



Implementation of network-coding approach for improving the BER performance in non-orthogonal multiple access (NOMA)-PON

Nan Feng ^{a,*}, Xiang Sun ^b

^a State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China

^b Smart Edge Computing and Networking Lab., Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM 87131, USA

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ABSTRACT

In the current passive optical networks (PONs), we address the challenge of dealing with asymmetric channel conditions and asymmetric data rates in order to meet the traffic demand of optical network unit (ONU) to ONU (O2O) communications. A joint network-coding (NC) and power domain non-orthogonal multiple access (NOMA) approach (NC-NOMA) is discussed. The novelty of this NC-NOMA scheme lies in the way the inter-ONUs communicates with an optical line terminal (OLT) at different modulation formats. Specifically, in the uplink communications, at each ONU side, multiple data streams from different ONUs are superimposed into one single symbol. Meanwhile, NOMA is considered by adjusting the optical transmission power of ONUs such that the OLT can decode the signals from different ONUs based on successive interference cancellation (SIC). At the OLT side, the adding zeros approach at the specific positions of the shorter bit sequence is introduced. In the downlink communications, the ONUs obtain their own data by decoding the received messages. By applying NC-NOMA, the ONU with better channel condition only needs to demodulate the fictitious symbols with a low order modulation format instead of demodulating the symbols with a high order modulation format. The simulation results show NC-NOMA with hierarchical adding zeros approach outperforms NC-NOMA with traditional zero padding approach in terms of having lower average end-to-end BER of ONUs without having additional complexity.

1. Introduction

Next generation passive optical networks (NG-PONs) are considered as one of the most promising technologies that can tremendously increase the throughput of optical access networks [1–4]. Intensity modulation (IM) and direct detection orthogonal-frequency division multiplexing (IM/DD OFDM), which is one of the key technologies in NG-PON, can significantly improve the performance of the network [5].

With the development of new applications, such as peer-to-peer (P2P) file sharing, video-on-demand (VoD), and three-dimensional (3D) interactive games, different optical network units (ONUs) are expected to communicate with each other, thus generating large amount of traffic [6–16]. Note that two ONUs cannot communicate with each other directly. The optical link between the two ONUs has to go through an optical line termination (OLT), which acts as an relay node to relay the traffic between the two ONUs. Hence, if multiple ONUs, which are connected to the same OLT, needs to conduct ONU-to-ONU (O2O) communications, then the OLT may become the bottleneck to relay traffic among different ONUs if the channel conditions and data rates are mismatched [17–36]. For mitigating the bottleneck on the OLT, two technologies have been proposed to achieve the two-way transmission

and to increase the capacity, i.e. the applied power domain non-orthogonal multiple access (PD-NOMA) [17–25] and network coding (NC) technologies [26–36].

First, PD-NOMA has been applied in the PON system where asymmetric channel conditions at the physical layer (PLY) usually exist due to the fact that the distances between different ONUs and their OLT are not the same. Different from the traditional orthogonal multiple access (OMA) based PON system (e.g., time division multiplexing PON (TDM-PON), wavelength division multiplexing PON (WDM-PON), and orthogonal frequency division multiple access PON (OFDMA-PON)), where different ONUs are allocated orthogonal resources (e.g., different time slots and/or frequencies) to mitigate the interference, PD-NOMA-PON allows different ONUs to transmit/receive signals to/from the same OLT simultaneously over the same frequency band, and thus can significantly improve spectrum efficiency (SE) and network throughput. Specifically, in the uplink (i.e., from ONUs to an OLT), different ONUs transmit their signals simultaneously over the same frequency but with different power to the same OLT, which receives the superimposed signals, and uses the successive interference cancellation (SIC) [17] technique to derive each ONU's signal sequentially. In the downlink

* Corresponding author.

E-mail addresses: fengnan@bupt.edu.cn (N. Feng), sunxiang@unm.edu (X. Sun).

(i.e., from an OLT to different ONUs), the OLT superposes the signals (which are sending to different ONUs with different modulation schemes) by applying hierarchical modulation (HM), which is a technique to multiplex multiple signals with different modulation schemes into one signal. Once an ONU receives the superimposed signal from the OLT, it demodulates the superimposed signal by applying SIC to obtain its own data stream.

Second, in order to further improve the throughput of ONU-to-ONU (O2O) communications, the network coding (NC) paradigm has been proposed [26–29]. Basically, the OLT encodes the messages in order to reduce the total amount of traffic in terms of the number of the messages sending to its ONUs. For example, as shown in Fig. 1, ONU1 tries to send message b to ONU2, and ONU2 tries to send message a to ONU1. First, both ONU1 and ONU2 send message b and a to the OLT simultaneously by applying PD-NOMA (the messages a and b represent different modulation schemes, such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM)). After receiving the two messages, instead of relaying them to ONU1 and ONU2 in two different slots, the OLT encodes the two messages by conducting exclusive-or (XOR) and broadcasts the encoded message to the two ONUs, thus reducing the number of transmitted messages (or number of time slots) in relaying the two messages to ONU1 and ONU2, respectively. Once receiving the encoded message, each ONU XORs the received message with its transmitted message to obtain the desired message.

However, in order to implement NC in the O2O communications, two ONUs should have the same data rate of sending data streams to their OLT [9,10]. Fig. 1(b) and (c) show the O2O communications in the traditional PON and NC-PON system, respectively, where the O2O communications in traditional PON requires four time slots, and the O2O communications in NC-PON requires three time slots. Practically, different ONUs may adopt different modulation schemes (according to their SNRs with respect to the OLT), thus incurring different data rates to the OLT. As depicted in Fig. 1(b), applying different modulation schemes for the ONUs results in OLT unable to conduct XOR to encode messages directly. Thus, in order to implementing NC in the downlink communications for transmitting data from the OLT to different ONUs, the OLT should conduct the adding zeros process on a shorter length bit sequence.

Despite the two promising technologies (NOMA and NC) are both well studied how to integrate the two technologies in O2O communications, which could potentially enhance SE and system capacity, is still unveiled. It is challenging to integrate NOMA and NC in the context of NG-PONs. In addition, despite some comprehensive solution to asymmetric channel and data rate mismatch issues by applying NC in wireless networks [30–36], none work has focused on solving the data rate mismatch in NOMA-NC-PON. Thus, this paper investigates on the solution to solve the asymmetric channel and data rate mismatch issues by applying NC in NOMA-PON. Basically, in order to implement NC and support HM in the downlink communications, the OLT should conduct the adding zeros process on a shorter length bit sequence. The hierarchical zero-padding method is proposed to use for transmitting data from the OLT to different ONUs in NC-NOMA-PON. The main contributions of the paper are listed as follows.

1. We illustrate the motivations and challenges of applying NC in NOMA-PON to improve the throughput of PON. Integrating NC with NOMA-PON to achieve O2O communications is first investigated. That is, in the PON upstream communications, the power domain NOMA is applied in each ONU by adjusting the optical transmission power. In the downstream communications, NC is applied to enable the ONUs to receive their desired data.
2. We propose the joint hierarchical modulation and NC method (where the hierarchical adding zeros approach is applied to handle the asymmetric channel and data rate mismatch issues in context of O2O communications in NOMA-PON. Specifically,

the transmitted bit sequence consists of two subsequences: high-priority (HP) bits and low-priority (LP) bits. The basic idea of the hierarchical adding zeros is that the OLT receives and distinguishes the corresponding bits with different priorities based on HM from ONUs. The OLT makes hierarchical adding zeros at the specific positions of the shorter bit sequence and decodes the superimposed messages from ONUs to make the NC operation. Thus, the end-to-end (E2E) bit error rate (BER) of the ONU with low order modulation format is only influenced by the corresponding HP bits from the encoded symbol. Thus, as compared to traditional adding zeros approach, the average E2E BER is improved without having additional complexity.

3. The performance of the proposed NC-NOMA-PON is demonstrated via extensive simulations.

2. Background and related work

Before discussing the NC-NOMA scheme, this section mainly provides an introduction of the NC and HM concepts in the context of NG-PON.

2.1. The NC in NG-PON system

Recently, various NC schemes in PON have been proposed and studied. Basically, an OLT receives the messages from two different ONUs during the first two time slots. Then, the OLT XORs the received messages to generate a new message, which is broadcasted to the two ONUs during the third phase. Belzner et al. applied the NC technology in Ethernet PON (EPON) [6], and the simulation results demonstrate that NC can effectively reduce the E2E delay as well as packet loss ratio. Maier et al. [7–9] demonstrated that the better network performance by applying NC in fiber-wireless (FiWi) access networks. Zhao et al. [10] proposed to apply NC and the corresponding dynamic bandwidth allocation (DBA) in a service interoperability EPON (SIEPON) to improve the energy efficiency of the network. In addition, in order to further improve the SE, physical-layer network coding (PLNC) is applied in PON, which allows two ONUs to transmit optical signals at the same time based on the property of optical power addition. For instance, Wang et al. demonstrated that PLNC can be applied to an all-optical virtual private network (VPN) implementation in TDM-PON, and thus increases the capacity of VPN by 100% as well as provides more secure services [11]. Li et al. [12] introduced optical PLNC in OFDM-PON. Guan et al. [16] also applied PLNC in OFDM-PON, which can efficiently utilize network resources. Thus, applying the NC technology in the NG-PON systems can potentially improve the performance of the system. However, the existing NC based PON systems do not consider the rate mismatching issue of modulation constellation. However, this approach has to redesign the modulator and demodulator, and thus increases the complexity. In addition, the nesting modulation constellation was proposed to make full rate NC [33]. Moreover, in order to be adaptive to the physical layer rate, the joint of XOR-based NC and superposition coding (SC) was proposed in [34]. Therefore, in NG-PON, this rate mismatching issue implies different ONUs apply different modulation schemes, the XORing operation of NC is unable to conduct in OLT due to different lengths of the two messages. In order to support the NC implementation, the more suitable aligning of bit streams from different ONUs is required.

2.2. The NOMA in NG-PON system

Applying NOMA in NG-PON can potentially increase network performance in terms of SE and network throughput as compared to OMA. To achieve O2O communications in NOMA-PON, ONU nodes communicate with each other through the OLT. Specifically, in the uplink communications, multiple ONUs send their signals to the OLT over the same resource block (in terms of frequency band) but with different

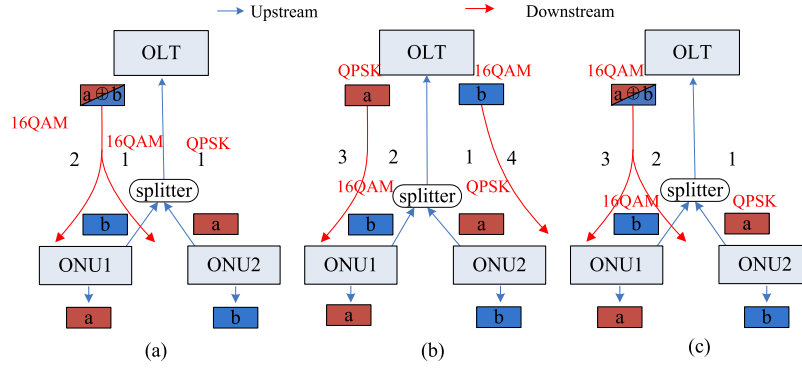


Fig. 1. The system model for (a) NC in NOMA-PON (b) no NC in O2O (c) with NC in O2O.

received optical power (ROP) at the OLT [19–25], thus potentially increasing the network capacity. In the downlink communications, the OLT broadcasts the superimposed signal to different ONUs to support the simultaneous transmission of multiple data streams from the OLT to the ONUs. In flexible optical access with synchronized downlink/asynchronous uplink, Lu et al. experimentally demonstrated that dynamically optimizing the power ratio of ONUs can improve BER and reliability especially for high path loss ONUs [18]. Lin et al. proposed the NOMA-PON [19–21], which can improve the network performance as compared to OMA-PON. Feng et al. proposed digital domain power domain multiplexing (PDM) and SIC to send two 2.5-Gb/s independent OFDM signals simultaneously over a 25 km standard single mode fiber (SSMF) [22] with DD. Wu et al. have proposed the dual polarization PDM coherent optical OFDM transmission in a 100-Gb/s transmission over 1440 km SSMF link [23]. This NOMA scheme and analytical approach can be extended to advanced modulation schemes and optical communication system. In addition, Guan et al. proposed NOMA in visible light communication (VLC) with advanced phase distortion and joint detection for adapting to different optical power ratios. Note that the inherent essence of NOMA is to consider the HM technology as part of the implementation [37–41]. Here, HM is one of the promising techniques for recent NG-PON by multiplexing and modulating multiple bit streams with different classes into one single symbol stream [42–58].

Although a lot of previous works have investigated on applying NC and NOMA in PON and VLC, none of the works discusses about the performance by integrating NC with NOMA in a PON system. Park et al. proposed the hierarchical 4/16QAM scheme by integrating the NC technology in asymmetric wireless relay channels [30]. However, this scheme is applicable as long as there is a direct wireless connection between two nodes, which is not true in the O2O communications in the context of the PON system. In addition, to cope with the performance degradation in asymmetric wireless relay channels, Zhang et al. proposed the hierarchical zero padding/network coding (HZPNC) scheme that can reduce the E2E delay and BER of users [35,36]. In this paper, we apply the similar principle by jointly applying NOMA and NC (where hierarchical zero padding is applied to align different bit streams) to improve the performance of the O2O communications in NG-PONs, which have not been discussed by the previous works. As compared to the traditional adding zeros approach, the hierarchical adding zeros approach can reduce the average E2E BER of the ONU with low order modulation format without having additional complexity.

3. Joint network coding and NOMA (NC-NOMA)

3.1. NOMA-PON system architecture with NC

In this section, we present the detail analysis by applying the NC-NOMA (i.e., joint NC and NOMA) scheme in the IM/DD-PON system architecture, which is shown in Fig. 2. The data streams from the ONUs

are transmitted to the OLT through NOMA a PON system. Each ONU can be connected to the OLT via a remote node (RN) which consists of distribution and feed fiber. Without loss of generality, we consider that two ONUs (i.e., ONU1 and ONU2) are trying to communicate with each other over a bidirectional link through the OLT. The channel conditions of the uplink and downlink are assumed independent, i.e., both the channels have different average signal-to-noise ratios (SNRs), which is the most general case in practical PON implementations. Assume that the SNR between ONU2 and the OLT is better than that between ONU1 and the OLT. Thus, the two ONUs are assumed to apply different modulation schemes in the uplink communications. That is, the modulation scheme applied by the ONU2 (denoted as M2-QAM) is higher than the modulation scheme applied by the ONU1 (denoted as M2/M1-QAM), i.e., $M1 < M2$. Here, M2/M1-QAM is hierarchical constellations. In particular, ONU1 uses 4QAM symbols. Meanwhile, in order to increase the system's flexibility, ONU2 uses 4/16-QAM symbol s_2 which consists of two HP bits and two LP bits. This means that the operation of two-layer 4QAM + 4QAM signal can provide a non-uniform 16QAM constellation.

In the uplink communications, both ONUs transmit their signals to the OLT simultaneously in the first timeslot. A NOMA transmitter (Tx) in each ONU consists of an advanced digital signal processing (DSP), which generates digitally modulated baseband OFDM signal, and an electro-optic modulator. Also, the transmission power of the ONUs could be adjusted in order to achieve PD-NOMA. Note that the process of generating the baseband OFDM signal by the DSP comprises several steps, i.e., serial-to-parallel (S/P) conversion, QAM symbol encoding, inverse Fast-Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analogue conversion (DAC). The channel of transmitting the optical signal over a SSMF is considered as an additive white gauss noise (AWGN) channel if the digital distortion is compensated.

At the OLT side, the OLT receives the IM optical signals from both ONUs and applies DD to convert the optical signals into electrical signals via the PIN, which is typically integrated with a trans-impedance amplifier (TIA). The superimposed electrical signal is sampled by an analog-to-digital converter (ADC), and then processed by the offline DSP procedure. Here, the offline DSP procedure contains synchronization, CP removal, FFT, channel estimation, equalization, SIC, QAM de-mapping, and BER calculation. It is worth noting that SIC is used to decode each ONU's signal from the superimposed signal sequentially, i.e., the signal of the ONU with highest SNR is first decoded, and then is subtracted from the original superimposed signal. The subtracted superimposed signal is then used to decode the signal of the ONU with highest SNR among the rest of ONUs (whose signals have not been decoded yet). The process continues until all the ONUs' signals have been decoded.

After decoding all the ONUs' signals, the OLT conducts the joint HM and NC (JHM-NC) operation and generates the encoded signal, denoted as y_{nc} . As the length of the received bit sequences per one symbol between the two ONUs may not be the same, the OLT can apply

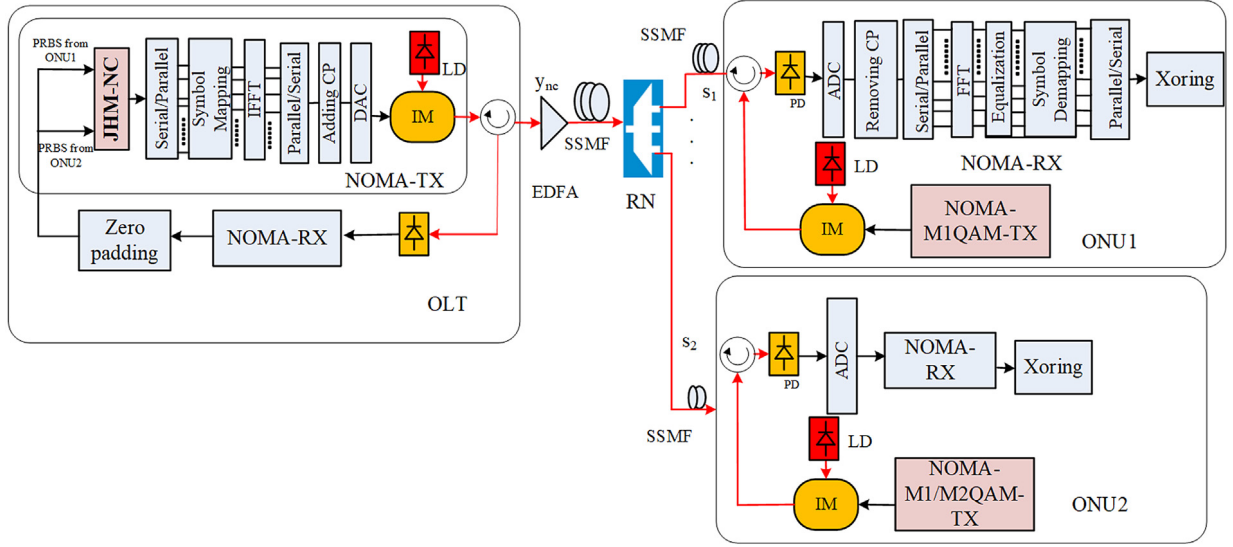


Fig. 2. The NC scheme in IM/DD-NOMA-PON system architecture.

zero padding by adding zero(s) at specific positions in the shorter bit sequences. Consequently, in the downlink communications (i.e., during the second timeslot), the OLT broadcasts the superimposed and fictitious signal y_{nc} to both ONUs. At the ONU side, ONU2 (with low signal power) simply demodulates the shared HP information and ONU1 (with higher signal power) demodulates not only the HP layer data, but also the specific LP layer data. Therefore, O2O communications can be achieved. The following paragraph explains the detail procedure of achieving zero padding in NC-NOMA-PON.

3.2. Zero padding of NC-NOMA-PON

Since ONU1 and ONU2 apply M1-QAM and M1/M2-QAM modulation schemes, respectively, the OLT may receive different number of bits (i.e., different lengths of messages) transmitted from these ONUs within a specific time period. In order to have the same length of the two messages from these ONUs while without increasing the complexity of demodulation in the OLT, zero padding is applied.

Originally, zero padding adds zeros at the end of the message with shorter length in order to enable the two messages to have the same length [59]. Assume that the contents of the two messages (from ONU1 and ONU2) received by the OLT are $r_{onu1} = 0010$ and $r_{onu2} = 00010100$, respectively. Thus, zero padding is applied in the message from ONU1 by appending zeros to the end of r_{onu1} (i.e., $r_{onu1} = 00100000$) such that the two messages have same length. Thus, the OLT will conduct the XOR operation to encode the two messages, i.e., $r_{olt} = 00100000 \oplus 00010100 = 00110100$. Here, the HP bits are modified/encoded, while the LP bits are unchanged. The encoded message r_{olt} is then broadcasted to both ONUs. Once receiving the broadcasted message, both ONU1 and ONU2 will obtain their own message by applying the 16-QAM demodulation method.

Instead of applying traditional zero padding, we use the hierarchical zero padding scheme, where zeros are added at particular positions of r_{onu1} [36]. Specifically, the message, which is modulated based on the 16-QAM format by ONU2, is divided into two bit streams, i.e., high and low priority bit streams. At the OLT side, the OLT decodes the two received signals by using HM 4/16/64-QAM. The HM4/16/64-QAM consists of two different transmission priorities, i.e., HP bits and LP bits. The HP bits stream are XORed with the 4QAM modulated bits transmitted from ONU1, and the LP bits are unchanged. Note that the first two bits of each symbol are HP bits. Since ONU2 uses HM 4/16-QAM, as shown in Fig. 3(b), the bits of ONU2 r_{onu2} consists of HP bits $r_{onu2-h} = 0001$ and LP bits $r_{onu2-l} = 0100$. Meanwhile, the bits of ONU1

$r_{onu1} = 0010$ is XORed with r_{onu2-h} and the generated bits are placed on the position of HP bits again. Then, we have $r_{olt-h} = 0011$. The LP bits $r_{onu2-l} = 0100$ remain unchanged and placed on the LP bit positions of the OLT, that is, $r_{olt-l} = 0100$. Thus, we have $r_{olt} = 00011100$.

The hierarchical zero padding method can also be implemented by the following way [36]. The bit streams from ONU1 r_{onu1} is considered as HP bits, that is, $r_{onu1-h} = 0010$. Also, zeros, which will be added to r_{onu1-h} , are considered as LP bits, i.e., $r_{onu1-l} = 0000$. As shown in Fig. 3(c), a new bit stream r_{onu1} is generated by the OLT by adding r_{onu1} to r_{onu1-h} , i.e., $r_{onu1} = 00001000$. The bit stream r_{onu1} is then XORed with the bit stream from ONU2 to generate a coded bit stream r_{olt} , i.e., $r_{olt} = r_{onu1} \oplus r_{onu2} = 00001000 \oplus 00010100 = 00011100$. The bit stream r_{olt} is modulated by the fictitious 4/16/64QAM modulation scheme [60,61] and broadcasted to both ONUs.

From the above example, we can derive that zeros are always added at the end of the bit streams with short length in the traditional zero padding scheme. However, in hierarchical zero padding, zeros are added at specific locations in the bit streams with short length. By applying hierarchical zero padding at the OLT, we can see that ONU2 only needs to decode HP bits by using fictitious 4QAM rather than decoding both HP and LP bits by using 16-QAM. Thus, the hierarchical zero padding approach can handle the rate mismatch challenge without having performance degradation caused by the high order modulation format. In addition, the hierarchical zero padding approach can be further extended to the higher modulation schemes when the SNRs are higher.

4. Performance evaluation

In this section, the performance of the proposed NC-NOMA approach is evaluated via MATLAB and VPI 8.5. We set up an IM/DD NOMA-PON architecture based on Fig. 2, where two ONUs try to communicate with each other via an OLT. The simulation parameters are summarized in Table 1. In the uplink communications, the 4QAM and 4/16 QAM modulation schemes are assumed to be used in ONU1 and ONU2, respectively. The PD-NOMA can be implemented by adjusting the transmission power of ONU1 and ONU2. In the simulations, the ratio of ONU1's transmission power to ONU2's transmission power is varied among 4:1, 3:1, and 2:1, respectively. The difference of the transmission power between the two ONUs are varied from 3 to 6 dB, which is much lower than 15 dB (which is considered as the maximum difference of the power attenuation from the two ONUs to the ODN in the PON system [51,62]). The reason for having the difference of

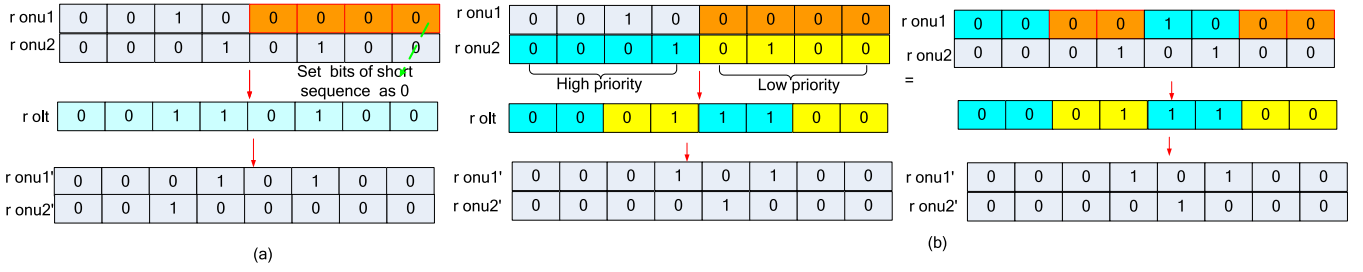


Fig. 3. The traditional zero padding and hierarchical zero padding scheme in implementation of NC.

the transmission power between the two ONUs much lower than 15 dB is that we do not consider the optical loss caused by the multi-stage optical splitter. Note that the difference of the transmission power between the two ONUs could be optimized such that the performance of NOMA in uplink communications could be maximized.¹ In the downlink communications, the communications from the OLT to an ONU is modeled as a type of point to point communications with some optical link loss. In addition, various impairments may deteriorate signals transmitted on both uplink and downlink. In order to mitigate the impairments, both the OLT and ONUs must perform channel estimation before demodulating the signals. To mitigate the linear impairments in the DSP enabled receivers, the frequency-domain zero-forcing (ZF) channel equalization technique is applied in the simulation. The ZF equalization technique uses the channel transfer function (which can be derived by analyzing the training sequence (TS) at the receiver) to restore the received signal [25,63]. Also, we use a Mach-Zehnder modulator (MZM) as an optical intensity modulator in the simulation. A vestigial side band (VSB) filter [64] is applied to mitigate the power fading effect induced by chromatic dispersion (CD) in the simulation.

Moreover, at the OLT side, after implementing the SIC scheme to decode the superimposed signal, a classic demodulator (which demodulates symbols based on the minimum Euclidean distance) is used to demodulate symbols from the ONUs. Note that it is impossible for the two remote ONUs to share the same coherent laser source and to have the same channel responses, thus resulting in signal phase shifting in the OLT. Accordingly, the constellation in the OLT cannot be well aligned in the practical implementations [65–68], which may lead to the OLT unable to demodulate the signals from the two ONUs. In the simulation, we manually adjust the delay offset of symbols by making the phase correction [25,63] and amplitude scaling of the constellation through the training methods to solve the phase offset problem. Note that the asynchronous issue in NOMA uplink communications can be resolved by applying the advanced digital signal processing (DSP) method. For instance, the phase pre-distorted scheme at the transmitter [65] and the further phase pre-distorted joint detection scheme at the receiver [66] are proposed to solve the symbol misalignment problem in visible light communications. Here, the principle of phase pre-distorted is to find the optimal phase difference of the two signals that can minimize the BER [65].

4.1. Channel characteristics

In order to estimate the subcarriers' channel responses, we measure the related channel transfer function, which represents the system's amplitude frequency response. For example, consider a link with a 30 km SSMF transmission distance and the ROP equaling to -5.13 dBm. Fig. 4(a) and Fig. 4(b) show the related amplitude frequency responses and electrical spectrum profiles, respectively. Based on Fig. 4, we can derive that the amplitude frequency response of a channel is approximate linear when the ZF frequency-domain channel equalization

Table 1

Simulation setup.

Parameter	Value
Number of OFDM symbol	100
Number of training symbol	20
ONU1's modulation scheme	4QAM
ONU2's modulation scheme	4/16QAM
IFFT size	256
Cyclic prefix	32
Number of subcarrier	107
Sampling rate	24 (GSa/s)
ONU1's LD frequency (Hz)	193.1 T
ONU2's LD frequency (Hz)	193.1 T+100 G
ONU1's LD output power	20 15 10 (mW)
ONU2's LD output power	5 (mW)
Optical filter's bandwidth	21.7 GHz
Optical filter's Gaussian order	1.35
Distance between a ONU and the OLT	Various (km)
EDFA amplifier gain tilt	0 (dB)
EDFA noise factor	4 (dB)
PIN noise factor	$10e-12$ (A/(hz) ^{1/2})

technique is applied, which could mitigate the effect induced by CD. Note that we only use half of the total number of the subcarriers to derive the channel transfer function. This is because the designed TS is existed in the interleaved manner to avoid any nonlinear signal and signal beat interference (SSBI) effect due to the square-law detection of the PD [25]. From Fig. 4(b), we can see the relative flat electrical spectrum in 10 GHz, which indicates that the NOMA signal can be successfully modulated and demodulated.

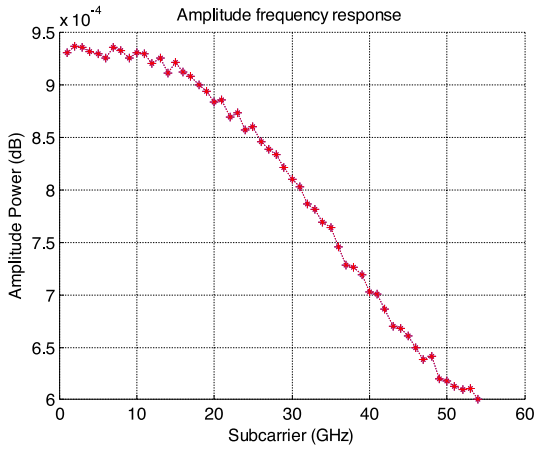
4.2. The constellation arrangements of NOMA-PON

At both the OLT and ONU side, the probability of the OLT successfully demodulating a symbol transmitted from an ONU equals the probability of having the symbol located in its related demodulation decision region. Thus, how to derive the accurate demodulation decision region may significantly affect the BER performance after the demodulation.

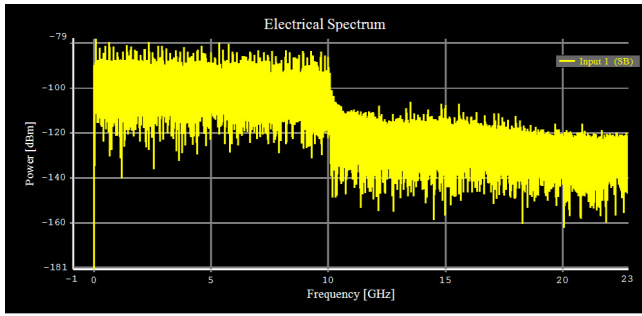
Assume that the electrical power ratio of 4/16QAM is 2:1. Fig. 5(a), (b), and (c) show the constellation arrangements of fictitious HM-4/16/64-QAM when the optical transmission power ratios of the two ONUs are 4:1, 3:1, and 2:1, respectively. We can see that a different optical transmission power ratio of the two ONUs may have a different constellation arrangement. That is, once the electrical power ratio of hierarchical 4/16-QAM is fixed, the HM scheme redefines the constellation arrangement of the existing QAM based on the optical transmission power ratio.

The optimal decision factors are based on the constellation's Euclidean distance. Specifically, the OLT first demodulates the bits of one 4QAM symbol (i.e., the layer with a longer Euclidean distance), and then uses SIC to decode the bits of the other 4QAM symbol (i.e., the layer with a shorter Euclidean distance). Without considering NC, the superposed modulation can be treated as a three-layer 4QAM modulation. Assume that the electrical power ratio of 4/16QAM becomes 3:1.

¹ Note that this paper does not discuss the optimal transmission power ratio of the two ONUs to maximize the performance of NC-NOMA.



(a) Channel amplitude frequency responses



(b) Electrical spectrum profiles

Fig. 4. Channel characteristics.

Then, Fig. 6(a), (b), and (c) show the constellation arrangements of fictitious HM-4/16/64-QAM when the optical transmission power ratio of the two ONUs are 4:1, 3:1, and 2:1, respectively. By increasing the optical transmission power ratio, ONU1 has higher optical transmission power than ONU2.

As shown in Fig. 6(a), (b), and (c), from an energy point of view, with the increase of the optical power ratio, the corresponding ONU2 stream get less power to send, and the BER performance is worse. This is because more available energy is given to the ONU1 stream. With the same similar conclusion, for the superimposed bits stream in different layers, the minimum Euclidean distance (normalized by the symbol energy) of the symbol determines its decision boundary. The decision boundary further affects the system BER performance.

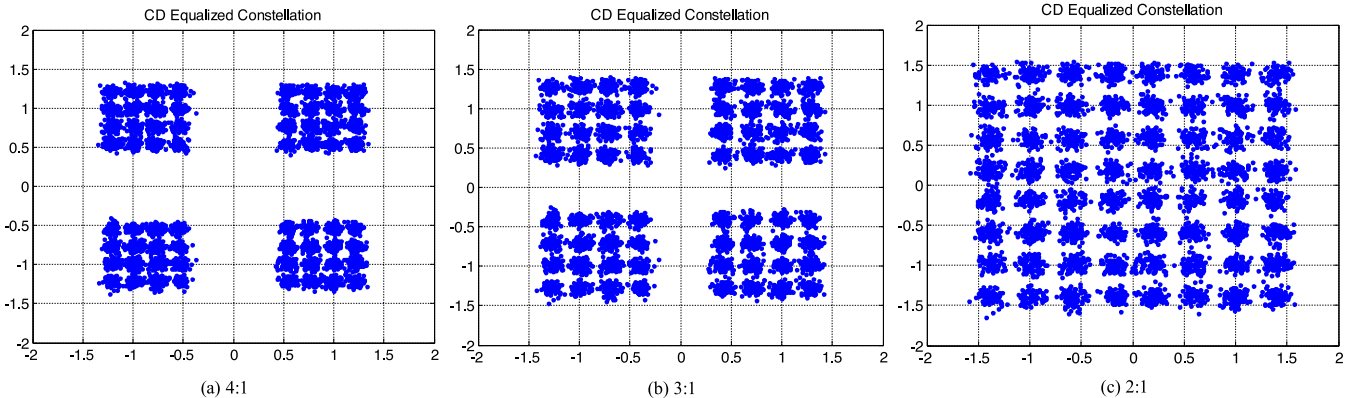


Fig. 5. Constellation arrangements of HM-4/16/64-QAM when the electrical power ratio of 4/16QAM is 2.

4.3. The E2E BER performance of NOMA-PON

Next, we will discuss how the electrical power ratio of an ONU, the transmission power ratio of the two ONUs, and the transmission distance between the OLT and the ONUs affect the E2E BER in NC-NOMA-PON.

4.3.1. Relationship between electrical power ratio and E2E BER in the B2B case

Assume that the optical transmission power ratio of the two ONUs is 2:1 in the back-to-back (B2B) scenario. Fig. 7(a) and (b) show the E2E BER over different ROPs when the electrical power ratio of 4/16QAM is 2:1 and 3:1, respectively. Here, TZP and HZP indicate traditional zero padding and hierarchical zero padding in NC-NOMA, respectively. Note that the dots, which indicate BER equal to zero, is not plotted in Fig. 7.

From the figures, we can see that the HZP scheme (i.e., NC-NOMA with HZP) incurs the similar E2E BER and ROP of ONU1 as compared to the TZP scheme (i.e., NC-NOMA with TZP). However, HZP has a lower E2E BER and higher ROP of ONU2 than TZP. This is because ONU2 only needs to demodulate the fictitious 4QAM instead of 16-QAM in the HZP scheme, while ONU2 has to demodulate 16-QAM in the TZP scheme. As a result, the E2E BER of ONU2 is only affected by the BER of the HP bits (which is lower than the BER of the LP bits) transmitted from the OLT in HZP.

We further analyze the sensitivity of receivers, which is defined as the minimum received optical power to achieve the hard-decision forward error correction (HD FEC) threshold, i.e., BER = 3.8×10^{-3} [69]. When the electrical power ratio is 2:1, as shown in Fig. 7(a), HZP increases the receiver sensitivity of ONU2 and the average receiver sensitivity (of ONU1 and ONU2) by 0.75 dB and 0.4 dB, respectively, as compared to TZP. When the electrical power ratio becomes 3:1, as shown in Fig. 7(b), the values of E2E BER for both ONUs are reduced. This is because the interlayer interference (ILI) may reduce the correctness of demodulating symbols in the OLT. In the uplink communications, the OLT may decode a 4QAM symbol by first determining the quadrant of the 4QAM constellation. As a result, the interference between quadrants is reduced, and thus the corresponding BER is reduced.

4.3.2. Relationship between optical transmission power ratio and E2E BER

Assume that the electrical power ratio is 2:1. Fig. 8 shows the E2E BER and ROP in HZP and TZP under different optical transmission power ratios.

From the figure, we can see that once the optical transmission power ratio is fixed, the BER performance is improved by increasing ROP. Also, the E2E BER of both ONUs incurred by HZP is always lower than that incurred by TZP. In addition, in the TZP and HZP scheme, the increment of the average receiver sensitivity for both ONUs is reduced as the optical transmission power ratio increases. This is because, given

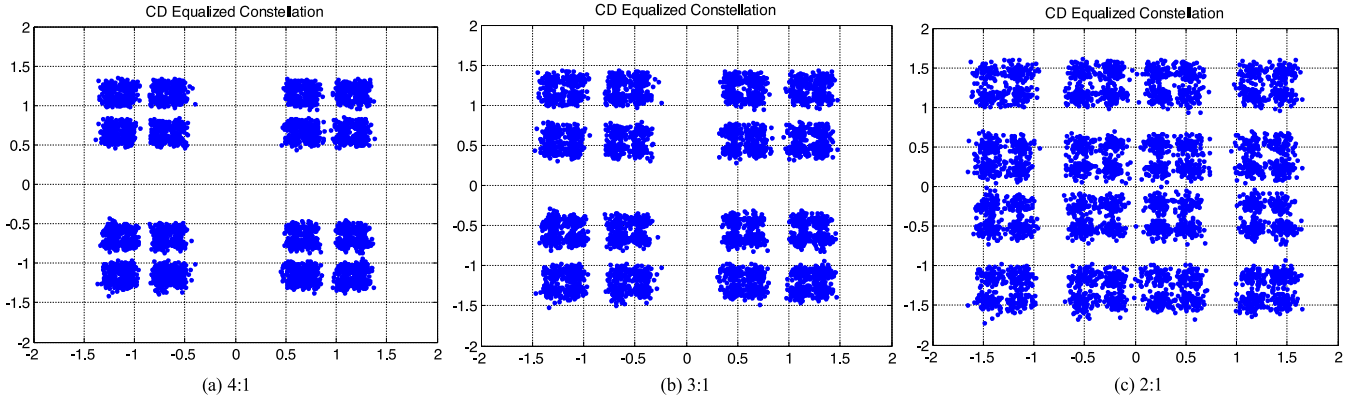


Fig. 6. Constellation arrangements of HM-4/16/64-QAM when the electrical power ratio of 4/16QAM is 3.

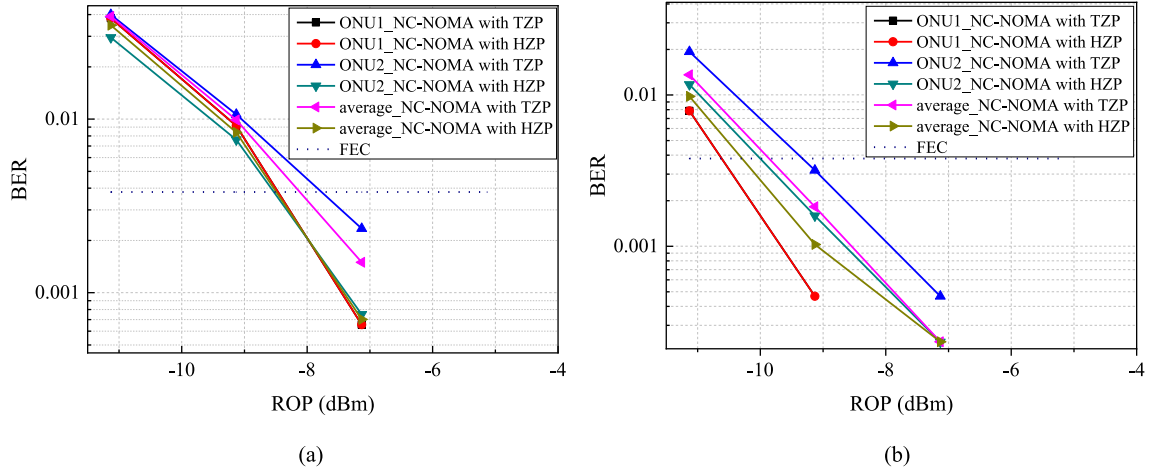


Fig. 7. E2E BER of TZP and HZP for B2B case with the same optical power ratio 2 (a) electrical power ratio of 4/16QAM is 2:1 (b) 3:1.

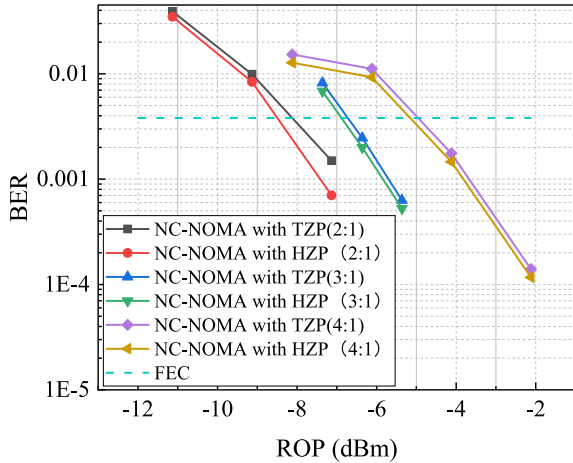


Fig. 8. BER of TZP and the HZP for the average value of both ONUs with the same electrical power ratio 2 under different optical power ratio of both laser in B2B case.

energy per superimposed symbol, the distance between constellation points and the I/Q axis increases as the optical transmission power ratio increases. As a result, ONU1's symbols are easier to be demodulated, which reduce the BER of ONU1. However, reducing the BER of ONU1 may increase the BER of ONU2 [55–57]. Therefore, a better channel condition between ONU2 and the OLT is needed to guarantee the BER of ONU2.

Note that, in the uplink communications in NOMA-PON, the OLT may not successfully demodulate the symbols from the two ONUs if a small optical transmission power ratio is applied. For instance, under a 30 km SSMF transmission distance, Fig. 9(a), (b), and (c) show the superposed constellation arrangements when the optical transmission power ratio is 1.6:1, 1.2:1, and 1:1, respectively.

From the figure, we can see that one constellation point may not be distinguished from another. This is because the OLT cannot decode the two individual signals (from ONU1 and ONU2, respectively) from the received superimposed signal by applying the SIC technology. As shown in Fig. 10, increasing the optical transmission power ratio can substantially reduce the BER of the two ONUs.

Several existing works, such as the phase pre-distortion scheme [65] and the maximum-likelihood (ML) based detector [66], have been proposed to improve the high BER of the ONUs in the small optical power ratio transmission scenario. However, reducing the optical transmission power ratio can substantially increase the BER of the two ONU. Therefore, a smaller optical transmission power ratio is not recommended in the uplink communications for this NC-NOMA-PON scenario.

4.3.3. Relationship between optical power ratio/electrical power ratio and E2E BER in the SSMF transmission case

Once the optical signal transmitted over an SSMF, the signal is distorted due to various channel impairments, such as channel loss, bandwidth limit, CD linear impairment, and non-linear SSBi impairments. Also, the channel impairments are more severe as the length of the SSMF becomes longer. Thus, it is important to analyze how the length of the SSMF affects the E2E BER and ROP in NC-NOMA-PON.

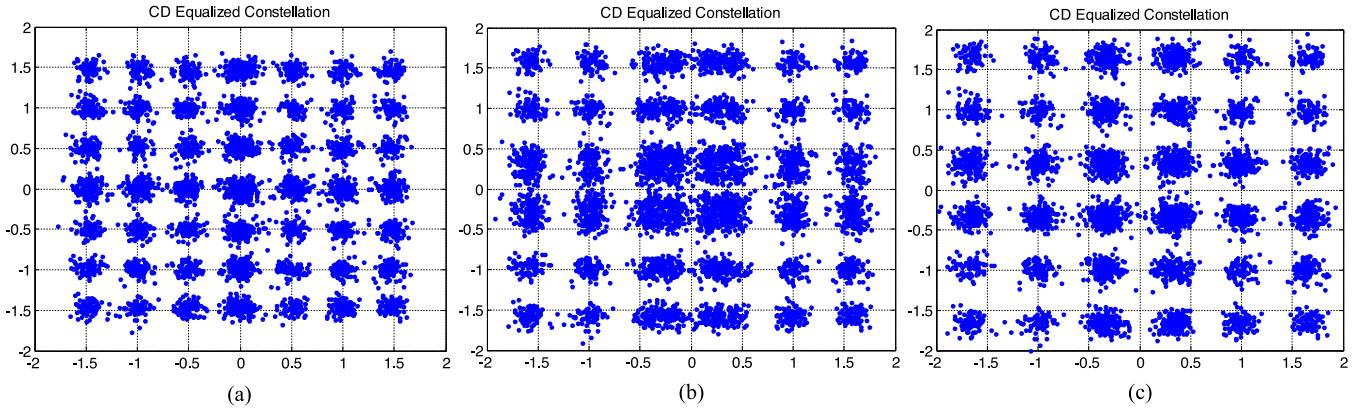


Fig. 9. The superposed constellation of power ratio is (a) 1.6:1, (b) 1.2:1, and (c) 1:1 with 30 km SSF.

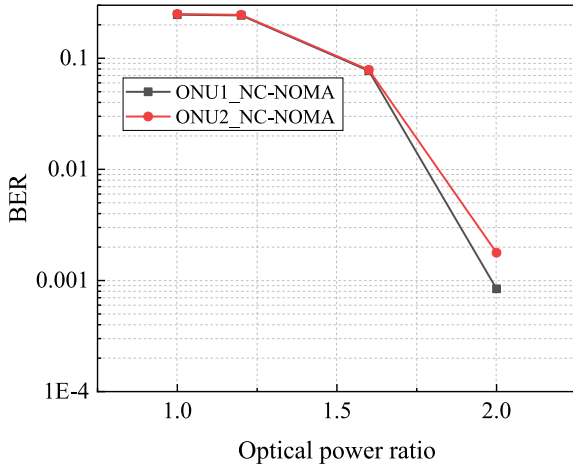


Fig. 10. BER vs relative small optical power ratio.

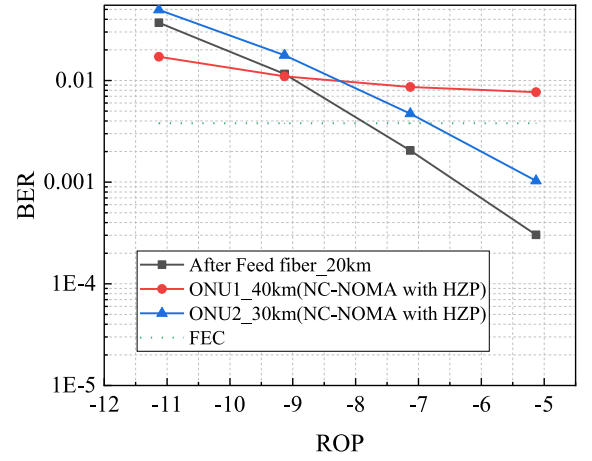


Fig. 11. BER of the HZP in NOMA-PON, whereas the electrical and optical power ratio of both laser are both 2:1.

Assume that the length of the feed fiber between the OLT and the optical splitter in ODN is 20 km, and the length of the distribution fibers from the optical splitter to ONU1 and ONU2 are 20 km and 10 km, respectively.

Fig. 11 shows the E2E BER and ROP for both ONUs when the optical transmission power ratio and the electrical power ratio are both 2:1. From the figure, we can see that the E2E BER of ONU1 cannot satisfy the BER requirement defined by the FEC threshold because only applying ZF compensation in the DSP cannot completely eliminate the channel impairments. For example, nonlinear SSBI cannot be mitigated by the DSP in this simulation setup, and thus increase the BER. To improve the E2E BER of ONU1, some advanced DSP technologies, such as the iterative method [55], Volterra filter, and pre-equalizers, can be applied to mitigate nonlinear SSBI in the NC-NOMA-PON.

Fig. 12 shows the E2E BER and ROP for both ONUs in NC-NOMA-PON when the optical transmission power ratio and the electrical power ratio are both 3:1. From the figure, we can see that the E2E BER of ONU1 can satisfy the FEC threshold. However, the E2E BER is ONU2 increased by 1.2 dB as compared to the case in Fig. 11 (i.e., when the optical transmission power ratio and the electrical power ratio are both 2:1). Thus, there is an E2E BER tradeoff between ONU1 and ONU2, and the tradeoff can be adjusted by changing the optical transmission power ratio and the electrical power ratio. Changing the value of electrical power ratio and optical power ratio for NC-NOMA can flexibility arrange the constellation points. Thus, the balance between the different receiver sensitivity levels for two ONUs is depending on their power allocation [69,70], which is a key issue in not only unidirectional but also the bidirectional NOMA-PON.

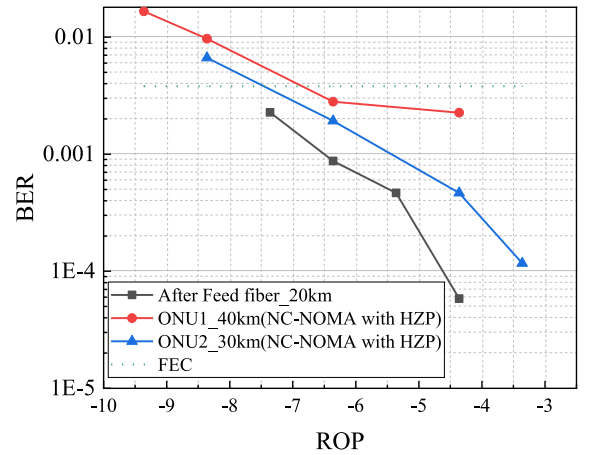


Fig. 12. BER of the HZP in NOMA-PON, whereas the electrical and optical power ratio of both laser are both 3:1.

The effects of electric power ratio, optical power ratio, and SSF transmission distance can change the received power ratio at the OLT. Thus, it is worth to investigate how the system performance varies by selecting different values of parameters. It can provide a certain design guideline of the IM/DD NC-NOMA-PON.

5. Conclusion

In this paper, the IM/DD NOMA-PON system with asymmetric channels has been investigated. In addition, the NC-NOMA scheme has been employed, and the performance of applying HZP and TZP has been discussed. We analyzed the E2E BER and ROP of the ONUs in NC-NOMA-PON with TZP and with HZP via extensive simulations. The simulation show that the HZP scheme has lower average E2E BER than that of the TZP scheme for the ONU with higher order modulation. In addition, we demonstrated the performance of the NC-NOMA scheme not only in the B2B case but also in the SSMF transmission case. Due to the impact of nonlinear distortion in the PON channel, how to choose the suitable locations of ONUs and employ the impairment mitigation techniques are crucial. In the paper, we only considered the IM/DD based NC-NOMA-PON system with one OLT and two ONUs. In our future work, we will investigate how to optimize the system configurations of NC-NOMA-PON when more than two ONUs are deployed.

CRediT authorship contribution statement

Nan Feng: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Xiang Sun:** Formal analysis, Funding acquisition, Investigation, Methodology, Writing - review & editing.

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