This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2721955, Journal of Lightwave Technology

Power Division Non-Orthogonal Multiple Access (NOMA) in Flexible Optical Access with Synchronized Downlink / Asynchronous Uplink

Feng Lu, Mu Xu, Lin Cheng, Jing Wang, and Gee-Kung Chang, *Fellow, IEEE*

***Abstract*—The data traffic in optical access networks increase dramatically, driven by wired and wireless services. Limited by the available bandwidth with low-cost optical and electrical devices, modulations and multiple access schemes with higher spectral efficiency is desirable. The current time division multiplexing and wavelength division multiplexing cannot fulfill the requirement due to low spectral efficiency and high cost. The multi-stack flexible optical access network shows its benefit by low cost, reduced fiber deployment, increased flexibility and ultra-high network extension capability. With varies path losses to different users, the network performance is significantly limited by users with high path losses generated by more couplers or long fibers. These users cannot have good service qualities using existing multiple access schemes. We propose to use the power division non-orthogonal multiple access with synchronized downlink and asynchronous uplink. The performance and reliability are significantly improved for high path loss users, by optimizing all users as a group and adjusting the power ratio adaptively. In the uplink, the asynchronous transmission enables low latency and simple DSP in optical network units. The simulation shows significantly better performance. And the proposed scheme is experimentally demonstrated by our testbed with 2.5-dB increased power margin in synchronized downlink, and one order-of-magnitude BER floor reduction in asynchronous uplink.**

***Index Terms*—Asynchronous transmission, non-orthogonal multiple access, optical access networks, power division multiple access, successive interference cancellation.**

I. INTRODUCTION

THE increasing data traffic generated by fixed and mobile services are demanding tremendous bandwidth, low latency, high flexibility, reliability and service quality for next generation optical access networks [1, 2]. The optical access architecture is sensitive to the cost of devices. Hence, low-cost electrical and optical devices are preferable, limiting the available bandwidth and optical transmitting power. Current on-off keying (OOK) based passive optical network (PON) including time division multiplexing (TDM)-PON and wavelength division multiplexing (WDM)-PON cannot fulfill the data rate requirement by rapidly growing services with low deployment cost [3, 4]. Modulations with high spectral efficiencies are developed for higher data rate occupying a similar bandwidth, using symbols with more than two states. Orthogonal frequency-division multiplexing (OFDM) with quadrature amplitude modulation (QAM) is one of the strongest candidates in future optical access networks since it provides high spectral efficiency and is easy to do frequency domain equalization (FDE) [5-7]. But the OFDM signal has several drawbacks including relatively low sensitivity and low power efficiency limited by the high peak-to-average power ratio (PAPR). Both factors limit the power budget.

On the other hand, the optical access network is the last chain for connecting users. It needs to expand rapidly with low additional cost with high flexibility. In traditional coupler-based optical distribution networks (ODN), it is very hard to be changed once deployed. The new ONU are connected by deploying a fiber all the way back to the master coupler, as Fig. 1(a) shows. To lower the hurdle of expansion, the multi-stack structure is proposed and deployed, shown in Fig. 1(b). When a new subscriber or 5G base station needs to be connected, we just add one coupler at the closest connected optical network unit (ONU), and connect the new ONU through a short fiber. Since it is difficult for operators to predict the user distribution at the beginning and hard to replace couplers after deployment, it is feasible to deploy couplers with identical ratio outputs. However, as the network grows, more users may be connected to some branches. Hence, the connected users have very different losses in the network, partially due to a different number of couplers served by. Different path losses may also be generated by the different fiber lengths and additional losses in connectors. We define the path loss as the sum of all losses in couplers, connectors, and fibers.

As a result, it is challenging for us to provide excellent high-speed services to all ONUs in the flexible access network, especially using OFDM modulation. The service quality is greatly limited by the user with the largest path loss since OFDM treats each user independently by allocating different orthogonal resource blocks to different users. In this case, the user with the worst link cannot have a good service quality, even though other users may have plenty of margins. The overall service quality in the network is impaired.

Hence, we introduce the power division non-orthogonal multiple access (PD-NOMA) in flexible optical access

All authors are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA. (e-mail: fenglu@gatech.edu).

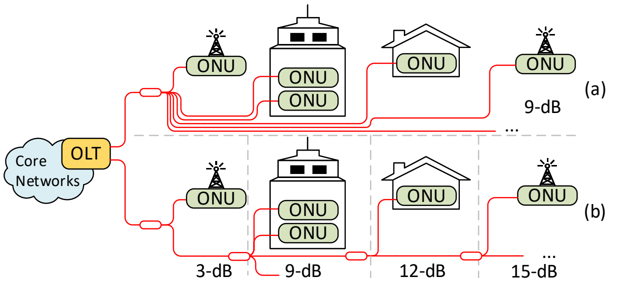

Fig. 1. (a) Optical access networks with similar path losses to all users. (b) Flexible optical access networks with uneven path losses for improved flexibility and reduced cost.

networks. The PD-NOMA with successive interference cancellation (SIC) is a technology to serve multiple users with optimized power budget/sensitivity adapting to link conditions, which is actively investigated in the 5G mobile systems and millimeter-wave radio-over-fiber systems [8-10]. We can serve multiple users with different power budgets adapting to their path losses, and increase the sensitivity of the worst user. By digitally controlling and optimizing all users as a group, we are able to improve the overall service quality. The scheme is also capable of adapting to the uncertainty in fiber networks generated by temperature uncertainty, aging and so on, by periodically measuring the link condition and applying updated signal parameters, making it reliable for long term operation.

The synchronized PD-NOMA can be utilized in the downlink since the signal is generated in the centralized optical line terminal (OLT). For the uplink, synchronized PD-NOMA requires ranging and time synchronization in ONU, since a tight synchronization is mandatory to keep the orthogonality of subcarriers in OFDM. But it requires additional DSP and generates extra delays, which is not feasible for future ultra-low latency access networks, especially if it is working as the 5G mobile fronthaul or backhaul. Hence, asynchronous transmission is feasible in the uplink [11, 12].

In this paper, we propose to use asynchronous PD-NOMA for the uplink in flexible access networks with multiple stacks, with features including simple DSP and reduced latency. For the downlink, a single wavelength is shared by all users with synchronized PD-NOMA. Only low-cost colorless optical couplers are deployed in all remote nodes (RNs). By the proposed architecture, we are able to improve the service quality by optimizing all users as a group and adjusting their transmission quality adaptively. The transmission quality, performance, and reliability are significantly improved without modifying the physical architecture. In the experiment, we improve the power margin for downlink by more than 2.5-dB, and reduce the uplink BER by one order of magnitude.

II. Proposed Architecture and Synchronized/Asynchronous PD-NOMA

In this paper, we propose to use a single wavelength in the downlink. No expensive array waveguide gratings (AWGs) are needed in RNs, so the existing TDM-PON infrastructure can be reused. With the broadcast scheme, all users receive the same waveform with varies signal SNR due to different received optical powers. Different user information is separated by digital multiple access schemes.

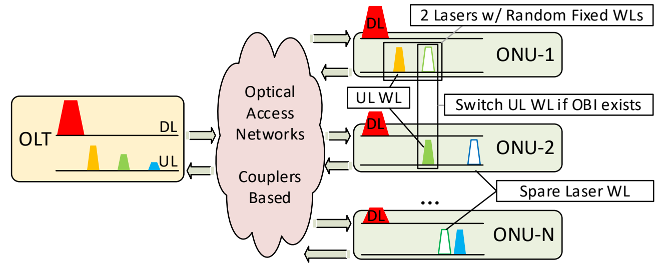

Fig. 2. Proposed system architecture with shared downlink wavelength and DWDM uplink without tunable lasers in ONUs.

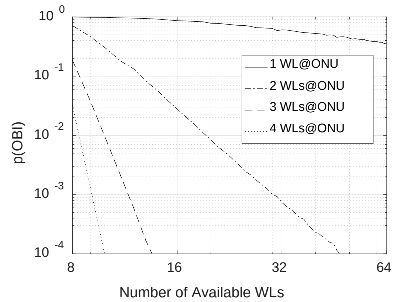

Fig. 3. Probability of OBI in proposed architecture with 1 to 4 lasers in each ONU.

For the uplink, we propose a dense wavelength division multiplexing (DWDM)-NOMA scheme. Users are equipped with lasers with random fixed wavelengths. Since we only use couplers in RNs, even we require the ONU to be compatible with any RN port, no wavelength tunable lasers are needed. Different wavelengths are combined in the RNs, and only one PD is deployed in the OLT. After PD, all signals are combined in the electrical domain. Similar to downlink, the electrical multiple access scheme is needed in the uplink, like orthogonal frequency-division multiple access (OFDMA) or NOMA.

Optical beating interference (OBI) may be one challenge if multiple ONUs have the lasers with the same wavelength and transmit simultaneously, which generates penalties and requires additional processing [13]. Hence, we propose to deploy two low-cost lasers with two different random wavelengths in each ONU (one working laser and one spare laser), to increase its reliability and robustness to OBI. If OBI is observed, one of the conflicting ONUs switches the transmitting wavelength to avoid OBI. In Fig. 3, the proposed scheme can reduce the probability of OBI from more than 60% (with a single laser in ONU) to less than 0.08% with a spare laser in ONU, assuming we have 8 ONUs in the network with 32 available wavelengths. In addition, the wavelength selection and switching only happen when the network is firstly deployed. If new ONU is connected, most of the switching only happens in the new ONU. So, the proposed scheme does not interrupt the real-time traffic as a result.

Using this physical architecture in Fig. 1(b), significantly different transmission qualities can be generated due to various path losses. In the downlink, due to a different number of couplers in the link and different fiber distances, the ONU has varies received optical powers (ROPs), which suggests different SNRs after the PD in ONU. For the uplink, the ONU connected by more couplers and longer fiber suffers from higher path losses. With similar optical output, the ROP in OLT from this user is lower, which impairs the transmission.

We propose to use the PD-NOMA in both downlink and uplink of the flexible optical access network. The user information can be multiplexed in frequency division, time division, and more importantly, power division. By assigning different powers to different users, the information can be separated even they share the same frequency and time resource. Since the noise is added in the power division, the PD-NOMA can distinguish user data, and also provides varies transmission qualities to/from ONUs.

If we sort the user index by descending power ratio, the equivalent signal-to-interference-plus-noise ratio (SINR) for uplink and downlink are in (1), with P_k, h_k and n_k for the transmission power, path response and noises corresponding to the user with index k. We do not consider SIC error. For downlink, all ONUs share the power from one laser in OLT, so the sum of the power allocated should be within the OLT transmitting power, and the power ratio is determined by the digital power ratio embedded in the transmission waveform only. To balance the performance of different users with different path losses, usually we assign a greater power to the user with a higher path loss and lower ROP. In the uplink, the power allocation is limited by the laser output power in each ONU individually. The power ratio is determined by both the ONU transmission power and the path loss. With higher loss, typically we assign smaller power ratio, to make full use of the path loss difference and maximize the ROP in OLT.

$$SINR_k = \frac{P_k\left|h_k\right|^2}{P_{\text{int},k}+N_k} = \begin{cases} \dfrac{P_{k,DL}\left|h_k\right|^2}{\sum\limits_{i>k} P_{i,DL}\left|h_k\right|^2 + n_{ONU,k}}, \sum\limits_k P_{k,DL} \le P_{\max,OLT} & Downlink \\ \dfrac{P_{k,UL}\left|h_k\right|^2}{\sum\limits_{i>k} P_{i,UL}\left|h_i\right|^2 + n_{OLT}}, P_{k,UL} \le P_{\max,ONU} & Uplink \end{cases} \tag{1}$$

Two types of PD-NOMA are introduced in this paper. For synchronized PD-NOMA, information for different users is multiplexed in the constellation level [14], and the OFDM symbols are all synchronized, as shown in Fig. 4(a). It means the SIC is applied after OFDM demodulation. For asynchronous PD-NOMA used in uplink, the SIC is applied directly to the waveform, since the OFDM symbols for different users are not synchronized [shown in Fig. 4(b)] and a single FFT window can never recover all user data.

An example of synchronized/asynchronous PD-NOMA decoding with SIC decoder is shown in Fig. 5. Without loss of generality, we assume an application of three users with each user requiring 2-bits per symbol. We refer the user-1, user-2, and user-3 to the user with highest, intermediate and lowest power ratio. The transmitted power ratio associated with each user is [0/-7/-14]-dB. It is chosen because based on QPSK modulation each user, it needs at least 6-dB granularity for correct SIC between layers. The extra 1-dB is reserved for the performance gradient between users fitting into different sensitivity requirements.

For synchronized PD-NOMA, we did time synchronization, cyclic prefix (CP) removal, fast Fourier transform (FFT) and channel estimation/equalization. After that, 64 constellation points can be observed. User-1 does not need to do SIC, but

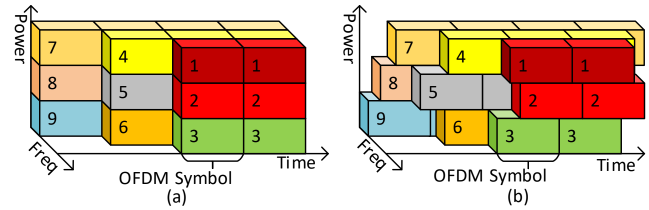

Fig. 4. (a) Synchronized PD-NOMA in downlink and (b) asynchronous PD-NOMA in uplink, with numbers corresponding to different user resources.

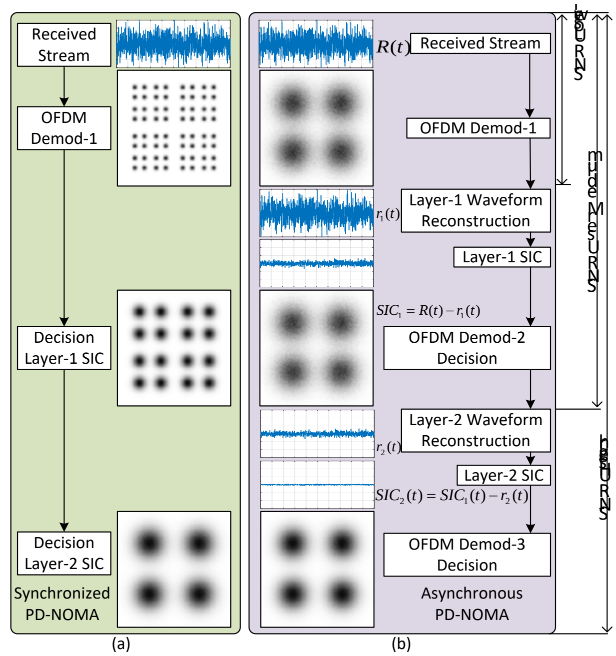

Fig. 5. Flow chart of (a) synchronized PD-NOMA with constellation level SIC and (b) asynchronous PD-NOMA with waveform level SIC

only direct slicing as QPSK constellation. Additionally, the user-2 needs to decode the information for user-1, and reconstruct the symbols for user-1. After that, the interference from user-1 is canceled in user-2 by subtraction, and the user-2 decision is executed. Finally, user-3 conducts the SIC for user-1/2, and decodes the residual constellations. The additional DSP complexity is small since only extra QAM decoding and subtraction is needed in ONU.

For asynchronous PD-NOMA in the uplink, all decoding is in the centralized OLT. Single OFDM is not applicable because the beginning of OFDM symbols from different users are not aligned that severe interference is generated not only between users, but also between symbols and subcarriers. Intersymbol and inter-subcarrier interference cannot be handled by constellation-level SIC. So, the received constellation on high-level decoding is blurred and cannot be used in decoding the lower level information. Instead, SIC is working on the waveform level. Firstly, user-1 does OFDM demodulation, and retrieve the information from this user. After that, it reconstructs the waveform transmitted from user-1, by using the decoding result, channel estimation, and time synchronization information. After SIC by subtracting the user-1 waveform from the received waveform, OLT can do time synchronization again and demodulate the OFDM signal for user-2. Then, the user-2 information is retrieved and removed. Finally, OLT demodulates the OFDM signal after

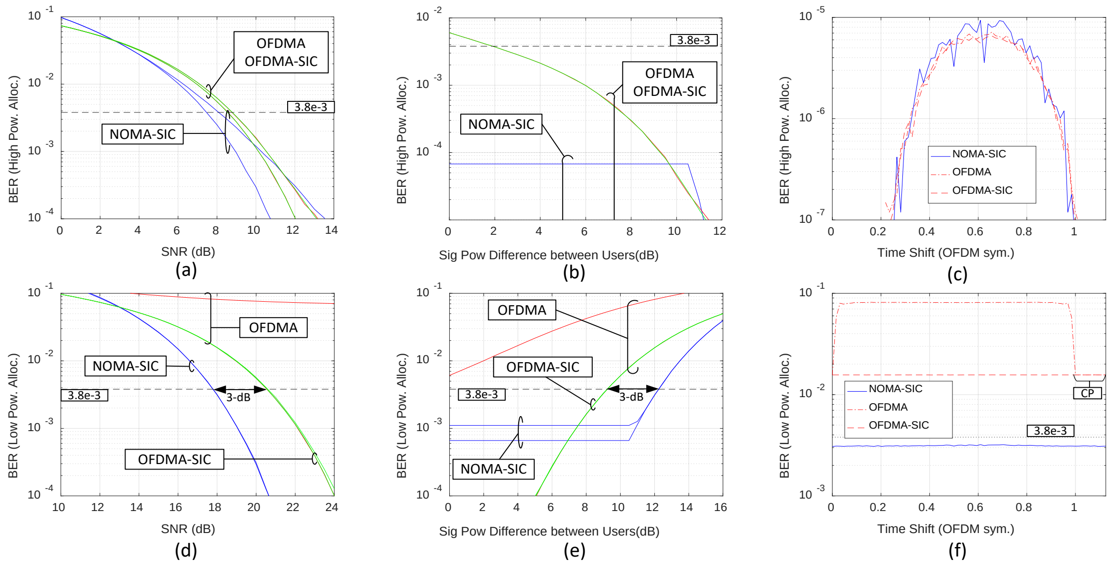

Fig. 6. Simulation results. SNR results with (a) high-power-ratio user and (d) low-power-ratio user. Extra path loss results with (b) high-power-ratio user and (e) low-power-ratio user. Synchronization results with (c) high-power-ratio user and (f) low-power-ratio user.

removing the interference from user-1 and user-2, and retrieves the information from user-3. Since all DSP is centralized in OLT, the additional DSP complexity is tolerable.

$$\text{Power Ratio} = \begin{cases} \begin{bmatrix} P_{1,DL}\left|h_m\right|^2 \\ \cdots \\ P_{N,DL}\left|h_m\right|^2 \end{bmatrix} = \begin{bmatrix} P_{1,DL} \\ \cdots \\ P_{N,DL} \end{bmatrix}, & \begin{matrix} \text{Downlink} \\ \text{at } m^{th} \text{ user} \end{matrix} \\ \begin{bmatrix} P_{1,UL}\left|h_1\right|^2 \\ \cdots \\ P_{N,UL}\left|h_N\right|^2 \end{bmatrix}, & \begin{matrix} \text{Uplink} \\ \text{at OLT} \end{matrix} \end{cases} \quad (2)$$

Typically, the user with fewer levels of SIC (higher power ratio) has better performance. The performance difference can be adjusted by changing the power ratio, which is measured at the receiver. For the downlink, the power ratio is determined by the power ratio defined in the waveform; for the uplink, the power ratio is determined by the output powers by ONUs and their path losses, shown in (2). If we increase the power allocated for one specific user, the performance with this user will be improved, but the performance for other users will be degraded. By properly mapping the user to different SIC levels and controlling the power ratio, we can have an optimized and improved performance to all users with minimized forward error correction (FEC) overhead [15].

Several issues exist in PD-NOMA: security, user number, and channel estimation. The security issue exists in downlink since the ONU with lower power ratio needs to decode bits to other users for SIC, leading to information leakage risk. It can be solved by using the combination of OFDMA and PD-NOMA, that different user with varies security requirements can be separated by other orthogonal divisions. The combination of OFDMA and PD-NOMA can also increase the number of users supported since it is significantly limited by the highest received SNR in PD-NOMA. The channel estimation is a challenge in asynchronous uplink because training symbols are blurred by other users. It can be minimized by time domain averaging and frequency domain interpolation, enabled by the large packet in fiber access (compared to wireless communication) and better channels in the wired media.

III. Simulations

In simulations, we introduce OFDMA as a comparison. To achieve the same spectral efficiency, no guard band is reserved in OFDMA, so the interference between subcarriers may be observed if the OFDM symbols from users are not synchronized. To cancel the interference from other users due to non-orthogonality, OFDMA-SIC is also compared in the simulation. The principle of OFDM-SIC is like NOMA-SIC that we can decode the information from the high-power user, and recover the waveform from the specific user incorporating the channel estimation information. Then, the waveform is subtracted from the original received one to remove its interference to other adjacent frequency users. After that, lower-power users can demodulate the residual signal with reduced interferences.

We control the power ratio on the receiver side. So, the same simulation model can be used for both uplink and downlink. We show the BER under synchronized scenario to simulate the downlink [using the SIC decoding scheme in Fig. 5(a)], and the BER under full unsynchronized scenario (OFDM symbols from different users arrives the OLT with half of the OFDM symbol duration interval) simulating the worst case of asynchronous transmission in the uplink [using the SIC decoding scheme in Fig. 5(b)]. The real uplink performance should be between the synchronized scenario and fully unsynchronized scenario [16]. Each label in Fig. 6(a, b, d, e) marks two curves, corresponding to the synchronized and fully achromous BER performance. Under some circumstances, both curves are overlapped.

To simply and clearly show the results, we simulate the system with two users. Each user requires 2-bits per symbol, accumulating 16 constellation points each symbol. The system uses OFDM consisting of 32 subcarriers, and 12.5% cyclic

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2721955, Journal of Lightwave Technology

prefix (CP) is used. For OFDMA scheme, each user is assigned 16 subcarriers. We assume it is an ROP sensitive system that the electrical noise in the receiver is dominating the system noise. Fig. 6(a-c) shows the performance of the high-power-ratio user, corresponding to the higher path loss user in downlink, or lower path loss user in uplink. Fig. 6(d-f) shows the performance with the other low-power-ratio user.

We firstly simulate SNR performances. The power ratio difference is set to be 12-dB. We sweep the received SNR to show the performance. The required SNR for the high-power-ratio user with 3.8e-3 (corresponding to 7% overhead hard-decision FEC requirement) is 7.3-dB to 8.1-dB for PD-NOMA. Comparing with 8.5-dB to 8.8-dB requirement with OFDMA, 0.7-1.2-dB SNR improvement is observed. For the low-power-ratio, we can reduce the SNR requirement from 20.7-dB to 17.7-dB, comparing with OFDM-SIC. If no SIC is used in OFDMA, a very high BER floor (>6%) is observed when fully unsynchronized, which is generated by the leakage from the high-power users, making the scheme unusable.

Fig. 6(b, d) show results with varying power differences. In PD-NOMA, the BER is minimized at a specific power difference. The power difference is defined the ROP difference between the high-power-ratio user and low-power-ratio user. If the low-power-ratio user's power is greater than the optimal, we reduce the output power of this user to achieve the best performance. In simulations, we fix the SNR of the high-power-ratio user at 18-dB, and varying the power to/from the other user. The optimal power difference is 10.5-dB, so the BER keeps constant in PD-NOMA if the power difference is below 10.5-dB. For the high-power-ratio user in Fig. 6(b), below 1e-5 BER is observed if both users are synchronized. If they are fully unsynchronized, PD-NOMA can always keep the BER below 3.8e-3, but the OFDMA with/without SIC can never achieve this performance when the power difference is within 2-dB. For the low-power-ratio user, NOMA can improve the power difference tolerance from 9.2-dB to 12.2-dB. It suggests that NOMA can support one user with 15-km longer fiber or one extra coupler, and still maintain below 3.8e-3 BER for all ONUs.

Depending on how well users are synchronized, different BERs can be observed for both users. When both users are synchronized, best performance can be observed; when their offset is half of the OFDM symbol duration, the worst performance is generated, due to expanded constellations and noisy training symbols. The synchronization performance is shown in Fig.6 (c, f). The SNR is 18-dB, with 12-dB power ratio difference. The time shift is swept between 0 to 1.125 (including CP). For the downlink, the time shift is always 0; for uplink, any offsets can be generated with the same probability. From results, the high-power-ratio user can always achieve very low BER below 1e-5. Still, slight performance degradation is observed with offsets in all schemes. However, for the low-power-ratio user, PD-NOMA is able to keep the BER below 3.8e-3, while OFDMA-SIC/OFDMA BER can be beyond 1%/7% if the time shift is greater than CP.

IV. Experimental Setup

A bi-directional optical access testbed is built to verify the feasibility of proposed PD-NOMA scheme. Only low-cost directly modulated lasers (DMLs) with fixed wavelengths and optical couplers are used.

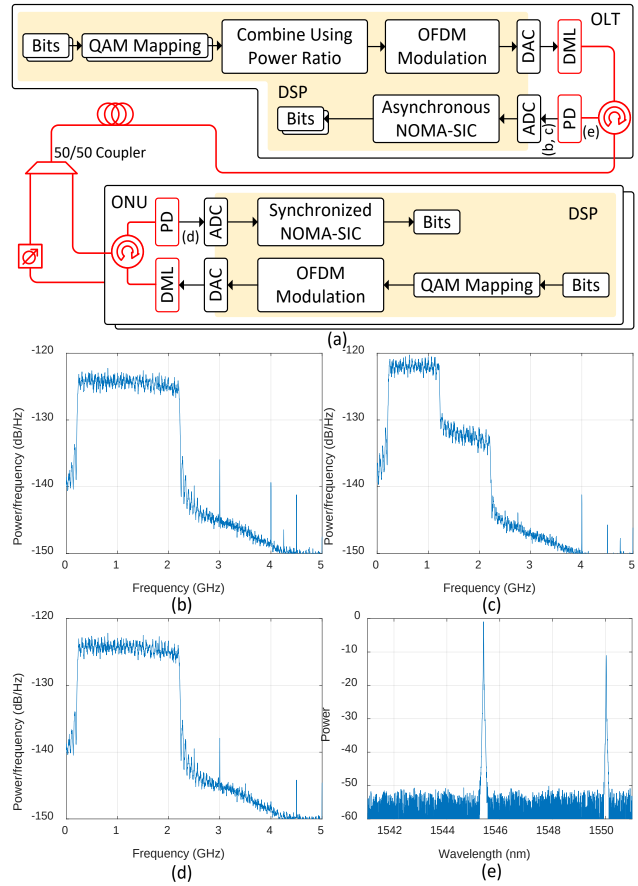

Fig. 7. (a) Experimental setup. Received electrical spectrum with (b) PD-NOMA and (c) OFDMA in uplink with 9-dB power difference. (d) Received electrical spectrum in downlink with PD-NOMA or OFDMA. (e) Received optical spectrum in uplink with 9-dB power difference.

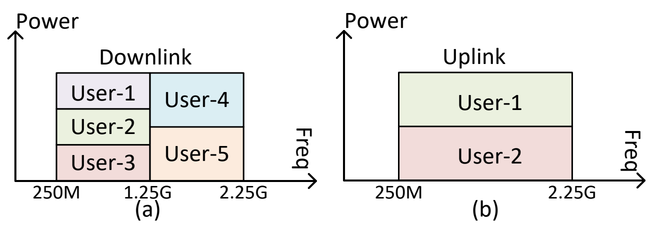

Fig. 8. Resource allocation in power and frequency division for (a) downlink and (b) uplink.

The experimental setup is shown in Fig. 7(a). With different bit streams into the access network, we map the bits into QAM symbol streams individually. A single symbol stream is generated by combining all QAM streams using the optimized power ratio. After that, a conventional OFDM modulation is used with zero padding, inverse fast Fourier transform (IFFT) and CP insertion. After a digital-to-analog converter (DAC), the electrical signal is used for directly driving a DML for downlink optical signal generation. After a circulator in OLT, the signal goes to a 50/50 coupler by 25-km single mode fiber. One port of the output is directly connected to one ONU; the other port is connected to a fixed optical attenuator to simulate different path losses between ONUs. In the ONU, the signal is detected by a PD, and sampled by an oscilloscope. The digital samples are fed into the digital NOMA-SIC decoder using synchronized scheme. For the uplink, the signal is generated by

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2721955, Journal of Lightwave Technology

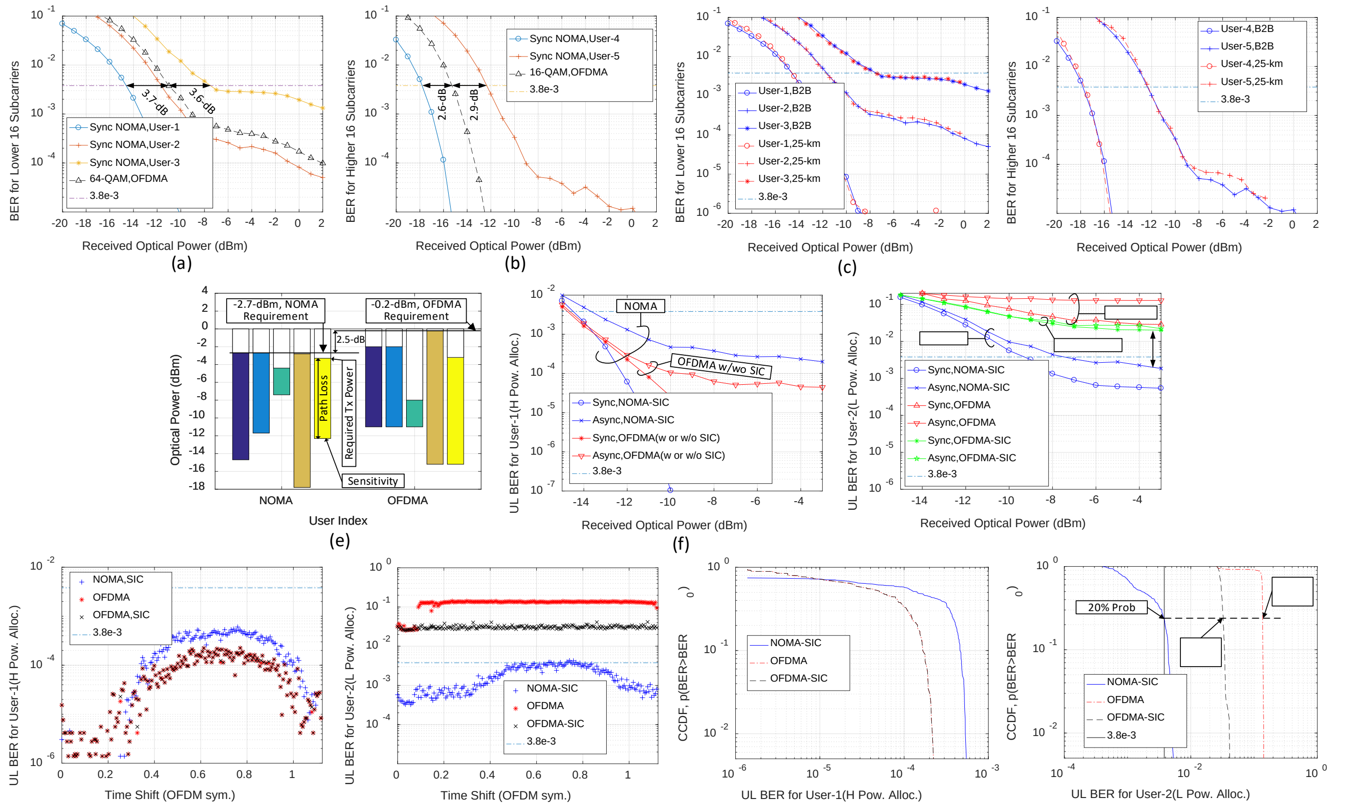

Fig. 9. Experimental results. Downlink sensitivity with (a) lower 16 subcarriers and (b) higher 16 subcarriers. Downlink sensitivity with fiber transmission in (c) lower 16 subcarriers and (d) higher 16 subcarriers. (e) Required transmission power in downlink. Uplink sensitivity for the user (f) with high power ratio and (g) with low power ratio. BER under varies time shifts (between users) for user with (h) high power ratio and (i) low power ratio. BER CCDF in uplink for the user (j) with high power ratio and (k) with low power ratio.

a standard OFDM modulation, sampled by a DAC, and transmitted through a DML independently. In the OLT, the signal is decoded by asynchronous PD-NOMA decoder.

We use the OFDM signal with 2-GHz bandwidth in both uplink and downlink, consisting of 32 subcarriers. The intermediate frequency is 1.25-GHz, and 12.5% CP is used. Five individual data streams are multiplexed in the downlink combining power division and frequency division multiple access, shown in Fig. 8(a). The lower 16 subcarriers are shared by three users in power division with 64 constellation points using the power ratio of [0, -7, -14]-dB, and the higher 16 subcarriers are shared by two users with 4 constellations using normalized power ratios of [0, -7]-dB. Each user has a 1.78-Gbps data rate, accumulating 8.89-Gbps in the downlink. For the uplink, we set up two independent users. They are multiplexed in the power division, shown in Fig. 8(b). The uplink data rate is 3.56-Gbps from each user, accumulating 7.11-Gbps in uplink.

We can control and change the time shift between uplink ONUs. OFDM with 64-QAM in lower 16 subcarriers and 16-QAM in higher 16 subcarriers are measured as the reference in downlink, as well as OFDMA with 16-QAM in uplink.

V. Experimental Results and Discussion

The experimental result is shown in Fig. 9. We firstly test the downlink sensitivity using the resource allocation in Fig. 8(a). Fig. 9(a, b) shows the performance of users using lower/higher 16 subcarriers. Since all OFDM streams are generated by a single source, the symbols are fully synchronized. From results in Fig. 9(a), we are able to improve the sensitivity from -11-dBm to -14.7-dBm for the user with the highest power ratio, corresponding to 3.8e-3 BER. A 3.7-dB sensitivity improvement is achieved. On the other hand, the user with lowest power ratio has impaired performance with 3.6-dB degradation. For the higher 16 subcarriers in Fig. 9(b), the sensitivity is significantly higher since only 4 constellations are mapped with each symbol. The required ROP is -17.8-dBm and -12.3-dBm for PD-NOMA, comparing with -15.2-dBm in OFDMA.

The varies performance can be fit into the different path losses in the flexible access network, shown in Fig. 9(e). The lower edge, the height and upper edge of color boxes are corresponding to the sensitivity, the path loss and required transmission power from the specific ONU. The maximal required power of all boxes is the required transmitting power in OLT for the network serving all ONUs with good performances. For example, with ONUs with path losses of 3/9/9/12/15-dB depicted in Fig. 1(b), the PD-NOMA requires -2.7-dBm transmitting power, comparing with the -0.2-dBm required by OFDMA. PD-NOMA can reduce the required transmitting power by 2.5-dB without modifications on the physical architecture, providing BERs below 3.8e-3 to all users. We also compare the optical back to back performance with 25-km transmission performance, and no obvious penalty is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2017.2721955, Journal of Lightwave Technology

generated, shown in Fig. 9(c, d). It is because of the high spectral efficiency and low signal bandwidth.

The uplink sensitivity results are shown in Fig. 9(f, g). We fix the optical power difference to be 9-dB. Both synchronized and full unsynchronized uplink transmission are measured, and the real uplink transmission performance should be between the two boundaries. For the user with higher power ratio, the SIC in OFDMA has no performance gain, and the BERs are well below 3.8e-3. But for the other user in Fig. 9(g), NOMA can keep the BER below 3.8e-3 with ROP beyond -7.5-dBm, while OFDMA can never achieve this point, even with SIC. With -3-dBm ROP, the NOMA BER is below 2e-3, while OFDMA BER is beyond 2e-2. More than one order of magnitude BER floor improvement is achieved with NOMA in uplink.

If the OLT output power is 12.2-dBm with an optical amplifier, the power budget with the highest sensitivity user can be 30-dB in the downlink with the required ROP of -17.8-dBm. For the uplink, the required total ROP is -8-dBm with the highest sensitivity user, the ROP from the high-loss user is -17.5-dBm. So the power budget is 25.5-dB with DML output of 8-dBm. The proposed scheme provides a good power budget, while providing a higher spectral efficiency than OOK-based PON, and removes the requirement on uplink synchronization. The sensitivity can be improved by adjusting the power ratio and using pre optical amplifier in OLT.

Different synchronization scenarios in uplink are simulated and measured, with results in Fig. 9(h, i). We set the ROP to -5-dBm, and the power difference is 9-dB. For the user with higher power ratio, the BER is slightly higher than OFDMA, but both schemes can keep the BERs below 3.8e-3 for any synchronization scenarios. For the low-power-ratio user, the BER is significantly increased. For most cases, NOMA can keep the BER below the threshold, while BER with OFDMA cannot achieve this BER requirement.

To calculate the probability of having good services for all users, we have the complementary cumulative distribution function (CCDF) value of BER in uplink. For the high-power-ratio user in Fig. 9(j), the service quality is always excellent with BER below 1e-3. For the other user, with about 80% probability, we observe BER below 3.8e-3 with NOMA. But for OFDMA, with the same probability, the BER is increased to 3e-2/1e-1 with or without SIC, shown in Fig. 9(k). In sum, with the synchronized downlink and asynchronous uplink, NOMA-SIC provides improved performance and reliability when compared with OFDMA or OFDMA-SIC.

VI. Conclusion

In this paper, we propose to use the PD-NOMA with SIC in flexible optical access networks. In the low-cost networks, the coupler-based multi-stack architecture is feasible due to reduced network complexity and minimized fiber deployment, with no wavelength tunable lasers required. By deploying more than one fixed wavelength lasers in the ONU, the OBI probability is significantly reduced. In such access networks, the path losses to/from ONUs are very different, which generates biased performance with current schemes.

The PD-NOMA scheme can serve multiple ONUs with different path losses, with optimized and balanced service qualities. We propose to use the synchronized PD-NOMA in downlink, and asynchronous PD-NOMA in uplink for reduced ONU complexity and uplink latency. With varies path losses in the network, PD-NOMA has better performance and high reliability when comparing with OFDMA, verified by simulations and experiments. We experimentally demonstrate the bi-directional synchronized/asynchronous transmission with PD-NOMA. The required transmission power is reduced by 2.5-dB in downlink, suggesting 2.5-dB increased power margin. And the BER floor in uplink is significantly reduced by one order of magnitude. In the asynchronous uplink transmission experiment, PD-NOMA provides tolerable BER under most cases, while the OFDMA can never fulfill the BER requirement. With features including low cost, high flexibility, high ability for network expansion and improved performance, we believe the proposed synchronized and asynchronous PD-NOMA can be a strong candidate in multiple access schemes for future flexible optical access networks.

References

[1] N. Cvijetic, et al. "SDN and OpenFlow for dynamic flex-grid optical access and aggregation networks." *Journal of Lightwave Technology*, vol. 32, no. 4, pp. 864-870, 2014.

[2] X. Liu and F. Effenberger. "Emerging Optical Access Network Technologies for 5G Wireless." *Journal of Optical Communications and Networking*, vol. 8, no. 12, pp. B70-B79, 2016.

[3] F. Effenberger. "The XG-PON system: Cost effective 10 Gb/s access." *Journal of lightwave technology*, vol. 29, no. 4, pp. 403-409, 2011.

[4] A. Banerjee, et al. "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review." *Journal of optical networking*, vol. 4, no. 11, pp. 737-758, 2005.

[5] D. Qian, et al. "108 Gb/s OFDMA-PON with polarization multiplexing and direct detection." *Journal of Lightwave Technology*, vol. 28, no. 4, pp. 484-493, 2010.

[6] E. Giacoumidis, et al. "Adaptive loading algorithms for IMDD optical OFDM PON systems using directly modulated lasers." *Journal of Optical Communications and Networking*, vol. 4, no. 10, pp. 769-778, 2012.

[7] J. Yu, et al. "Centralized lightwave WDM-PON employing 16-QAM intensity modulated OFDM downstream and OOK modulated upstream signals." *IEEE Photonics Technology Letters*, vol. 20, no. 18, pp. 1545-1547, 2008.

[8] Y. Saito, et al, "Non-orthogonal multiple access (NOMA) for cellular future radio access," *Vehicular Technology Conference (VTC Spring)*, 2-5 June 2013.

[9] L. Dai, et al, "Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends," *Communications Magazine*, vol. 53, no. 9, pp. 74-81, September 2015.

[10] F. Lu, et al, "Non-Orthogonal Multiple Access with Successive Interference Cancellation in Millimeter-Wave Radio-Over-Fiber Systems," *Journal of Lightwave Technology*, vol. 34, no. 17, pp. 4179-4186, 2016.

[11] G. Wunder, et al. "5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications." *IEEE Communications Magazine*, vol. 52, no. 2, pp. 97-105, 2014.

[12] S. Kang, et al. "Universal filtered multi-carrier system for asynchronous uplink transmission in optical access network." Proc. of SPIE, vol. 9772 paper 97720W-3, 2016.

[13] J. Ma. "Simple signal-to-signal beat interference cancellation receiver based on balanced detection for a single-sideband optical OFDM signal with a reduced guard band." *Optics letters*, vol. 38, no. 21, pp. 4335-4338, 2013.

[14] N. Yoshimoto, et al. "DSP-based optical access approaches for enhancing NG-PON2 systems." *IEEE Communications Magazine*, vol. 51, no. 3, pp. 58-64, 2013.

[15] T. Mizuochi. "Next generation FEC for optical communication." *Optical Fiber Communication Conference*, paper OTuE5, 2008.

[16] J. Cui, et al. "Impact of symbol misalignment on 5G non-orthogonal multiple access." *IEEE 25th Wireless and Optical Communication Conference*, 2016.