OFDMA- PON: High Speed PON Access System

Soumen Biswas, Sarosij Adak

Abstract— Principal requirements and technology trends of advanced DSP for high-speed, real-time Orthogonal Frequency Division Multiple Access (OFDMA)-based PON are analyzed. Key benefits emerge from component integration, mass production and parallel activity in long-haul fiber systems. Future PON technologies are highly cost-efficient to remain attractive and practical. OFDM technology that is well-suited for future PON Systems. But it requires advanced Digital Signal Processing (DSP). Moreover, we provide an analysis of primary cost factors in a practical DSP-based OFDMA-PON implementation and survey the most recent achievements in this domain. Due to the combination of highly attractive advanced features and favorable related trends in long haul fiber transmission, OFDMA-PON can be regarded as a very promising solution for future PON-based access.

Keywords—OFDM, OOFDM, Passive Optical Network (PON).

I. INTRODUCTION

DEMAND for high-speed data communication Services has recently been increasing as a result of the popularity of Internet services. Optical access deployments happening worldwide, with regional customized flavors built on generic transmission. Orthogonal frequency division multiplexing (OFDM) is a promising technique for high-data-rate wireless communications because it can combat inter-symbol interference (ISI) caused by the dispersive fading of wireless channels. OFDMA-PON technology is novel DSP-based platform for speed, flexibility and cost-efficiency in future high-speed PON access systems.

Currently, the main target future ultra-high speed PON systems is to provide higher per-user data rates to an increased number of subscribers, and achieve longer transmission distances. For instance, the ability of the future ultra-high-speed PON to deliver arbitrary analog and digital services over a common platform, facilitating access network convergence, has emerged as a highly desirable trait from the network carrier perspective [4]. Likewise, full-scale adaptive bandwidth allocation to different users and services with fine bandwidth tunability has been identified as an equally attractive feature [4, 5]. Through such advanced features, the ultra-high-speed access network is envisioned to flexibly accommodate emerging services and applications. Finally, it is critical that future optical access systems be highly cost efficient. Unlike long-haul fiber optic networks where distance bandwidth products are sufficiently large to leverage high implementation cost, PON-based access networks (< 100 km) must maintain low hardware and operational expenses to remain attractive and practical [1].

II. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

A. Basic Principles of OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. OFDM is similar to FDMA in that the multiple user access is achieved by subdividing the available bandwidth into multiple channels that are then allocated to users. However, OFDM uses the 10 spectrum much more efficiently by spacing the channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers.

B. Orthogonality Defined

Orthogonality is defined for both real and complex valued functions. The functions $\phi_m(t)$ and $\phi_n(t)$are said to be orthogonal with respect to each other over the interval $a < t < b$ if they satisfy the condition:

$$\int_a^b \varphi_m(t)\,\varphi_m^*(t)\,dt = 0, \quad \text{Where } n \neq m \tag{1}$$

OFDM splits the available bandwidth into many narrowband channels (typically 100-8000), each with its own sub-carrier. These sub-carriers are made orthogonal to one another, meaning that each one has an integer number of cycles over a symbol period. Thus the spectrum of each sub-carrier has a “null” at the centre frequency of each of the other sub-carriers in the system, as demonstrated in Figure 1 below. This results in no interference between the sub-carriers, allowing then to be spaced as close as theoretically possible. Because of this, there is no great need for users of the channel to be time-multiplexed, and there is no overhead associated with witching between users. This overcomes the problem of overhead carrier spacing required in FDMA.

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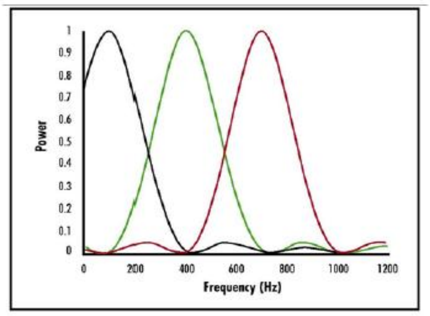

Figure 1: Orthogonality of Sub-carriers

C. OFDM Carriers

As-fore mentioned, OFDM is a special form of Multi Carrier Modulation (MCM) and the OFDM time domain waveforms are chosen such that mutual Orthogonality is ensured even though sub-carrier spectra may over-lap. With respect to OFDM, it can be stated that Orthogonality is an implication of a definite and fixed relationship between all carriers in the collection.

It means that each carrier is positioned such that it occurs at the zero energy frequency point of all other carriers. The sinc function, illustrated in Figure 2 exhibits this property and it is used as a carrier in an OFDM system.

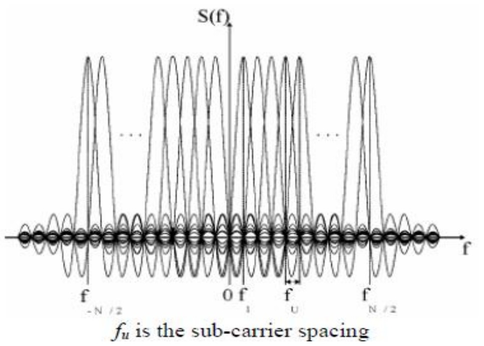

Figure 2: OFDM sub carriers in the frequency domain

III. OPTICAL OFDM IN ACCESS

Spectral efficiency is an important aspect of WDM systems. Optical OFDM's spectral efficiency is up to 1 bit/s/Hz, in principle. This method utilizes the Orthogonality between the spectral profiles of each channel. The N multiplexed signals, whose frequency spacing is Δf, can be represented as

$$S(k\Delta t) = \sum_{n=0}^{N-1} d_n(k\Delta t)\, e^{j2\pi(f_0+n\Delta f)k\Delta t} \qquad (2)$$

where $d_n(t)$ is the data sequence of the nth channel, T is the symbol interval and $\Delta t = T/N$ is the sampling interval. The multiplexed data sequence can be separated using a discrete Fourier transform (DFT),

$$d_n = \sum_{k=0}^{N-1} S(k\Delta t)\, e^{-j2\pi(f_0+n\Delta f)k\Delta t} \qquad (3)$$

We can implement the optical DFT as shown in Figure 3. In eq.(3), the terms S($k\Delta t$) and $e^{-j2\Delta k\Delta f\Delta t}$ physically represent an optical delay line with delay time $k\Delta t$, and a phase shifter, respectively. The summation means an optical coupler. Furthermore, we require bit synchronization at the input and an optical gate at the output, because the optical DFT is effective for the duration of unchanged $dn(t)$.

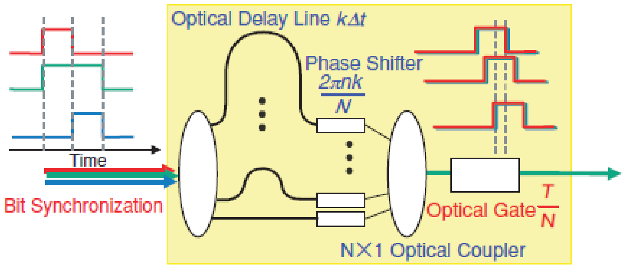

Figure 3: Optical Circuit for Discrete Fourier Transform

IV. OFDM BASED PON

As a candidate technology for future ultra-high speed optical access, optical OFDMA offers significant advantages from both the physical layer and networking perspectives. First, as a multicarrier transmission technique, optical orthogonal frequency-division multiplexing (OFDM) adopts a "divide and conquer" approach to ultra-high speed fiber optic transmission. This is achieved by subdividing a high-bandwidth signal into many partially overlapping yet non-interfering lower-bandwidth tributaries, or OFDM subcarriers, as illustrated in Figure 4. Through the principle of Orthogonality, for a system with N total OFDM subcarriers, the OFDM subcarrier frequencies, fn, are selected as

$$f_n = n/T\ ,\ n=1,2,.....N \qquad (4)$$

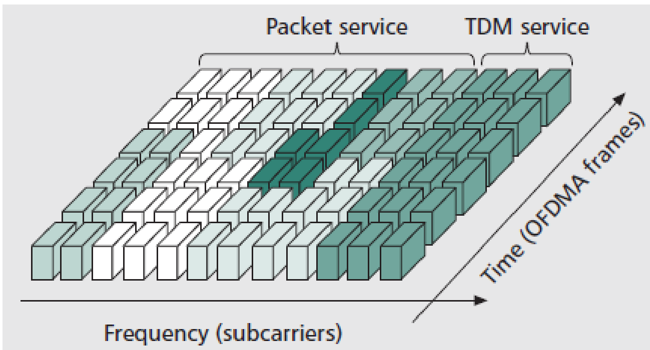

Figure 4: Frequency and Time domain partitioning of an OFDMA frame

Where T denotes the symbol time on each OFDM subcarrier. By keeping T fixed and increasing N, a high-speed OFDM signal is generated that exhibits very high resilience to dominant linear impairments in fiber, including both chromatic dispersion (CD) and polarization mode dispersion (PMD) [7-9]. Moreover, OFDM boasts a highly efficient DSP-based implementation based on the fast Fourier transform (FFT), which also enables straightforward adaptation of the modulation format on each OFDM subcarrier.

A corollary of this result is that spectral efficiency can be increased cost effectively within a fixed physical bandwidth by employing multilevel signaling, such as *M*-ary quadrature amplitude modulation (QAM) with $M \geq 4$. Consequently, the physical layer benefits of optical OFDM based PON are analogous to those that have made OFDM the technology of choice in high speed wireless systems, as well as copper-based digital subscriber line (DSL). For further information on optical OFDM signal generation, the reader is referred to [7–9].

From a networking point of view, each optical OFDM subcarrier can be regarded as a transparent pipe for the delivery of arbitrary network traffic. Moreover, as a bandwidth resource with sub-wavelength granularity, OFDM subcarriers can also be dynamically assigned to different services and/or different users depending on the specific network demand [4]. This is effectively the fundamental paradigm behind dynamic bandwidth allocation and heterogeneous service provisioning in OFDM-based PON, which can also readily be extended to OFDMA-PON, by subdividing an OFDM band between multiple users and/or combining OFDM and TDMA, such that each OFDM subcarrier can be further split among different services users in different time slots, also in a dynamic fashion. As a result, in OFDMA-PON dedicated sub-channels, which can be composed of one or more OFDM subcarriers and/or time slots, become fine-grained transparent pipes for the delivery of arbitrary analog or digital signals for both circuit- and packet-switched applications.

Figure 5 illustrates the downstream transmission of heterogeneous services in OFDMA-PON. The frequency and time domain partitioning of an OFDMA frame is first performed by the optical line terminal (OLT), with the resulting time/frequency schedule broadcasted to all of the optical network units (ONUs) over non-reserved OFDM subcarriers and preconfigured time slots. In forming the schedule, the OLT can reserve some subcarriers as dedicated transparent pipes and encapsulate packet-based data into remaining OFDM bands and time slots, according to the specific frequency and time domain scheduling results. For example, dedicated subcarriers (denoted by rectangular OFDM sub-bands in Fig. 5) can be reserved as orthogonal transparent pipes for legacy TDM (T1/E1) services and radio frequency (RF) mobile base station signals, respectively. Conversely, the remaining subcarriers in Figure 5 can transparently support packet-based Ethernet traffic over the same platform. As the traffic load, type, or user profile of the network change, the subcarrier assignment can be reconfigured accordingly. With this approach, OFDMA-PON is both flexible and extensible to any emerging/future applications, including legacy analog lines, digital multimedia transmission, cellular backhaul, layer 2 virtual private networks (VPNs), security channels for storage networks, and so on.

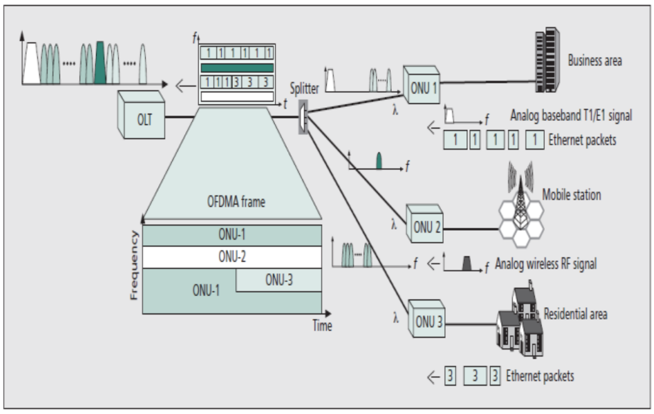

Figure 5: OFDMA PON architecture for delivery of heterogeneous services.

To complete downstream transmission, the OFDM frame and any other analog signals are mixed by an electrical coupler to drive the optical modulator. At the ONU side, following photo detection, each ONU selects its own data or signal from its pre-assigned subcarrier(s) and/or time slots, as communicated by the OLT scheduler. To transmit upstream traffic, each ONU maps its data and/or signal to its assigned OFDM subcarrier(s), nulls all remaining subcarriers, and performs OFDM modulation to generate a complete frame. For upstream transmission, each ONU maps its data and/or signal to its assigned OFDM subcarrier(s), nulls all remaining subcarriers, and performs OFDM modulation to generate a complete frame. In Figure 4, for example, ONU-3 would assign zeros to the subcarriers carrying the traffic of both ONU-1 and ONU-2, and use its pre-assigned OFDM subcarriers for upstream Ethernet packet transmission. It is also noted that ONUs with a variety of services and data rates can all be supported in a heterogeneous OFDMA-PON, which can help achieve a high degree of network flexibility and effectively manage cost.

V. OFDMA-PON TRANSMISSION USING POLARIZATION MULTIPLEXING WITH DIRECT DETECTION

Due to data rate limitations imposed by current electronic digital-to-analog converters (DACs), increasing spectral efficiency by polarization multiplexing — transmitting independent data streams in both orthogonally polarized components of the optical signal — is of great value in 100 Gb/s OFDM-based PON. Moreover, the inherent complexity of coherent optical receivers restricts their use in cost-sensitive access and metro application, making direct (non-coherent) ONU-side photo detection of the polarization multiplexed (POLMUX)- OFDM signal preferable. In order to implement POLMUX-OFDM with direct detection, however, a challenge that is not present in coherently detected

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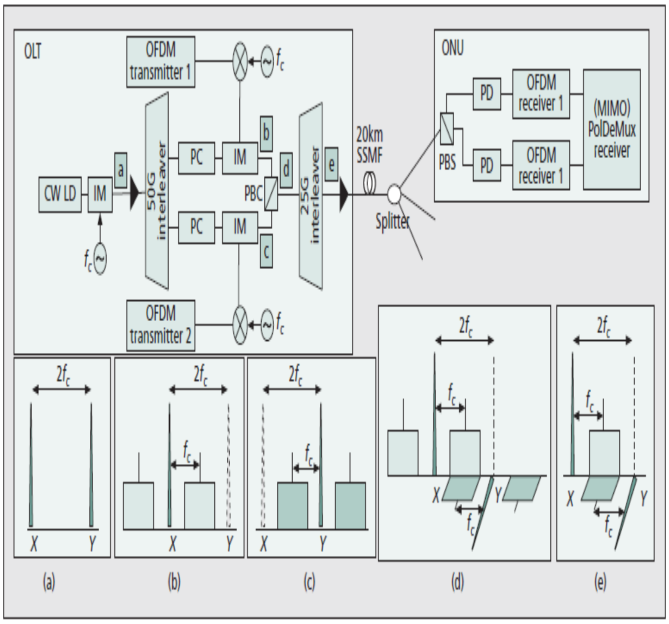

Figure 6: Proposed POLMUX-DD architecture (top) and frequency domain description of POLMUX-OFDM signal generation (bottom).

POLMUX transmission must first be addressed. Specifically, with coherent receivers polarization information is preserved such that full post-photo detection separation of the polarization-multiplexed data bands can readily be achieved. Under direct detection, however, the polarization information is lost during the non-coherent photo detection process. As a result, destructive interference can occur between signals on incoming polarization components [5]. At the photo detector output, this interference can translate to partial or complete signal fading [5]. Consequently, a DSP-based algorithm that solves the cross-polarization interference problem described here, while also maintaining the cost-efficient structure of a traditional direct detection receiver, emerges as the optimal solution for enabling 100 Gb/s POLMUX downstream transmission in OFDMA-PON. Figure 6 shows the schematic diagram of the proposed OFDMA-PON featuring POLMUX and direct detection [5]. At the OLT, a continuous wave laser drives an intensity modulator (IM) that is modulated by a clock source with frequency *fc*, generating two optical carriers, X and Y, separated by two times the clock source frequency, as in Fig. 6a. For example, when *fc* = 12.5 GHz, the two optical carriers are 25 GHz apart in the frequency domain. Next, an optical interleaver is used to separate the two optical carriers, X and Y, as illustrated in Figs. 6b and 6c, respectively. It is noted that in Figs. 6b and 6c, the optical carrier denoted by the dashed lines is in fact filtered out by the optical interleaver and is only shown as a reference to explain the frequency domain placement of the modulated OFDM signals. Each individual optical carrier next drives a separate IM, modulated by an independent radio frequency (RF) OFDM signal, which is generated by upconversion of the baseband OFDM signal via the in-phase quadrature- phase (IQ)-mixer. In the system of Fig. 6, the baseband OFDM signal was generated from N = 256 subcarriers, with M = 16-quadrature amplitude modulated (QAM) symbols loaded on each subcarrier. The RF carrier frequency of the IQ mixer is selected to be the same as that of the clock source modulating the first IM. Next, the two IM outputs are combined with a polarization beam combiner (PBC) to generate a POLMUX-OFDM signal with dual POLMUX carriers having orthogonal polarizations, as shown in Figure 6d. Finally, the two outer OFDM side bands are filtered out with another optical interleaver, as shown in Fig. 6e, and the resulting output signal is sent downstream. The example PON architecture of Fig. 6 adopts a 20 km transmission range with a 1:32 passive optical splitter to emulate the standardized class B+ optical distribution network. At the receiver side, the POLMUX-OFDM signal is divided by a polarization beam splitter (PBS), and the two PBS outputs are directly detected by two separate photodiodes. At this stage, the OFDM signals are still RF signals, so following ADC they are down converted to the baseband by two OFDM receivers. Finally, the DSP-based polarization demultiplexing (PolDe-Mux) processor successfully recovers the original OFDM data in each polarization via novel DSP algorithms described in [5]. It is also noted that the PolDeMux processor is designed for an arbitrary incoming polarization state, such that any variations among ONU-side polarization states will not affect algorithm performance. By leveraging advanced DSP to simplify front-end optics this way, 108 Gb/s downstream OFDMA-PON transmission over a single wavelength was experimentally demonstrated via polarization multiplexing and direct detection in [5], over 20 km of standard single-mode fiber and a 1:32 optical split ratio. This is currently the highest single wavelength downstream transmission rate experimentally demonstrated in any PON system.

VI. UPSTREAM OFDMA-PON TRANSMISSION USING SOURCE-FREE ONUS AND COHERENT DETECTION

In order to achieve high ONU-side cost efficiency, it is desirable that ONU-side operation, including high-speed upstream transmission, be “colorless” rather than adopt an architecture that is wavelength-specific to each ONU [10]. This can be achieved in OFDMA-PON by transmitting all upstream OFDM ONU signals over a common wavelength, λ. In this case it is necessary to upgrade the OLT-side receiver to a coherent receiver in order to avoid interference between upstream ONU signals that are all operating at a common wavelength [10]. It is noted that although such an OLT receiver upgrade may slightly increase cost, it is a minor penalty, since it can be amortized over all ONUs in the network, and can also notably improve upstream transmission performance by increasing the optical power budget. Figure 7 shows the proposed OFDMA-PON architecture for colorless single-wavelength 100 Gb/s upstream transmission. As shown in Fig. 7, in the OLT there are four continuous wave laser sources: λ1 for downstream (DS) transmission, λ2 as a distributed carrier for upstream (US) transmission, and λ3 and λ4 for coherent OLTside detection of the US signals. For DS transmission, an electrical OFDMA signal generated as described in [10] is used to drive an IM operating at λ1, combined with an unmodulated signal on λ2, as shown in Fig. 7a, and distributed to all ONUs through the same fiber path. At each ONU, an optical filter separates the DS OFDMA signal (λ1) from the distributed laser source (λ2), as in Fig. 7b,

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such that each ONU can reuse λ2 as the US optical carrier by biasing the ONU-side IM to achieve optical carrier suppression (Fig. 7c). Consequently, since the ONUs all use a distributed rather than an internal laser source for US transmission, they are effectively optical laser *source-free*. For US transmission, all ONUs in the network are categorized into *odd* and *even* groups, with the US signals from each group combined with a separate optical coupler. Next, the aggregate odd and even group signals are combined with an optical interleaver, such that US signals from the odd ONUs occupy the upper optical frequency sideband to the right of the suppressed optical carrier, λ2. Conversely, the US signals from the even ONUs occupy the lower optical frequency sideband to the left of λ2, as shown in Fig. 7d. Following 20 km upstream transmission over standard single mode fiber (SSMF), the signals in the odd and even groups are separated at the OLT, and coherent detection is then performed at the OLT for even and odd ONU groups, using λ3 and λ4, respectively, as in Fig. 7e and Fig. 7f. We note that since OLT-side even and odd coherent receivers each process a single sideband optical signal, there is no interference between signals in the two ONU groups during optoelectronic conversion, and the electrical OFDM signals from the odd and even ONUs can be fully recovered. The optoelectronic conversion is done with four photoreceivers, with the resulting electrical signals sampled by a real time oscilloscope. Finally, the US OFDM data symbols are recovered through offline DSP work as described in [10].

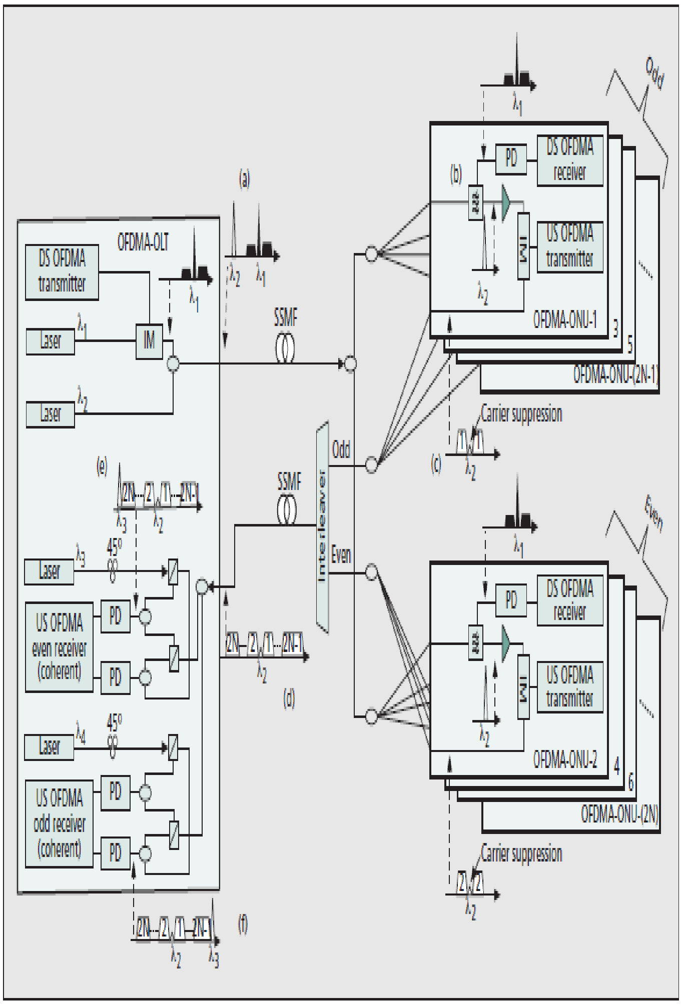

Figure 7: Upstream OFDMA-PON architecture with source-free ONUs and coherent OLT-side detection.

Recently, the colorless architecture of Fig. 7 was used to demonstrate 108-Gb/s single-wavelength US OFDMA-PON transmission over 20 km SSMF and a 1:32 optical split, achieved by six simultaneously transmitting ONUs [10]. The key enabling features were optical laser source free ONUs and OLT-side coherent detection that enabled optical double sideband transmission and full regeneration of the upstream electrical OFDMA signals. It is noted that this is also the highest single-wavelength upstream transmission rate in any PON reported to date.

VII. OFDM-PON TRANSMISSION

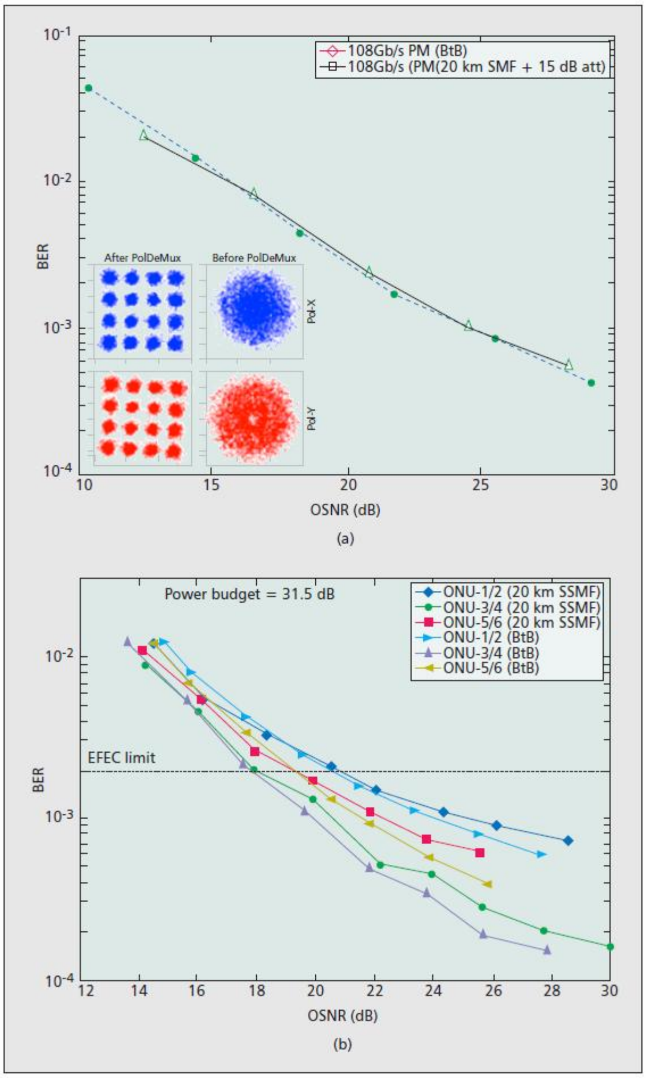

Figure 8: a) Experimental BER results for 108 Gb/s downstream OFDMAPON;b) experimental BER results for 108 Gb/s upstream OFDMA-PON.

Figure 8 plots the measured bit error rate (BER) vs. the optical signal-to-noise ratio (OSNR) for both back-to-back (BtB) and class B+ PON transmission (20 km SSMF with an additional 1:32 optical split) for 108 Gb/s DS (Fig. 8a) and 108 Gb/s US (Fig. 8b) OFDMA-PON experiments [5, 10]. Each BER value was based on 106 measurements, and computed through offline DSP. First considering downstream OFDMA-PON transmission performance in Fig. 8a,

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a comparison of the BtB and class B+ PON transmission curves reveals that the fiber chromatic dispersion penalty is negligible. This is directly attributed to the high linear dispersion tolerance of the OFDM modulation format. Moreover, for 108 Gb/s transmission over the class B+ PON, BER = 1.4 × 10–3 was achieved at OSNR = 21 dB, which corresponds to error-free operation after mandatory forward error correction (FEC). As shown in the inset of Fig. 8a, the novel DSP based PolDeMux algorithms for POLMUX OFDM with direct detection were highly effective in processing the channel-distorted data to recover the original 16-QAM data symbols in both polarizations. By exploiting advanced DSP in this way, superior performance and flexibility were achieved while notably simplifying ONUside optical receiver-end complexity. In Fig. 8b the BER vs. OSNR performance for 108 Gb/s upstream OFDMA-PON transmission is shown, with measurements made for six simultaneously transmitting ONUs in both BtB) and class B+ PON configurations. The slight BER variations among ONUs were caused by optical device variability and limitations of the electronic measurement equipment. Nonetheless, we note from Fig. 6b that at OSNR = 21 dB, each ONU achieved the FEC limit BER = 2 × 10–3 after class B+ PON transmission, with a total 31.5 dB power budget. This notable increase in the power budget is enabled by the OLT-side coherent receiver, indicating that the US architecture can be used over longer transmission distances and/or higher optical split ratios (class C/C+ PON, for example.) Moreover, it is noted that, as in DS OFDMA-PON transmission, the chromatic dispersion penalty is negligible due to the powerful linear dispersion resilience of optical OFDM-based transmission.

VIII. CONCLUSION

By enabling a converged ultra-high-speed multiservice platform with fine-grained dynamic bandwidth allocation, OFDM-based PON can significantly increase the data rates and flexibility of future PON-based access networks. It is expected that the significant progress in DSP-based processors for next-generation long-haul fiber systems, as well as component integration and mass production, will have favorable effects on the cost profile of practical OFDMA-PON implementations. As such, OFDMA-PON may be viewed as an attractive candidate for future ultrahigh-speed PON systems.

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