM4 [31–35], which adjust Euclidean distances between the constellation levels according to the SNR of an optical link.

Both Nyquist PAM4 and HM techniques can improve the

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performance of NG-TDM PON in different perspectives. However, previous works do not conduct the performance analysis on the Nyquist pulse-shaped hierarchical PAM4 (N-HM-PAM4) scheme by applying IM/DD as the optical detection solution. Furthermore, the relationship between N-HM-PAM4 and the advanced impairment compensation techniques has not been investigated in NG-TDM PON. The major contributions of the paper are listed as follows. 1) At the OLT side, we apply the new modulation scheme, i.e., N-HM-PAM4 (which incorporates Nyquist PAM4 into HM), to improve the SE of the link from an OLT to its ONUs. In addition, at the ONU side, we apply the required digital signal processing (DSP) including the linear overlap frequency-domain equalization (OFDE) and iterative nonlinearities cancellation functionalities to compensate the channel's impairment and achieve a high power budget transmission. 2) We investigate the performance of N-HM-PAM4 in terms of bit error ratio (BER) and the received optical power (ROP) by the varying some system parameters such as optical modulation index (OMI), iterative cancellation number, power ratio, and the distance between the OLT and its ONU.

This paper is organized as follows. In Section 2, we summarize the related works. In Section 3, we illustrate the principle of the N-HM-PAM4 modulation with key components of DSP in a transceiver. In Section 4, we illustrate the simulation setup and analyze the simulation results. The paper is concluded in Section 5.

2. Related work

In this section, we provide an overview of HM in optical access network and illustrate the impact of impairment equalizations as well as other related concepts in the existing works.

2.1. A HM-PAM4

Many works have investigated to apply HM in the NG-TDM PON system [24–30]. Iiyama et al. applied a new HM constellation, which combines the On-Off keying (OOK) modulation (where a traditional ONU can be used to demodulate OOK signals) and the upgraded modulation, such as PAM (where an ONU should be upgraded to demodulate PAM signals), in an OLT. Santa et al. [30] implemented a low-cost interleaved detection scheme to detect the HM-PAM4 signal in the downstream scenario. In the proposed detection scheme, higher order modulations are used by the link between an OLT and an ONU with sufficient power margins, and lower order modulations are used by the link between an OLT and an ONU with lower power margins. Linden et al. [31–35] studied and developed the adaptive non-uniform PAM4 constellation scheme. This scheme is realized by pairing most-significant-bit (MSB) and least-significant-bit (LSB) sub-streams onto one PAM4 symbol. In addition, they made comparison analysis between PIN-photon detector and avalanche photodiode (APD) based transmission. However, according to the survey of these previously examined compensation methods, few researchers have considered configration of applying the N-HM-PAM4 modulation/demodulation scheme by using a digital Nyquist pulse shaped filter at the OLT side. In addition, the N-HM-PAM4 complemented with distortion compensation algorithm is used at the ONU side to mitigate the signal distortion problem in the IM/DD detection scheme.

2.2. The description of the signal distortion

Given the distance between an OLT and its ONUs, the performance of the system is degraded owing to the signal impairments, which result from power fading and linear/nonlinear ISI. Different equalization technologies have been implemented in NG-TDM-PON to mitigate signal impairments.

First, signals in IM/DD suffer from the power fading over the transmission frequency. Thus, in order to extend the transmission distance, applying vestigial side band (VSB) filer is used to reduce CD

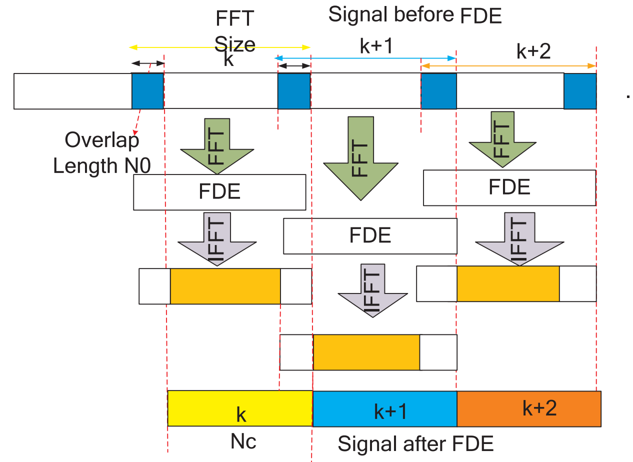

Fig. 1. The principle of HM-PAM OFDE.

induced power fading effects by eliminating one of the sidebands of signals [36–39].

In addition, applying an OFDE filter between an OLT and an ONU was demonstrated to significantly reduce the linear ISI [40–43]. Fig. 1 shows the basic principle of an OFDE filter. The incoming digital data streams are first divided into data blocks, which are then transformed from the time domain into the frequency domain by applying fast Fourier transform (FFT). The block length N_{FFT} equals N_0 + Nc, where N_0 is the length of overlap samples (which is a part of the block) and Nc is the length of samples of current data block. After the equalization, a frequency domain data block is then multiplied with a inverse channel transfer function. Afterwards, the block is transformed back from the frequency domain into the time domain by applying inverse FFT (IFFT). In order to avoid the cyclic problem in FFT, the overlap samples N_0 in a block is discarded. Thus, the rest of samples Nc are stored as equalized results.

Furthermore, signals in IM/DD suffer from the nonlinear ISI, which is also called signal-signal beat interference (SSBI). With respect to the nonlinear ISI cancellation techniques, the symbol pre-distortion algorithm [21], nonlinear *p-th* order pre/post-Volterra equalizer [23], and the iterative ISI cancellation algorithm [22] can be applied to compensate the nonlinear ISI and improve the overall performance. Among these schemes, the iterative ISI cancellation has the highest performance. The process of the iterative ISI cancellation scheme is shown in Fig. 2. Specifically, after the FFT operation, the signal *I(k)* is conducted the normal demodulation process. That is, the signal *I(k)* will be transmitted to an OFDE equalizer, which can significantly reduce the linear ISI in the signal *I(k)*, and the decision module. Then, the detected signal $\hat{D}^{(i)}(k)$ are used to reconstruct the nonlinear ISI, and the calculated results are return as feedback to cancel the nonlinear ISI in the sigal *I(k)*. Then, the signal *I(k)* after the nonlinear ISI cancellation are demodulated again, and the iterative process would get the more accurate demodulated signals (i.e., less interference).

In order to achieve a higher compensation, the joint linear and nonlinear equalization solution can be taken into account. In previous works, Liu et al. proposed a Nyquist SCM modulation by using digital filter and linear OFDE and iterative equalization algorithm [16]. Ju et al. proposed a Nyquist PAM4 modulation by using an analog filter and the linear FDE and iterative equalization algorithm [17].

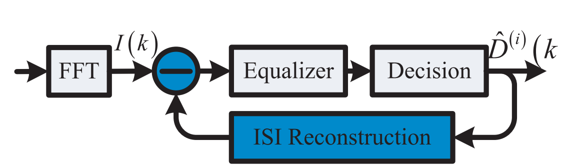

Fig. 2. Iterative ISI Cancellation Process.

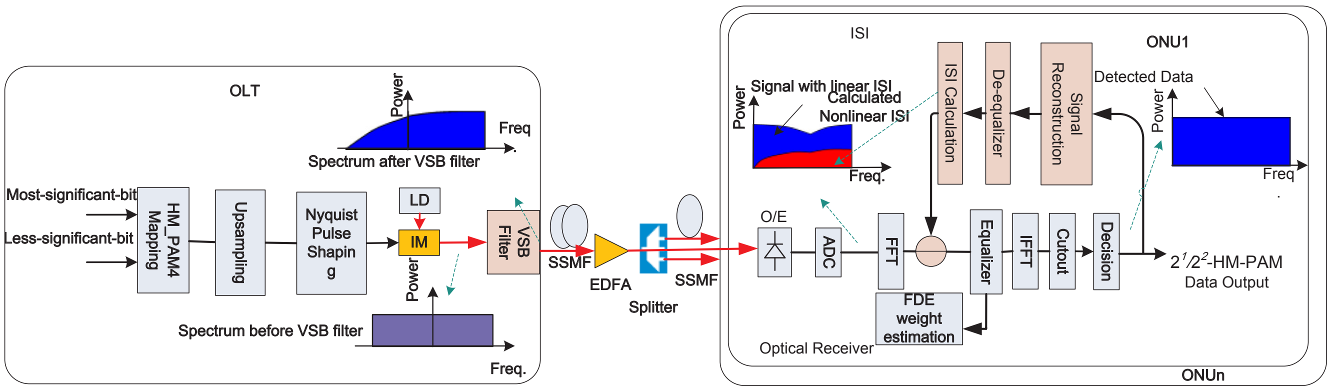

Fig. 3. The N-HM-PAM4 modulation in downstream NG-TDM PON.

In this paper, at the OLT side, we describe an N-HM-PAM4 mapping constellation with unequal level Euclidean distances to modulate data based on digital filter shaping. Meanwhile, at the ONU side, the linear OFDE and nonlinear iterative ISI cancellation equalization methods are adopted in order to signtificantly compensate the signal distortion.

3. System and signal models

Fig. 3 illustrates the N-HM-PAM4 modulation in the downstream scenario in NG-TDM PON. The architecture allows multiple ONUs to communicate with the same OLT based on a splitter. In the downstream scenario, different ONUs share the same wavelength to download their data from the OLT in the TDM manner. That is, each ONU is allocated a specific time slot to download its data from the OLT. Note that the channel condition between *an* ONU and its OLT can be indicated by the ROP. Without loss of generality, we will illustrate the N-HM-PAM4 modulation by considering the case that there are two groups of ONUs connecting to the same OLT. The ONUs from the same group have the same SNR with respect to the OLT, and the ONUs from different groups have different SNRs. The ONUs are indexed based on their SNR to the OLT. Denote R_i as the data rate of transmitting data from the OLT to ONU i. The value of R_i depends on the SNR between the OLT and ONU i as well as the other parameters (i.e., modulation format and DSP). Assume that each ONU requires a different BER and data rate. The basic idea of the N-HM-PAM4 modulation architecture is to adjust the related power ratio based on the SNR value between the ONU and the OLT such that the required BER and data rate of the ONU is satisfied. Specifically, at the OLT side, the transmitted bits are divided into two sub-streams, i.e., MSB and LSB sub-streams. The high important/priority bit will go to the MSB sub-stream and the low important/priority bit will go to the LSB sub-stream. We denote the two-layer $2^n/2^m$-HM-PAM modulation [44], i.e., the first n bits in the first layer and the rest m-n bits in the second layer. Thus, $2^n/2^m$ HM-PAM has m levels of real constellation points. The fictitious constellation points in level-i ($i < m$) represents symbols corresponding to the i-th bit. Fig. 4 shows an example of $2^1/2^2$-HM-PAM. The HM-PAM $2^1/2^2$ (PAM 2/4) is implemented in two layers, i.e. the two PAM2 sub-streams are merged in the same symbol.

The value of parameter α in HM-PAM 2/4 determines the priority of the bits. Here, $\alpha = 2d_1/2d_2$, where $2d_1$ and $2d_2$ represent the distance between the points in the first and second level of hierarchy, respectively. The decision boundary for MSB is 0. Meanwhile, the decision boundary for LSB depends on the middle threshold of the labeled constellation points. Thus, $2^n/2^m$-HM-PAM is a generalized PAM with flexible Euclidean distance among constellation points. In a more general case, the extension of two-layer HM-PAM 2/4 on both inphase (I) and quadrature (Q) axis can be considered as the corresponding generalized HM quadrature amplitude modulation (QAM). The expectation of BER in additive white gaussian noise (AWGN) for both HM-PAM 2/4 and HM-QAM were analyzed in [44]. Thus, HM-PAM 2/4 allows the

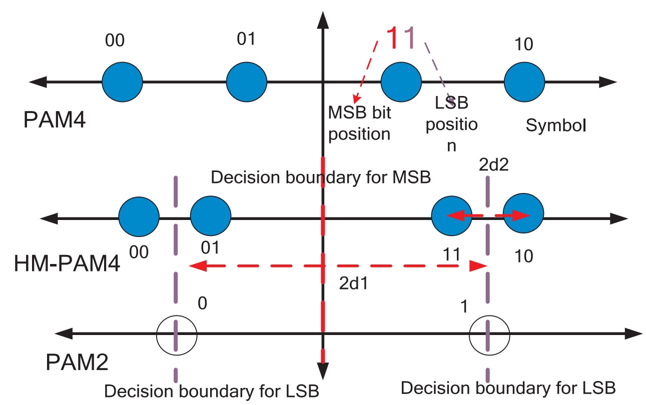

Fig. 4. The principle of HM-PAM $2^1/2^2$.

simultaneous transmission data from the OLT to different ONUs by overlapping the constellation points of the ONUs in the OLT. In particular, the power ratio χ is a function of the minimum opening of the three eyes in the process of generating symbol constellation diagram C, which can be represented by Eq (1) [32]. Here, χ indicates the amount of the inner constellation levels moving toward the outer constellation levels in HM-PAM 2/4.

$$C = [-3, -1 - (2\chi), 1 + (2\chi), 3], \ 0 \leqslant \chi \leqslant 1. \tag{1}$$

When $\chi = 0$, the constellation levels are equal to uniform PAM (without HM). When $\chi = 1$, the inner levels completely overlap with the outer levels, and thus PAM 2/4 degrades to PAM2. As a result, the generated MSB and LSB data are assigned to the group of ONUs with high SNR and low SNR, respectively. The flexible modulation level allocates a portion of the high order HM-PAM2/4 format to each ONU. As a result, instead of decoding 2 bits per symbol for a single ONU, all of the ONUs can simultaneously decode 1 bit encoded with the same HM-PAM4 format. That is, some MSBs can be decoded successfully at a lower ROP. Then, in order to encoded data with N-HM-PAM4, the digital domain root-raised-cosine (RRC) shape spectrum filter with a roll-off factor is used. The encoded data are sent to a digital-to-analog converter (DAC), an intensity modulator (IM), and a VSB filter sequentially. After the optical signal transmitted over the standard single-mode fiber (SSMF), an erbium doped fiber amplifiers (EDFA) is used in the link to compensate for the power fading of optical signals. At the ONU side, as shown in Fig. 3, a photo detector (PD) is used to convert the optical signal into the electrical signal, which is further converted into digital signal based on an analog-to-digital converter (ADC). Then, FFT is applied to implement OFDE in the frequency domain. After equalization, an IFFT operation is performed to obtain the time-domain channel estimation. The derived time-domain channel estimation is based on the training process. Then, the signal after equalization is

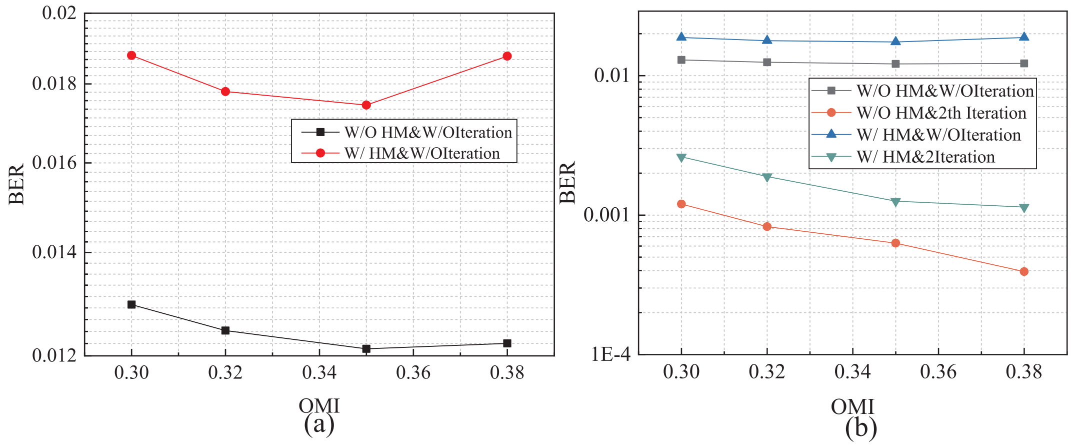

Fig. 5. The measured BER versus different OMI values after 100 km transmission (a) with and without HM (b) iterative cancellation conditions.

decoded. Note that to mitigate the nonlinear ISI, an N-HM-PAM4 signal is carried out channel reconstruction. The reconstructed N-HM-PAM4 signal is conducted by inverse equalization. Finally, the nonlinear ISI is calculated, which is the key of the whole iterative algorithm. The estimated nonlinear ISI is obtained through the nonlinear ISI calculation module [17], and the calculated nonlinear ISI is subtracted from the signal before conducting channel equalization. Thus, the nonlinear ISI is removed from the received signal. In each iteration, the channel equalization and symbol decision will be conducted over the signal to improve the signal demodulation accuracy (i.e., reduce BER). Followed by the offline DSP, the N-HM-PAM4 modulated signal can be successfully classified and decoded by corresponding ONUs. The demodulation approach first extracts the MSB sub-stream from the received signal. For the ONUs that only require to demodulate the MSB sub-stream, a single-threshold receiver is sufficient. However, for the ONUs that require to demodulate both the MSB and LSB sub-streams, implementing a dual-threshold receiver is required. Note that, in our previous work [45], we have discussed the performance of MSB and LSB substreams by applying N-HM-PAM4, where Nyquist pulse shaping is implemented in the analogy electric domain and only the linear ISI cancellation technology is applied. In this paper, we are focusing on the performance of LSB substeams by applying N-HM-PAM4, where Nyquist pulse shaping is implemented in the digital electric domain and both linear ISI and nonlinear ISI cancellation technologies are used to mitigate the interference.

4. Simulation and results

Simulations are comprehensively conducted to evaluate the performance of the proposed N-HM-PAM4 scheme in the NG-TDM PON system. Note that DSP is used in the OLT and ONUs for signal generation and detection in the simulation.

At the OLT side, two pseudo-random binary-sequences (PRBS) with the order of 15 are used to generate two MSB and LSB sub-streams, respectively, and the amplification power of the MSB and LSB sub-streams are set up independently. The HM-PAM4 sequence (with the length of 32,768 symbols) is up-sampled twice and applied a RRC filter with the roll-off factor equal to 0. The number of FFT points is 1024 and the guard interval is 1/64 of the symbol duration. A 20 GSa/s DAC is used and is driven by the N-HM-PAM4 signal sending from the OLT. Also, an externally modulated electro-absorption modulator (EAM), which is driven by the N-HM-PAM4 signal, is applied in the simulation. In addition, a tunable laser operating at 1550 nm is used as the light source. The transmission power of the OLT is 4 dBm. The chirp parameter of the EAM is set to be 0. The VSB filter has a profile of a 1.35th-order Gaussian and 21.7 GHz of 3 dB bandwidth [16–17]. The signal propagates over the SSMF with CD and nonlinear index value equal to 17 ps/nm/km and 2.6e − 20, respectively. EDFAs are used to amplify the signal transmitted from the OLT. Moreover, an optical band pass filter is used in the ONU to reduce the amplified spontaneous emission (ASE). In addition, a variable optical attenuator (VOA) is used to emulate the additional power splitter insertion losses.

At the ONU side, shot and thermal noise are considered to be the dominant noise. A square root of the power spectral density (PSD) of the current thermal noise is assumed to be 10 $(pA/HZ)^{1/2}$. Here, the BER and the ROP are considered as the key performance of the NG-TDM PON system. Normally, for both MSB and LSB sub-streams, the BER threshold (i.e., 3.8e − 3) is defined by the 7% overhead of hard decision forward error correction (HD-FEC) Section 3. In the N-HM-PAM4 scheme, the MSB substreams received by an ONU are easy to be demodulated. In order to guarantee the ONU able to successfully demodulate the LSB substreams with an acceptable level, the ROP of the ONU should be high enough. Therefore, we mainly consider the BER of demodulating the LSB substreams in the ONU by varying several system parameters (i.e., OMI, the number of iterative cancellations, optical power ratio, and the distance between ONUs and OLT) in the HM enabled NG-TDM PON system.

4.1. Comparison of BER by varying OMI

Noted that OMI is defined as the ratio of root mean square for the N-HM-PAM4 signal's current to the half of the peak modulation of a direct current (DC) bias. Thus, OMI can be adjusted by varying the transmitted power of the signal. Fig. 5(a) shows how the BER changes by varying the OMI value when the distance between the OLT and the ONU is 100 km and the received optical power is − 14 dBm.

From the figure, we can derive that the optimal OMI values with and without HM are both 0.35. This is because a smaller OMI value leads to a larger signal noise penalty, thus increasing BER; however, a larger OMI value results in a higher transmission power, which increases nonlinear ISI, and thus increases BER. Next, we compare the measured BER by varying the value of OMI. Fig. 5(b) shows the measured BER of the LSB sub-streams when iterative nonlinear ISI cancellation technique is and is not applied. From the figure, we can see that when iterative ISI cancellation is not applied, the achieved BER is above the BER threshold owing to the severe residual nonlinearity characteristic. When the nonlinear iterative ISI cancellation technique is applied, the measured BER is significantly reduced and below the BER threshold. Note that the measured BER does monotonically change with respect to OMI. Thus, it is necessary to find the optimal OMI to minimize BER in both scenarios (i.e., HM with and without iterative ISI cancellation), which will be our future works.

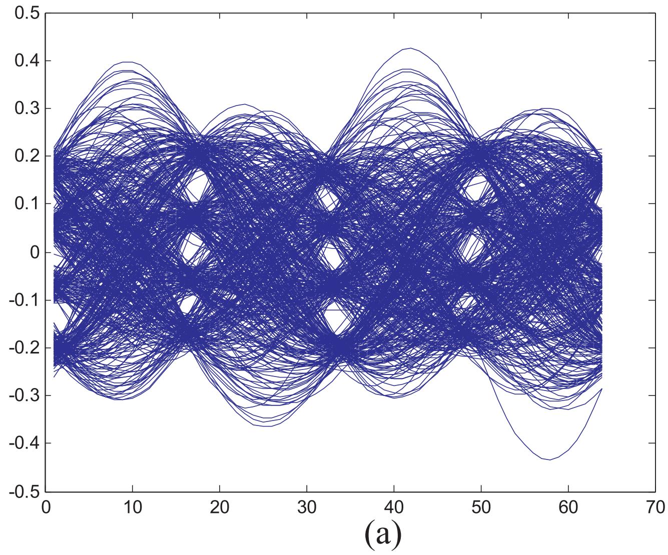

Fig. 6. (a) The measured eye diagrams of N-HM-PAM4 signals for LSB under (a) 0 (b) 0.1 power ratio values.

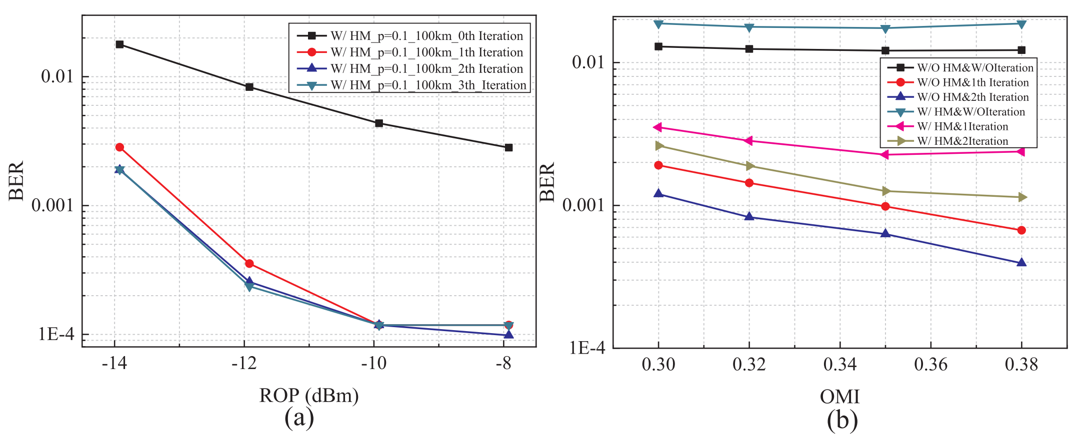

Fig. 7. The measured BER versus (a) ROP at a certain power ratio (b) OMI with/without HM after 100 km transmission.

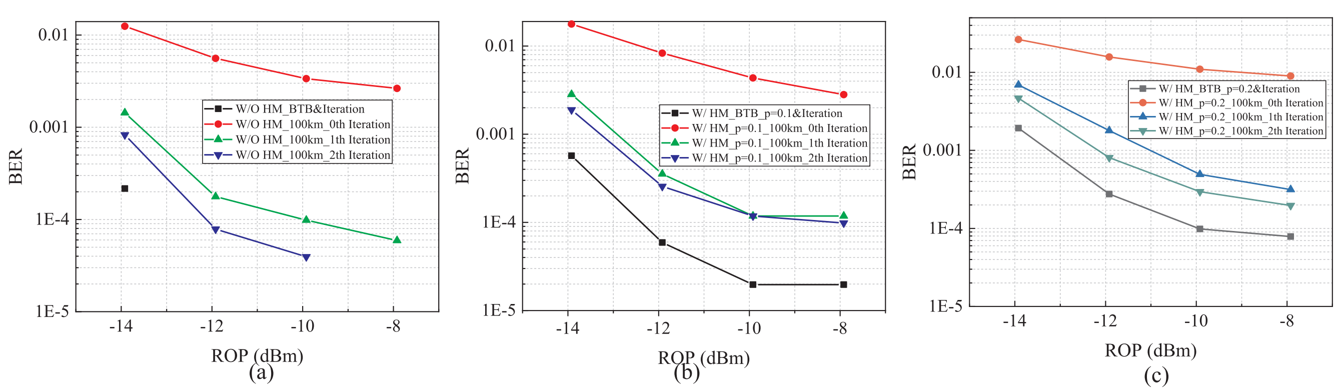

Fig. 8. The measured BER of LSB versus ROP after B2B and 100 km transmission (a) without HM (b) with HM at a 0.1power ratio (c) with HM at a 0.2 power ratio.

4.2. Comparison of eye diagrams of receiver by varying power ratio

We make a comparison of the received eye diagrams at the BER of 3.8e−3 (the 7%-overhead HD-FEC limit). Fig. 6(a) and (b) shows the eye diagrams of the N-HM-PAM4 signal with the power ratio of 0 and 0.1, respectively, where the transmission distance is 100 km. Since PAM-4 signals have four constellation levels, we can see three inter-dependent open eyes. From Fig. 6(a), we can find that the power intervals in the eye diagram are the same when the power ratio is 0. This essentially means that the eye diagram with respect to the PAM4 signal is equally spaced if HM is not applied. From Fig. 6(b), we can derive that the power intervals in the eye diagram are unequally spaced, which proves that the overall asymmetric PAM4 signal amplitude with enhanced opening of the middle eye and reduced upper and lower eyes can be generated by adjusting these relative amplitudes. Thus, the N-HM-PAM4 scheme shows non-uniform level distances. We can conclude that the N-HM-PAM4 scheme utilizes unequal distances between its modulation levels. The HM scheme can provide better protection of the

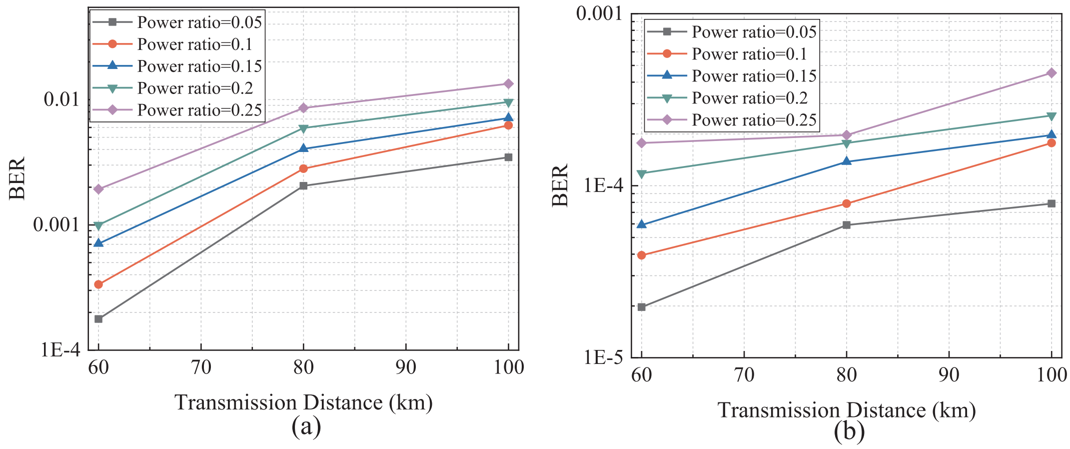

Fig. 9. The measured BER curves of LSB vs SSMF transmission distance for various power ratio (a) without iterative ISI cancellation (b) with iterative ISI cancellation.

higher priority sub-stream at the expense of providing worse protection of lower priority sub-stream by appropriately manipulating the constellation mapping. That is, enlarging the middle constellation distance can reduce BER of the first bit and increase BER of the second bit in an N-HM-PAM4 symbol.

4.3. Comparison of BER by jointly varying OMI and iterative cancellation number

Next, we will investigate how the proposed nonlinear iterative ISI post-digital compensation technique (which is mentioned in Section 2) impacts the performance of the system. Consider the scenario that the optical signal is transmitted from the OLT to the ONU over a 100 km SSMF and the power ratio is set to be 0.1. Fig. 7(a) shows BER by varying the ROP and the power patio.

From the figure, we can see that applying the nonlinear ISI cancellation can significantly reduce BER. Meanwhile, when the number of iterative cancellations increases, the BER value decreases accordingly. BER becomes relatively stable after the 2nd iterative cancellations. In addition, the iterative algorithm incurs a higher BER when the number of iterative cancellations continues to increase. Fig. 7(b) shows BER performance of the evaluated iterative algorithm by varying the OMI value when HM is and is not applied. The figure demonstrates that applying the iterative equalization can always reduce BER by selecting an OMI value. In addition, the HM constellation increases BER of the LSB sub-streams due to the fact that BER of the MSB sub-streams is reduced.

4.4. Comparison of BER and ROP by varying power ratio

In this section, we will evaluate the how the HM scheme and power ratio affects the performance of the system (in terms of the BER and ROP) under two scenarios, i.e., long-distance transmission (i.e., the optical signal is transmitted over a 100 km SSMF) and optical back-to-back (B2B) transmission. As shown in Fig. 8, the red curve always incurs the highest BER, which essentially indicates that once the iterative nonlinear ISI cancellation technique (i.e., the iterative algorithm) is applied, the BER of the LSB sub-streams can be reduced no matter whether HM is applied or not. Also, the system performance in the B2B transmission scenario is always better than that in the long-distance transmission owing to the B2B transmission incurs a higher SNR. In addition, from the figures, we can conclude that BER reduces as the power ratio increases once the HM scheme is applied.

As the power ratio increasing, BER of the LSB substreams is reduced. At the FEC limit (BER of $3.8e-3$), in case of without HM and nonlinear ISI compensation, the receiver sensitivity subject to 100 km transmission is -10.1 dBm. However, it is observed that the receiver sensitivities of LSB can be reduced by 2dBm when the power ratio is 0.1. The BER cannot satisfy the system requirements if the power ratio becomes 0.2.

4.5. BER under different transmission distance

We next evaluate the how the transmission distance (between an OLT and an ONU) and power ratio affect BER given the ROP value to be -7.91 dBm. Fig. 9(a) and (b) show the BER curves vs transmission distance without and with applying nonlinear ISI cancellation, respectively. Here, the selected optimal iterative cancellation number is two.

From Fig. 9, we can see that as the SSMF transmission distance increases, the SNR at the ONU reduces, and thusBER increases. By comparing Fig. 9(a) and Fig. 9(b), we can see that the linear and nonlinear ISI technology can significantly reduce BER. In addition, as the power ratio increases, the BER of the LSB sub-streams is significantly reduced, which is consistent with the results generated in previous simulations.

5. Summary

It is very challenging to achieve high optical power budget of PONs when these ONUs have different SNRs in the context of the NG-TMD-PON system. N-HM-PAM4 can apply different modulation formats to different ONUs based on the SNRs of the ONUs to improve the performance of the NG-TDM PON system. In addition, the OFDE and the iterative nonlinear ISI cancellation techniques are used to compensate for both linear and nonlinearities ISI in the NG-TDM PON system, and the performance improvement has been validated via extensive simulation. In the future, we will derive the optimal constellation mapping for the HM scheme.

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Appendix A. Supplementary data

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References

[1] K. Zhong, X. Zhou, J. Huo, et al., Digital signal processing for short-reach optical communications: a review of current technologies and future trends, J. Lightw.

Technol 36 (2) (2018) 377–400.
[2] K. Zhang, Q. Zhuge, H. Xin, et al. Demonstration of 50Gb/s/λ Symmetric PAM4 TDM-PON with 10G-class Optics and DSP-free ONUs in the O-band, in Proc. Opt. Fiber Commun. Conf. Exhib (OFC). (2018) pp. 1–3.
[3] K. Zhong, X. Zhou, T. Gui, et al., Experimental study of PAM4, CAP-16, and DMT for 100 Gb/s short reach optical transmission systems, Opt. Express 23 (2) (2015) 1176–1189.
[4] J. Yu, J. Shi, J. Zhang, et al., Transmission performance comparison for 100-Gb/s PAM4, CAP-16, and DFT-S OFDM with direct detection, J. Lightw. Technol 35 (23) (2017) 5127–5133.
[5] J. Shi, J. Zhang, N. Chi, et al., Comparison of 100G PAM-8, CAP-64 and DFT-S OFDM with a bandwidth-limited direct-detection receiver, Opt. Express 25 (26) (2017) 32254–32262.
[6] J Wei, K. Grobe, C. Wagner, et al. 40 Gb/s Lane Rate NG-PON using Electrical/Optical Duobinary, PAM-4 and Low Complex Equalizations, in Proc. Opt. Fiber Commun. Conf. Exhib(OFC). (2016)1-3.
[7] J Wei, E Giacoumidis. 40 Gb/s/λ optical amplified PAM-4 PON with transmission over 30 km SMF using 10-G Optics and simple DSP, in Proc. Opt. Fiber Commun. Conf. Exhib(OFC). (2017). Pp. 1–3
[8] J. Wei, N. Eiselt, H. Griesser, et al., Demonstration of the first real-time end-to-end 40-Gb/s PAM-4 for next-generation access applications using 10-Gb/s transmitter, J. Lightw. Technol 34 (7) (2016) 1628–1635.
[9] H. Zhang, S. Fu, J. Man, et al. 30km downstream transmission using 4 × 25Gb/s 4-PAM modulation with commercial 10Gbps TOSA and ROSA for 100Gb/s-PON, in Proc. Opt. Fiber Commun. Conf. Exhib. (OFC), Mar. (2014), pp. 1–3.
[10] J. Gao, N. Cheng, H. Zhang. Demonstration of the First 29dB Power Budget of 25-Gb/s 4-PAM System without Optical Amplifier for Next Generation Access Network, in Proc. Opt. Fiber Commun. Conf. Exhib. (OFC), Mar. (2016), pp. 1–3.
[11] S.M. Ghulam, M.O. Mohamed, H. Michael, et al., DSP-free 25 Gbit/s PAM-4 transmission using 10G transmitter and coherent amplification, IEEE Photon. Technol. Lett 30 (17) (2018) 1547–1550.
[12] X. Tang, J. Zhou, M. Guo, et al., 40-Gb/s PAM4 with low-complexity equalizers for next-generation PON systems, Opt. Fiber Technol. 40 (2018) 108–113.
[13] D. Rui, J. He, J. Yu, et al., Experimental demonstration of 20-Gb/s dual-band Nyquist PAM-4 transmission over a short-reach IMDD system using super-Nyquist sampling technique, Optic Lett. 43 (11) (2018) 2640–2643.
[14] N. Eiselt, D. Muench, A. Dochhan, et al., Performance comparison of 112-Gb/s DMT, Nyquist PAM4, and partial-response PAM4 for future 5G ethernet-based fronthaul architecture, J. Lightw. Technol 36 (10) (2018) 1807–1814.
[15] N. Kikuchi, R. Hirai. Intensity-modulated/direct-detection (IM/DD) Nyquist pulse-amplitude modulation (PAM) signaling for 100-Gbit/s/λ optical short-reach transmission. in Proc.European Conference on Optical Communication. (2014), pp. 1–4.
[16] N. Liu, X. Chen, C. Ju, et al., Nyquist 4-ary pulse amplitude modulation scheme based on electrical Nyquist pulse shaping and fiber Bragg grating filter, Opt. Eng. 54 (4) (2015) 046105.
[17] C. Ju, N. Liu, Iterative nonlinear ISI cancellation in optical tilted filter-based Nyquist 4-PAM system, Opt. Fiber Technol. 31 (2016) 42–46.
[18] K. Zhang, Q. Zhuge, H. Xin, et al., Intensity directed equalizer for the mitigation of DML chirp induced distortion in dispersion-unmanaged C-band PAM transmission, Opt. Express. 25 (23) (2017) 28123–28135.
[19] G. Karam, H. Sari, Analysis of predistortion, equalization, and ISI cancellation techniques in digital radio systems with nonlinear transmit amplifiers, IEEE Trans. Commun. 37 (12) (1989) 1245–1253.
[20] C.C. Wei, Small-signal analysis of OOFDM signal transmission with directly modulated laser and direct detection, Optics Lett. 36 (2) (2011) 151–153.
[21] N. Liu, C. Ju, X. Chen, Nonlinear ISI cancellation in VSSB Nyquist-SCM system with symbol pre-distortion, Optics Commun. 338 (338) (2015) 492–495.
[22] C.C. Wei, H.Y. Chen, H.H. Chu, et al., Analysis of nonlinear distortion and SSII cancellation in EAM-based IM/DD OFDM transmission, J. Lightw. Technol. 33 (14) (2015) 3069–3082.
[23] N. Liu, C. Ju, C. Li, Nonlinear ISI cancellation in Nyquist-SCM direct detection PON downstream scheme with Volterra pre-equalizer, Opt. Fiber. Technol. 45 (2018) 14–18.
[24] N. Iiyama, N. Shibata, J.I. Kani, et al. Application of hierarchical modulation to optical access network. International Conference on Optical Internet, 2014, pp. 1–3.
[25] N. Iiyama, J.I. Kani, J. Terada, et al., Feasibility study on a scheme for coexistence of DSP-based PON and 10-Gbps/λ PON using hierarchical star QAM format, J. Lightw. Technol. 31 (18) (2013) 3085–3092.
[26] N. Iiyama, J.I. Kani, J. Terada, et al. Demonstration of hierarchical star 8-QAM designed for coexistence of 10G-EPON and DSP-based PON with 30-dB loss budget. in Proc. Optoelectronics & Communications Conference Held Jointly with International Conference on Photonics in Switching. (2013) pp. 1–3.
[27] N. Shibata, J. Kani. Constellation design for next-generation hierarchically-modulated PON systems. Broadband Access Communication Technologies VII. 8645, (2013) pp. 1–3.
[28] N. Shibata, N. Iiyama, J.I. Kani, et al., Star-QAM constellation design for hierarchically modulated PON systems with 20-Gbps PSK and 10-Gbps OOK signals, J. Lightw. Technol. 32 (18) (2014) 3184–3191.
[29] P. Cao, X. Hu, Z. Zhuang, et al., Power margin improvement for OFDMA-PON using hierarchical modulation, Opt. Express 21 (7) (2013) 8261–8268.
[30] M.D. Santa, C. Antony, G. Talli, et al., Power budget improvement in passive optical networks using PAM4 hierarchical modulation, Photonics Technol. Lett 99 (2017) 1747–1750.
[31] R.V.D. Linden, X. Yin, N.C. Tran, et al., Demonstration of Upstream Flexible 2-/4-PAM Formats for Practical PON Deployments, VDE, 2016, pp. 1–4.
[32] R.V.D. Linden, N.C. Tran, E. Tangdiongga, et al., Optimization of flexible non-uniform multi-level PAM for maximizing the aggregated capacity in PON deployments, J. Lightw. Technol. 36 (12) (2018) 2328–2336.
[33] R.V.D. Linden, N.C. Tran, E. Tangdiongga, et al., Increasing flexibility and capacity in real PON deployments by using 2/4/8-PAM formats, J. Opt. Commun. Netw. 9 (1) (2016) A1–A8.
[34] L.V. Der, R.R. N.K. Tran, E. Tangdiongga, et al. Utilizing unused power budget to increase network capacity in practical PON deployments by introducing flexible modulation. in Proc. European Conference on Optical Communication. IEEE (2015) pp. 1–4.
[35] J. Zhang, J.S Wey, J. Shi, et al. Experimental demonstration of unequally spaced PAM-4 signal to improve receiver sensitivity for 50-Gbps PON with power-dependent noise distribution. in Proc. Opt. Fiber Commun. Conf. Exhib. (OFC). (2018). pp. 1–3.
[36] H.Y. Chen, J. Lee, N. Kaneda, et al., Comparison of VSB PAM4 and OOK Signal in an EML-based 80-km transmission system, Photonics Technol. Lett. 29 (23) (2017) 2063–2066.
[37] H.Y. Chen, N. Kaneda, J. Lee, et al., Optical filter requirements in an EML-based single-sideband PAM4 intensity-modulation and direct-detection transmission system, Opt. Express. 25 (6) (2017) 5852–5860.
[38] J. Zhang, J. Yu, X. Li, et al., 100 Gbit/s VSB-PAM-n IM/DD transmission system based on 10 GHz DML with optical filtering and joint nonlinear equalization, Opt. Express. 27 (5) (2019) 6098–6105.
[39] J. Lee, N Kaneda, Y. K Chen. 112-Gbit/s Intensity-Modulated Direct-Detect Vestigial-Sideband PAM4 Transmission over an 80-km SSMF Link. in Proc. European Conference on Optical Communication. VDE(2016) 1-3.
[40] J. He, H. Dong, R. Deng, et al., Enhanced performance of CAP system using an overlap frequency-domain equalization scheme, IEEE Photon. J. 8 (2) (2016) 1–8.
[41] Z. Zhou, J. He, J. Ma, Y. Xiao, et al., Adaptive modulation scheme for DML-based IM/DD FOFDM systems using overlap frequency-domain equalization, Opti Fiber Technol. 48 (2019) 213–217.
[42] D. Li, J. He, J. Tang, et al., Experimental demonstration of half cycle 64-qam nyquist-scm direct-detection optical communication system with data-aided estimation and overlap frequency-domain equalization, Opt. Eng. 53 (12) (2014).
[43] R. Kudo, T. Kobayashi, K. Ishihara, et al., Coherent optical single carrier transmission using overlap frequency domain equalization for long-haul optical systems, J. Lightw. Technol. 27 (16) (2009) 3721–3728.
[44] P.K. Vitthaladevuni, M.S. Alouini, A closed-form expression for the exact BER of generalized PAM and QAM constellations, IEEE Trans. Commun. 52 (5) (2004) 698–700.
[45] N. Feng, X. Sun, Nyquist four-level pulse amplitude modulation scheme (PAM-4) based on hierarchical modulation in IM/DD-TDM PON with hybrid equalization, Opt. Commun. 457 (2019) 1–8.