An Energy and Cost Efficient WDM/OFDMA PON System: Design and Demonstration

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***Abstract*—In this paper, we propose an energy and cost efficient WDM/OFDMA PON system, referred to as NEWOPS. Based on a new two-tiered semi-tree architecture, NEWOPS allows a large number of ONUs to be connected to OLT using only a handful of colorless transceivers. Due to the architecture, NEWOPS not only facilitates high spectral efficiency and flexible sub-channel bandwidth allocation, but also reduces the Rayleigh backscattering (RB) problem and achieves high energy and cost efficiency. Experimental results demonstrate that, taking only 5-GHz bandwidth for each wavelength, NEWOPS successfully achieves 20-Gb/s downstream and 10-Gb/s upstream OFDM-xQAM transmissions via the same fiber trunk. We depict that, to support 40 ONUs for example, NEWOPS achieves energy efficiency that is three to six times higher than that of a typical 10-Gb/s WDM/OFDM PON.**

***Index Terms*—Energy efficiency, Orthogonal Frequency Division Multiple Access (OFDMA), Passive Optical Network (PON).**

I. INTRODUCTION

PASSIVE optical networks (PONs) [1] have been considered to be one of the most promising solution for access networks due to its immense bandwidth and low-cost infrastructure. Existing PON systems can be categorized as one of three access types: time-division multiple access (TDMA), wavelength-division multiplexing (WDM), and orthogonal frequency-division multiple access (OFDMA). In these systems, while downstream data are simply broadcast from OLT to all ONUs, upstream data from ONUs to OLT are multiplexed in the domain of time, wavelength, frequency, or the combination of above.

In TDMA PONs, due to using a single wavelength, different ONUs transmit their upstream data in different time slots. Thus, the upstream traffic is exhibited in burst mode, which requires complicated burst mode receivers at the OLT. Unfortunately, the development of a high-speed burst mode receiver is currently still at its infant stage. Besides, based on a tree-and-branch architecture, TDMA PON systems give rise to power budget (receiver sensitivity) and scalability problems due to high insertion loss from the optical splitter. To combat the problems, current systems have to use expensive optical amplification devices (e.g., semiconductor optical amplifier (SOA) or erbium-doped fiber amplifier (EDFA)). Moreover, TDMA PON systems employ the simple non-return-to-zero on-off keying (NRZ-OOK) modulation, which poses a serious challenge to supporting high-data-rate transmissions in next-generation PONs.

OFDMA [1] and WDM PONs have thus been envisioned as prominent technologies for the next-generation PONs. Both technologies have their strengths and weaknesses. OFDMA PONs offer high spectral efficiency (thus lower bandwidth requirement) and flexible sub-channel bandwidth allocation. (Notice that, OFDM PON is a simpler variant of OFDMA PON. While OFDMA allows subcarriers to be dynamically allocated to each ONU, OFDM simply adopts static subcarrier allocation to ONUs.) The price paid, however, is the optical beat interference (OBI) problem [1], which results in severe degradation of the optical signal performance. Besides, due to employing high-order QAM modulation, OFDM PONs require higher signal-to-noise ratio (SNR) than TDMA PONs. The fact unfortunately imposes a limitation on the number of connected ONUs, giving rise to a scalability problem.

On the other hand, a WDM PON system is capable of supporting a large number of ONUs. However, WDM PON is inflexible as for allocating bandwidth on a sub-wavelength basis. To this end, hybrid WDM/TDMA PON systems that cascade the WDM multiplexer and optical splitter have been proposed to support more ONUs and reduce the optical power loss simultaneously. More importantly, a number of ONUs can share a wavelength in a TDMA manner, resulting in an improvement to wavelength utilization efficiency. However, such a hybrid system inevitably inherits all the problems from the native TDMA PON systems, including the limitation of data rates and the requirement of complicated high-speed burst mode receivers.

A promising solution to compensating the weakness of aforementioned systems has been a hybrid WDM/OFDM(A) PON system. Existing hybrid WDM/OFDM(A) PON systems perform signal transmissions by designating a different wavelength for each ONU while using OFDM only for signal modulation. As a result, the OBI problem is eliminated, and at the same time

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Manuscript received November 20, 2012; revised February 21, 2013; accepted July 13, 2013. Date of publication July 19, 2013; date of current version July 31, 2013. This work was supported in part by the National Science Council (NSC), Taiwan, under Grant NSC-100-2221-E-009-107-MY3, and in part by the NCTU/ICL Joint Research Project.

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Digital Object Identifier 10.1109/JLT.2013.2273932

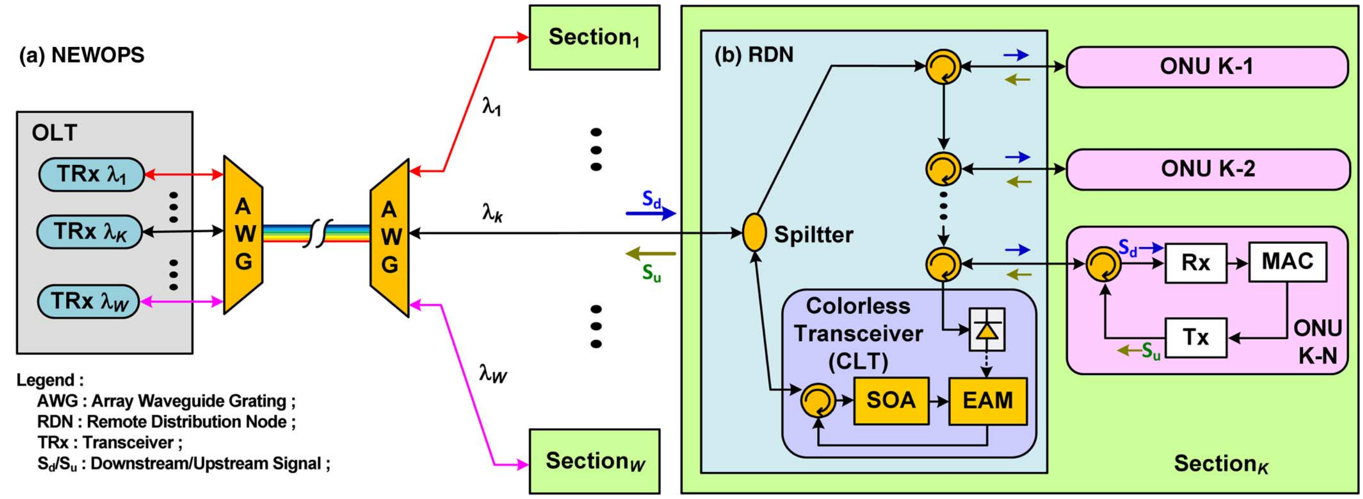


Fig. 1. NEWOPS. (a) system architecture, and (b) RDN internal structure.

high spectral efficiency can be achieved. Nevertheless, such a design poses a severe challenge to achieving high energy and cost efficiency [2].

Energy efficiency is often evaluated as bits per unit of energy, i.e., bits/Joule. When the system is subject to transmitting a given amount of data, higher (lower) energy efficiency corresponds to lower (higher) power consumption. On the other hand, when the system is subject to a given energy consumption, higher (lower) energy efficiency corresponds to higher (lower) transmission data rate or throughput. Existing hybrid WDM/OFDM(A) PON systems not only requires as many optical OFDM transceivers at OLT as the number of ONUs, the OFDM transceiver itself involves power-hunger digital signal processing tasks. Together with inflexible sub-wavelength bandwidth allocation that results in lower throughput, hybrid WDM/OFDM(A) PON systems suffer from poor energy efficiency. To increase energy efficiency, the WDM/OFDM PON proposed in [3] adopted adaptive line rate by dynamically adjusting the transmitted data rate based on the monitored traffic status. Under lower data rates, the optical OFDM transceiver is adjusted to operate at lower speeds, thereby decreasing power consumption. The price paid is the increased complexity of the optical OFDM transceiver for supporting multiple rates. Besides, the problem remains unresolved under high data rate traffic. The hybrid system in [4] proposed the use of optical switch to support dynamic selection/shut-down of optical OFDM transceivers at OLT to save energy. Under low traffic loads, some optical OFDM transceivers in OLT are switched off (i.e., put to the sleeping mode); while some others can be shared by different ONUs. In the latter case, the ONUs who share the same wavelength transmit their data using different OFDM subcarriers. Again, the energy efficiency problem remains unimproved under high traffic loads.

Regarding cost efficiency, due to the colorless requirement of WDM, each ONU re-uses the light source that is originated from OLT by means of colorless optical transceivers [4]–[8]. Notice that the colorless requirement here is referred to as the condition in which that each ONU has to use the same optical transceiver, which can support the reception of any wavelength injected remotely from the OLT, and launch (or re-use) the corresponding wavelength for easy operation and inventory management. To meet this need, these colorless transceivers are implemented by expensive devices, such as reflective SOA (RSOA) [4] and optical external modulators [5]–[8]. With more OFDM ONUs added to the hybrid PONs, the design of minimizing the number of costly colorless devices becomes a non-trivial task. Furthermore, such re-use of the light source for transmitting both downstream and upstream data gives rise to the Rayleigh backscattering (RB) problem. In the RB problem, the reflection of downstream signal causes interference to upstream optical signals, and vice versa, resulting in the degradation of both upstream and downstream signal performance. To mitigate the interference to upstream signals, the work [5] used the low-order OOK modulation format for transmitting upstream signals. The price paid is a decrease in data rate and spectral efficiency. To resolve the RB problem, the work [5], [6] proposed the use of additional fiber to transmit upstream signals, which is cost inefficient for PONs.

Our major goal of this work is to tackle the energy and cost efficiency problems from an architecture perspective. In this paper, we propose an energy and cost efficient WDM/OFDMA PON system (NEWOPS). Based on a new two-tiered semi-tree architecture, NEWOPS allows a large number of ONUs to be connected to OLT using only a handful of colorless transceivers. Due to the architecture, NEWOPS not only facilitates high spectral efficiency and flexible sub-channel bandwidth allocation, but also reduces the RB problem and achieves high energy and cost efficiency. Experimental results demonstrate that, taking only 5-GHz bandwidth for each wavelength, NEWOPS successfully achieves 20-Gb/s OFDM-32QAM downstream and 10-Gb/s OFDM-8QAM upstream transmissions via the same fiber trunk. We depict that, to support 40 ONUs for example, NEWOPS achieves energy efficiency that is three to six times higher than that of a typical 10-Gb/s WDM/OFDM PON.

The remainder of the paper is organized as follows. In Section II, we describe the architecture of NEWOPS. In Section III, we present the experimental set-up and demonstrate experimental results. Finally, concluding remarks are given in Section IV.

II. SYSTEM ARCHITECTURE

As shown in Fig. 1(a), NEWOPS is a two-tiered semi-tree-based PON, which connects a total of N or W × M ONUs to

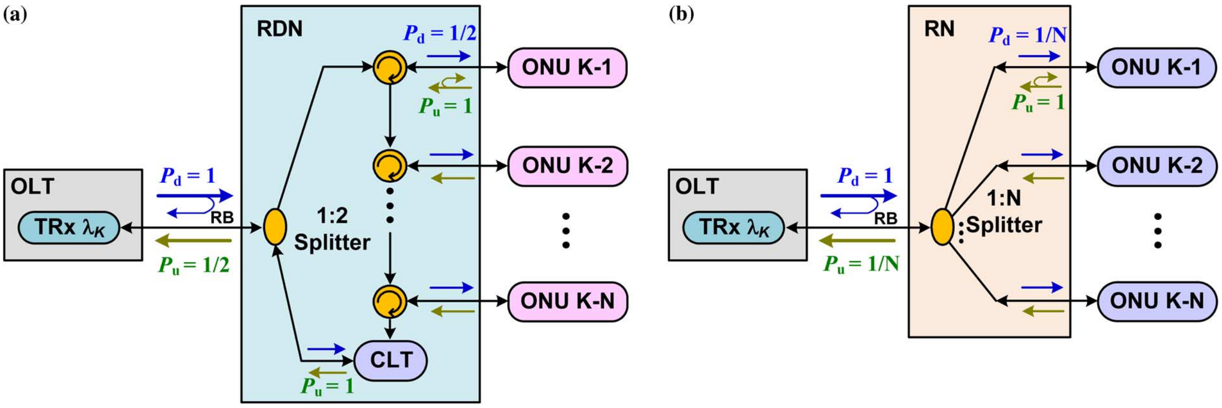


Fig. 2. The RB problem comparison. (a) NEWOPS, and (b) traditional tree-based PON architecture.

OLT, where W is the total number of wavelengths, and M is the number of ONUs in a section sharing the same wavelength. In the first tier, the OLT is directly connected to W sections of ONUs through a WDM multiplexer (i.e., array waveguide grating (AWG)), a WDM AWG demultiplexer, and W short trunk fibers. In this tier, the tree structure is exhibited and the transmission is on wavelength basis. In the second tier, each WDM AWG demultiplexer port is further connected to a section of M ONUs through a remote distribution node (RDN). In this tier, a virtual-tree [9] structure is employed, and the transmission is on OFDM basis.

As shown in Fig. 1(b), a RDN is composed of a splitter, M three-port bypassable circulators (each of which connects to an ONU), and a colorless transceiver (CLT). The splitter distributes the downstream OFDM signal to two optical beams. The first beam is directly passed to the first ONU in the section, then to the next, and finally to the last ONU in the section in a point-to-point manner. At each ONU, the downstream OFDM signal is received by the optical receiver and converted into its electrical form. The signal is dropped if the address matches with that of the ONU. At this moment, the ONU inserts its OFDM upstream data using the subcarriers to be determined by the medium access control (MAC) of the ONU. Together with the remaining downstream data, the combined OFDMA signal is modulated and optically transmitted to the next ONU (via any wavelength). Notice that, to ensure that path remains operative, one can use a power detection circuit [9] to drive the circulator to the "bypass" mode if an insufficient power is detected due to the breakdown or power-off of an ONU. In addition, because the signal is electrically regenerated at every ONU, the optical power budget is only needed to cover the optical link loss from OLT to the first ONU or from the CLT to OLT, while the first ONU can be managed to remain always-on. Specifically, the power loss of transmitting signals from the second ONU to the last ONU can be disregarded, due to point-to-point E-O-E conversion and short fiber distance between adjacent ONUs. Therefore, NEWOPS is free from the power budget problem, and highly scalable with an increasing ONU number.

The second optical beam is directed to the CLT that serves as a light source for the colorless upstream transmissions for the entire section. The CLT for a section consists of a photodiode, an electro-absorption modulator (EAM), a nonlinear SOA, and a circulator, as shown in Fig. 1(b). The photodiode is used to receive the aggregated upstream OFDM signal from the last ONU in the section. Before passing the light source to EAM, the light source that conveys unwanted downstream OFDM signal is first passed to the nonlinear SOA that operates in the saturation region in order to erase the downstream signal. The EAM then employs the optical beam to modulate the aggregated upstream data received by the photodiode. Finally, the upstream signal is passed through the circulator, the splitter of this section, and ultimately to the OLT via the same (downstream) fiber trunk.

Due to the two-tiered semi-tree architecture, NEWOPS can take full advantage of OFDM technology to achieve high bandwidth efficiency and flexible sub-channel bandwidth allocation without suffering from the OBI problem. Further, even when affected by Rayleigh backscattering, NEWOPS can achieve 20-Gb/s downstream and 10-Gb/s upstream signal transmissions with OFDM and adaptive QAM-modulation. Compared with other methods [5], [6], our architecture avoids the use of additional fibers or lower-efficiency modulation formats, such as OOK. At the same time, NEWOPS exploits WDM technology to support W × N ONUs at a low cost of using only W (instead of W × N) optical OFDM transceivers at the OLT, and W (instead of W × N) CLTs at the ONU side. Altogether, as will be shown in the next section, NEWOPS achieves higher energy efficiency compared to a typical tree-based WDM/OFDM PON.

Moreover, due to the new two-tiered semi-tree architecture, NEWOPS also reduces the RB problem, as depicted in Fig. 2. In the figure, we draw a schematic comparison between NEWOPS and the traditional tree-based PON architecture. For the ease of description, we only include a single wavelength in the illustration. First, we assume that the launched powers of all the transmitters in both architectures are identical ($P_d = P_u = 1$). For the downstream signal, it suffers from RB that is caused primarily by the upstream signal near to each ONU [10]. Therefore, the signal to RB interference ratio (SRIR) is approximately proportional to $P_d/P_u = 1/2$ for the first ONU in NEWOPS (see Fig. 2(a)) and 1/N for each ONU in the tree architecture (see Fig. 2(b)). As for the remaining ONUs in NEWOPS, the SRIR will be higher since no splitter is used between ONUs. Similarly, for the upstream signal, it suffers from RB that is caused primarily by the downstream signal near to the OLT. Therefore, the SRIRs are approximately proportional to $P_u/P_d = 1/2$ and 1/N in Fig. 2(a) and (b), respectively. As a result, compared to the traditional tree-based architecture, NEWOPS not only yields lower splitting loss, but it also enhances SRIRs for both down-

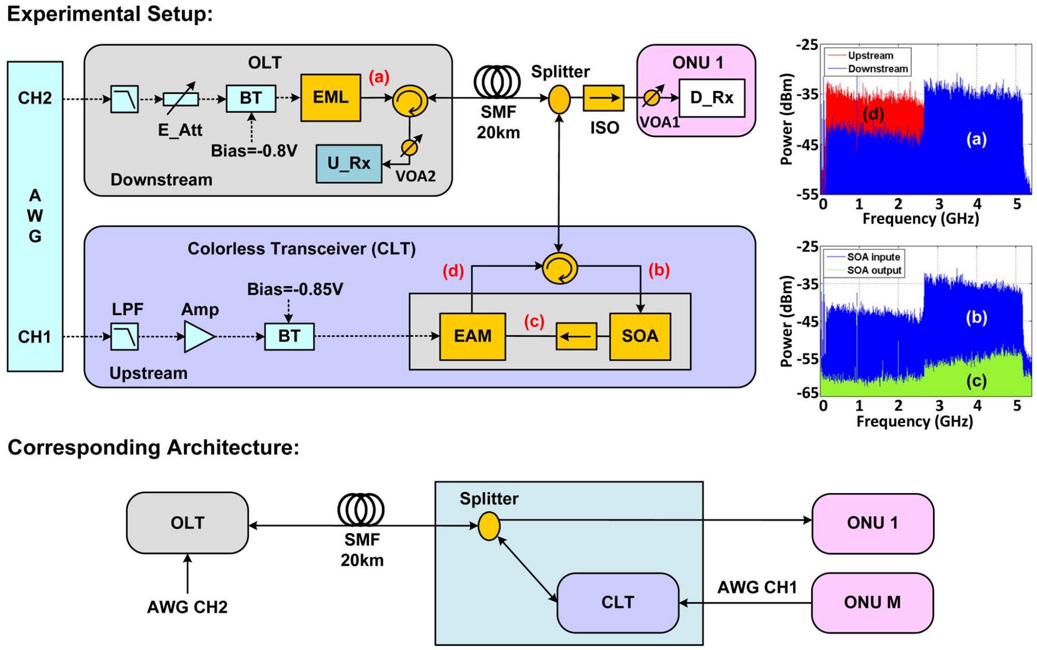


Fig. 3. Experimental setup, its corresponding architecture, and spectrum results of downstream and upstream signals. (a) downstream signal; (b) downstream signal after transmission; (c) downstream signal after being erased; and (d) upstream signal.

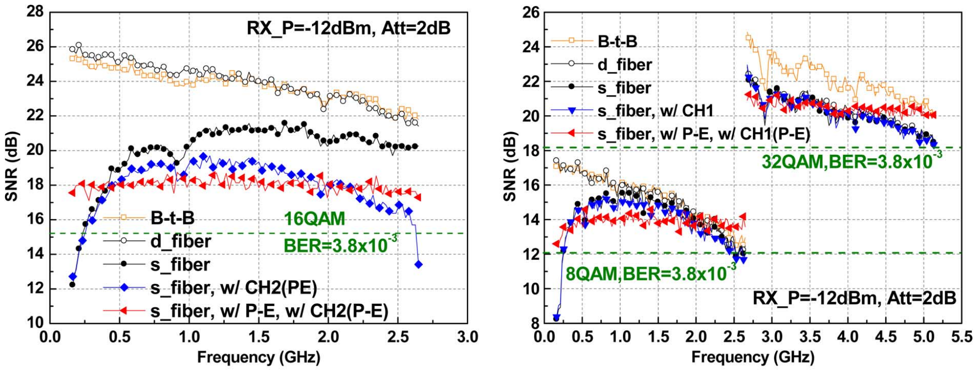
stream and upstream signals. It is worth noting that, the work in [10] also arrived at a similar result that lower optical loss between OLT and ONU can improve the SRIR performance.

III. EXPERIMENTAIL SET-UP AND RESULTS

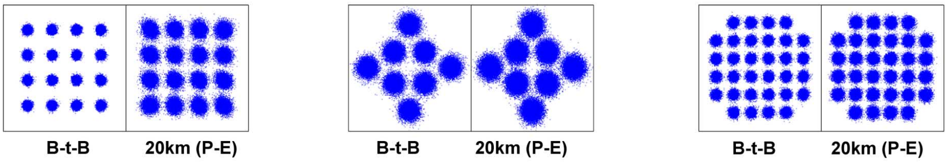
In Fig. 3, we show the experimental setup, its corresponding architecture, and the spectrum results of upstream and downstream OFDM signals at various stages. The OFDM signals are generated by an arbitrary waveform generator (AWG, Tektronix AWG7122) using the Matlab program. The sampling rate and digital-to-analog converter resolution are 12 GS/s and 8 bits, respectively. The downstream signal is generated from channel 2 (CH2). It consist of 8-QAM symbols that are encoded at subcarriers 7-113 and 32-QAM symbols at subcarriers 114-220, using a total bandwidth of 5 GHz, thus yielding a data rate of 20 Gb/s.

At OLT, we use a 3-dB modulation bandwidth of 10-GHz EML that is biased at -0.8 V through a bias tee (BT) and modulated with downstream OFDM data, after changing the input signal power of electro-absorption modulated laser (EML) via an electrical attenuator. The optical output power and wavelength of the EML are 2 dBm and 1550 nm, respectively. It is worth noting that, 2-dBm EML was used due to the lack of access to high powered EML in our laboratory. High powered EML—at 6 dBm, for example—should be used to provide sufficient optical power budget. To get around the problem, we used 2-dBm EML in our experiment to emulate the output optical signal of a 6-dBm EML passing through the first AWG multiplexer in Fig. 1. The downstream signal spectrum is shown in Fig. 3(a). After optical modulation, followed by a 20-km single-mode-fiber transmission, an optical power splitter splits the signal to the downstream receiver (D_RX) of ONU1 and the SOA of the CLT. A variable optical attenuator (VOA1) is located in front of the ONU1 receiver to emulate the optical power loss from the AWG demultiplexer and optical circulator in Fig. 1. The downstream signal spectrum after transmission is shown in Fig. 3(b). After the SOA, the power is suppressed by 20 dB, as shown in Fig. 3(c). The upstream OFDM data is generated from channel 1 (CH1) of the AWG. The signal is modulated by the colorless light source via an EAM biased at -0.85 V. The upstream signal consists of an OFDM signal of 23.44-MSym/s 16-QAM symbol that is encoded at subcarriers 7-113 with a bandwidth of 2.51 GHz, achieving a total data rate of 10.04 Gb/s, as shown in Fig. 3(d). An optical isolator is placed between the SOA and EAM to prevent signal reflection. The optical upstream signal is finally sent to the upstream receiver (U_RX) of OLT via a circulator. A variable optical attenuator (VOA2) is also located in front of the OLT receiver to emulate the optical power loss from the AWG multiplexer and demultiplexer in Fig. 1. Notice that the SOA eraser cannot fully eliminate the downstream signal before passing to EAM. To prevent the upstream signal from the interference caused by the residual downstream signal, the electrical power of the subcarriers 7-113 (the left side of the blue area) of downstream signal is purposely diminished prior to the transmission compared to that of the subcarriers 114-220 (the right side of blue area), as shown in Fig. 3(a).

Furthermore, we show in Fig. 4 the SNR performance and constellation diagrams of the downstream and upstream OFDM subcarriers, under four different cases. In the first case, the upstream and downstream data are carried via different fibers. As shown by the two “d-fiber” curves in Fig. 4(a) and 4(b), the results serve as the baseline information for the best-case scenario in which transmissions are free from RB and residual signal interference. In the second case, the upstream and downstream data are transmitted via the same fiber, but only with the downstream data encoded and upstream data replaced by a CW signal. As shown in “s-fiber” curves, the results show that RB accounts for considerable SNR degradation, especially for subcarriers of low frequencies. In the third case, both upstream and downstream data are encoded and carried via the same fiber. As shown in blue curves, we observe a $3 \sim 4$-dB SNR degradation for the highest frequency upstream subcarriers due to residual

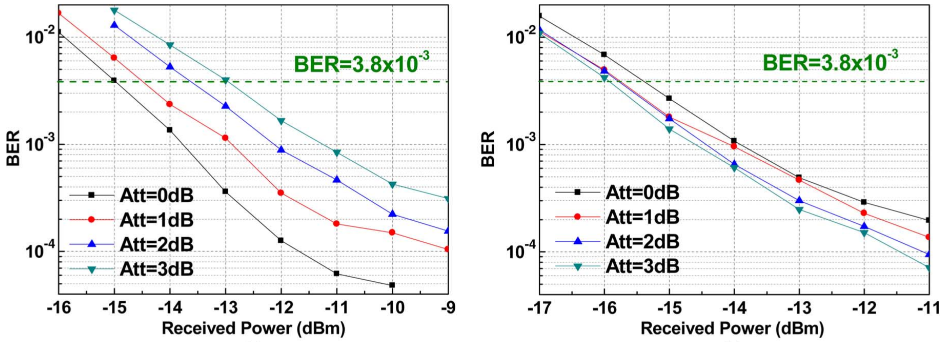


(a) Upstream SNR (b) Downstream SNR



(c) 16-QAM constellation (d) 8-QAM constellation (e) 32-QAM constellation

Fig. 4. SNR of (a) upstream signal, and (b) downstream signal; and constellation of (c) upstream 16- QAM, (d) downstream 8-QAM, and (e) downstream 32-QAM.



(a) (b)

Fig. 5. BER vs. received power of (a) upstream, and (b) downstream.

signal interference. In the last case, we follow the third-case scenario but apply power pre-emphasis. As shown in the red curves of Fig. 4, we observe a substantial improvement on SNR across all subcarriers for both downstream and upstream data. The determination of the downstream modulation voltage is a trade-off problem—higher voltage (lower attenuation) yields better downstream BER but poorer upstream BER (due to more residual signal after SOA). Experimental results plotted in Fig. 5 show that the system achieves superior receiver sensitivities. Specifically, with 0-dB attenuation applied, the system attains superior receiver sensitivities of -15 dBm and -15.4 dBm for transporting 20-Gb/s downstream and 10-Gb/s upstream signals, respectively. As for the optical power budget, since the ONU1 receiver sensitivity is -15 dBm, with a 2-dBm EML replaced by the a 6-dBm high powered EML, NEWOPS can support a 21-dB optical power budget from OLT to ONU1, which is sufficient for covering the 20-dB downlink loss. For upstream transmissions, the output power of the SOA is 14 dBm and the optical losses of the EAM and optical isolator are 6 dB and 1 dB, respectively, making the launch power of the CLT being equal to 7 dBm. Since the OLT receiver sensitivity is -15.4 dBm, the optical power budget is 22.4 dB, which is just enough to cover the 20-dB uplink loss.

To draw comparisons of cost and energy efficiencies between NEWOPS and existing PON systems, we introduce three existing hybrid WDM/OFDM PON systems: PON-1 [5], [7], PON-2 [8], and PON-3 [4]. They are briefly described in the following. In PON-1 [5], [7], each OLT-ONU connection is assigned an individual wavelength and the MZM-based CLT in ONU reuses the wavelength for the upstream signal. Since the wavelength is reused, twice the power loss from the optical distribution network (ODN) is induced. Thus, the system uses an EDFA at OLT to compensate the power loss. In OLT, the downstream OFDM signal is frequently up-converted to generate a guard band after the photo-detection in ONU to avoid intermodulation distortion (IMD), and the upstream OOK signal can be allocated in this guard band. Since the downstream optical OFDM signal is of double sideband (DSB), an optical filter is used at ONU to remove one sideband (called optical single side-band (OSSB)) to avoid the RF power fading problem.

For PON-2 [8], its architecture is similar to that of PON-1, except that the optical filter is allocated at OLT instead of ONU, and the optical coherent receiver is adopted in OLT to greatly improve the receiver sensitivity. In PON-3 [4], each OLT-ONU connection is also assigned a distinct wavelength. For upstream, instead of reusing the downstream optical signal, a multiple-wavelength source (MWS) is used at OLT to remotely provide the light source to the RSOA-based CLT in ONU. An optical switch is also used at OLT to dynamically select the OFDM

TABLE I
COMPARISONS OF DIFFERENT HYBRID WDM/OFDM PON SYSTEMS

Hybrid PON System	Spectral Efficiency	Sub-Wavelength Allocation (Upstream)	Cost	ONU's Data Rate (Gb/s)	Energy Efficiency
PON-1 [5,7]	–Frequency Up-Converted OFDM –10Gb/s with >10GHz	No	–Medium –N×TRx and 1×EDFA at OLT –1×Optical Interleaver at each ONU –1×CLT (MZM) at each ONU	10	Medium
PON-2 [8]	–Frequency Up-Converted OFDM –10Gb/s with >10GHz	No	–High –N×(Tx+Coherent Rx) and 1×EDFA at OLT –1×Optical Interleaver at each ONU –1×CLT (MZM) at each ONU	10	Low
PON-3 [4]	–OFDM –10Gb/s with 3.5GHz	No	–Medium –N×(TRx+LD), Optical Switch and EDFA at OLT –1×CLT (RSOA) at each ONU	1~10	Medium
NEWOPS	–OFDM –20Gb/s with 5GHz	Yes	–Low –W×TRx at OLT –W×CLT (SOA+EAM) for N×ONUs	1~20	High

transceivers based on the traffic load, and unused OFDM transceivers can be turned off to save the power consumption.

Table I compares spectral efficiency, sub-wavelength allocation, cost, ONU's data rate, and energy efficiency between NEWOPS and three different hybrid WDM/OFDM PON systems, PON-1, PON-2, and PON-3. Firstly, spectral efficiency is defined as the ratio of the data rate to required occupied bandwidth. PON-1 and PON-2 frequently up-convert the 10-Gb/s OFDM signal to 10 GHz, resulting in lower spectral efficiency. PON-3 achieves 10 Gb/s data rate within a 3.5-GHz bandwidth. Compared to these systems, NEWOPS is capable of transmitting 20-Gb/s OFDM signal within a 5-GHz bandwidth, yielding the highest spectral efficiency. Secondly, among the four systems, only NEWOPS is capable of supporting upstream sub-wavelength allocation via OFDMA without suffering from the OBI problem due to its unique architecture. Thirdly, considering the cost, all three systems need a CLT at each ONU and a corresponding optical OFDM transceiver at OLT. Therefore, they all require a total of N optical OFDM transceivers at OLT and N CLT's (MZM or RSOA) at the ONU side, which significantly increases the total cost. Further, PON-1 and PON-2 require additional optical filter at ONU to generate OSSB signal, while PON-2 uses N expensive and complicated optical coherent receivers at OLT, driving the cost even higher. Compared to these systems, the NEWOPS unique architecture requires only W OFDM transceivers at OLT and W CLTs at the ONU side, to support a total of $\mathrm{W} \times \mathrm{M}$ ONUs (where W is the wavelength number, and M is the number of ONUs in a section sharing the same wavelength). Fourthly, for the data rate performance, both PON-1 PON-2 are capable of providing a high but fixed downstream data rate of 10 Gb/s for each ONU. As opposed to them, PON-3 and NEWOPS can provide flexible and dynamic downstream rates between $1 \sim 10$ Gb/s and $1 \sim 20$ Gb/s, respectively, due to their OFDMA sub-wavelength allocation feature. Lastly, as for energy efficiency, despite the fact that PON-1 to -3 are capable of providing a 10-Gb/s data rate for each ONU, these systems use a high number of optical OFDM transceivers and EDFA in OLT—especially PON-2, which uses a complicated and energy-consuming coherent receiver—causing PON-1 and PON-3 to reach medium energy efficiency, and PON-2 to suffer from low energy efficiency.

To focus on energy efficiency, we further depict in Tables II and III the energy efficiencies of the above PON-3 system [4] and NEWOPS, respectively. Both PONs are assumed to have 40 ONUs $(\mathrm{N} = 40)$. While PON-3 uses 40 wavelengths $(\mathrm{W} = 40)$, NEWOPS adopts 8 wavelengths $(\mathrm{W} = 8)$ each of which supports 5 ONUs $(\mathrm{M} = 5)$ within a section sharing the same wavelength. The PON-3 system is based on RSOA-based remodulated colorless transceiver [4], and can operate at a data rate of $1 \sim 10$ Gb/s per wavelength based on selectable OFDM modulation modules in OLT [4]. The energy consumption of the components in Tables II and III are based on the articles in [11]–[14], and the energy consumption of OFDM DSP can be calculated roughly to be 18.2 mW/Gb/s, which is proposed in article [13]. The energy efficiency is defined as the ratio of the data rate of an ONU to the per-ONU energy consumption, while the per-ONU energy consumption is calculated as the total energy consumption for the entire PON (OLT plus all ONUs) divided by the number of ONUs, N. Pertaining to the data rate of an ONU, in the case of the PON-3 system, since each wavelength is dedicated to an ONU, each ONU therefore receives a data rate of $1 \sim 10$ Gb/s [4]. For NEWOPS, due to OFDM sub-channel-based bandwidth allocation of the total bandwidth, 20 Gb/s, each ONU receives a minimum of $20/5 = 4\ \mathrm{Gb/s}$ under fair sharing assumption, and a maximum of 20 Gb/s under the hot-spot-ONU assumption. The results in Tables II and III show that, compared to the PON-3 system that exhibits an energy efficiency, ranging from 0.162×10^9 (bit/Joule) to $1.62 \times$

TABLE II
ENERGY EFFICIENCY PER ONU FOR THE PON-3 SYSTEM [4] ($\mathrm{N} = 40, \mathrm{W} = 40$)

Components	Specifications	Quantity	Energy Consumption per ONU (Watt)	Energy Efficiency per ONU (bit/Joule)
OLT				Maximum: [10(Gb/s)/6.18W] =1.62×10^9 Minimum: [1(Gb/s)/6.18W] =0.162×10^9
DS Optical Tx	10-Gb/s DML/EML+Driver	N	1.2	
US Optical Rx	10-Gb/s PIN-TIA+LA	N	0.45	
Multi-Wavelength Source for ONU	Laser Diode+Driver	N	1.2	
OFDM TRx DSP	10 Gb/s	N	0.182	
ADC+DAC	10 GS/s	N	1	
EDFA/SOA	10 Gb/s	1	4.5/N	
ONU				
DS Optical Rx	10-Gbps PIN+TIA+LA	1	0.45	
US RSOA	RSOA+Driver	1	0.4	
OFDM TRx DSP	10 Gb/s	1	0.182	
ADC+DAC	10 GS/s	1	1	
Sum (N=40)			6.064+(4.5/N)=6.18	

TABLE III
ENERGY EFFICIENCY PER ONU FOR NEWOPS ($\mathrm{N} = 40, \mathrm{W} = 8, \mathrm{M} = 5$)

Components	Specifications	Quantity	Energy Consumption per ONU (Watt)	Energy Efficiency per ONU (bit/Joule)
OLT				Maximum: [20(Gb/s)/3.97W] =5.04×10^9 Minimum: [4(Gb/s)/3.97W] =1×10^9
DS Optical Tx	10-GHz DML/EML+Driver	1	1.2/M	
US Optical Rx	10-GHz PIN-TIA+LA	1	0.45/M	
OFDM TRx DSP	20 Gb/s	1	0.364/M	
ADC+DAC	12 GS/s	1	1/M	
ONU				
DS Optical Rx	10-GHz PIN+TIA+LA	1	0.45	
US Optical Tx	10-GHz DML/EML+Driver	1	1.2	
OFDM TRx DSP	20 Gb/s	1	0.364	
ADC+DAC	12 GS/s	1	1	
Colorless Optical TRx	10-GHz SOA+EAM	1	(0.6+1.2)/M	
Sum (M=5)			3.01+(4.81/M)=3.97	

10^9 (bit/Joule), NEWOPS achieves three to six times higher energy efficiency, ranging from 1×10^9 (bit/Joule) to 5.04×10^9 (bit/Joule).

IV. CONCLUSIONS

In this paper, we have proposed a novel two-tiered semi-tree-based WDM/OFDMA PON system, NEWOPS. Due to the new architecture, NEWOPS not only facilitates high spectral efficiency and flexible sub-channel bandwidth allocation, but also reduces the RB problem and achieves high energy and cost efficiency. Experimental results show that, using only 5-GHz bandwidth and adaptive modulation, NEWOPS successfully achieves 20-Gb/s OFDM-32QAM downstream and 10-Gb/s OFDM-8QAM upstream transmissions per each wavelength via the same fiber trunk. Based on per-ONU energy-efficiency calculation, we depict that, to support 40 ONUs for example, NEWOPS achieves energy efficiency that is three to six times higher than that of a typical tree-based 10-Gb/s WDM/OFDM PON.

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