OFDM for Next-Generation Optical Access Networks

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(Invited Tutorial)

***Abstract*—In this tutorial overview, the principles, advantages, challenges, and practical requirements of optical orthogonal frequency division multiplexing (OFDM)-based optical access are presented, with an emphasis on orthogonal frequency division multiple access (OFDMA) for application in next-generation passive optical networks (PON). General OFDM principles, including orthogonality, cyclic prefix use, frequency-domain equalization, and multiuser OFDMA are summarized, followed by an overview of various optical OFDM(A) transceiver architectures for next-generation PON. Functional requirements are outlined for high-speed digital signal processors (DSP) and data converters in OFDMA-PON. A techno-economic outlook for such a "software-defined," DSP-based optical access platform is also provided.**

***Index Terms*—Digital signal processing (DSP), optical access, optical communication, orthogonal frequency division multiplexing (OFDM), orthogonal frequency division multiple access (OFDMA), passive optical network (PON).**

I. Introduction

In recent years, optical orthogonal frequency division multiplexing (OFDM) has emerged as a dominant R&D area in the field of high-speed optical communications [1]–[15]. Fundamentally, OFDM is an elegant "divide-and-conquer" approach to high-speed transmission, in which high aggregate data rates are achieved by parallel transmission of partially overlapped (i.e., spectrally efficient), lower rate frequency-domain tributaries. OFDM dates back to the 1960s [16], [17], and owing in large part to the transformational advent of large-scale integrated digital technologies, OFDM has since been adopted in an impressive set of high-impact applications. These include high-end digital subscriber lines, digital and high-definition television broadcasting, as well as wireless broadband applications ranging from wireless local area networks such as IEEE 802.11a/g and IEEE 802.16, to 4G long-term evolution (LTE)-based cellular systems [1], [17]. OFDM has also been explored for power line communications [18] and cognitive radio systems [19], as well as free-space optical [20]–[22] and multimode fiber transmission [8], [23]. And, despite the apparent heterogeneity in the aforementioned application domains, there is an underlying common factor which renders OFDM compelling in each case—namely, the need for high-speed transmission over a bandwidth-constrained physical medium with inherent linear distortions that must be efficiently corrected (equalized).

That the case of fiber-optic transmission should fit in this category is in itself a dramatic departure from the historical modus operandi, wherein fiber bandwidth was regarded as a virtually inexhaustible resource and transmission speeds were sufficiently low to render linear distortion effects sufficiently negligible. However, with the explosive, multimedia-driven growth of Internet traffic [24], it became evident that: 1) unless fiber bandwidth was used more efficiently, the operational spectrum range of optical amplifiers would be exceeded [25], [26]; and 2) that the fiber channel itself imposes fundamental capacity limits [27]. These vital considerations first made the high-profile case for optical OFDM (O-OFDM) in the context of spectrally efficient, next-generation 100 Gb/s/λ long-haul fiber transmission [4], [9], [28]. Excellent O-OFDM performance was subsequently demonstrated in a variety of notable experiments—currently, 1.2 [13], 101.7 [14], and 26 Tb/s [15] mark the aggregate data rate records of noncoherent O-OFDM, coherent optical OFDM (CO-OFDM), and all-optical OFDM (AO-OFDM), respectively.

However, as 100 Gb/s/λ long-haul fiber transmission systems move closer to commercial reality, single-carrier (SC) quadrature phase shift keying (QPSK), the special case of M-ary quadrature amplitude modulation (QAM) with $M = 4$, leads multicarrier OFDM as the underlying modulation format of choice [29]–[31]. While open to some debate, it appears that this is to be attributed to an attractive transmitter-side simplicity of QPSK, as well as its superior performance in the presence of periodic fiber dispersion maps [32], [33]. In any case, with long-haul, point-to-point fiber transmission having been the first prominent avenue for O-OFDM, these indications inadvertently beg the question of whether the "SC versus O-OFDM" debate has been settled in general. In other words, is the 100 Gb/s/λ long-haul case representative of future fiber-optic systems at large, or does OFDM have particular advantages in other application domains, including optical access?

In the context of next-generation optical access, the case for OFDM is based both on the access network "capacity crunch" driven by digital video traffic, mobile backhaul, in-home networking, etc. [13], and, equally importantly, on a point-to-multipoint network topology that is unique to this fiber-optic application domain [34]. Specifically, with point-to-multipoint passive optical networks (PON) accounting for the vast majority of global fiber-to-the-home (FTTH) deployments, and the number of worldwide FTTH subscribers projected to reach 100 million by 2013 [35], the PON architecture will undoubtedly

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play a significant role in future optical access. Furthermore, in terms of topology, a direct analogy may be drawn between the PON—consisting of a centralized optical line terminal (OLT) communicating with remote, user-side optical network units (ONUs) over a feeder fiber terminated by a passive optical split—and a wireless base station managing mobile terminals over a fixed radio frequency (RF) channel [36]. In both cases, the bandwidth resources are shared by multiple users, which access the broadcast channel in a centrally controlled fashion. Consequently, in PON-based access, the importance of the OFDM "divide-and-conquer" approach encompasses both the physical and the medium access control (MAC) layers: OFDM tributaries (i.e., subcarriers) are beneficial both because they enable efficient spectrum use and equalization, and because they can be used as transparent, finely granular resources for dynamic, multiuser bandwidth access. The latter concept, known as orthogonal frequency division multiple access (OFDMA), is widely adopted in OFDM-based wireless networks [17], [36] and presents a unique advantage for future PON systems. Specifically, the highly bursty traffic profile in PON, combined with a drive towards multi-service coexistence on a single platform, would make flexible, transparent inter user and/or service bandwidth sharing a premium [34].

In addition to dynamic bandwidth assignment, next-generation PON systems are also envisioned to address an aggressive set of service and network drivers [35], [37]–[39]. These include 40^{+} Gb/s and 10^{+} Gb/s aggregate downstream/upstream data rates over target reaches up to 100 km, with up to 1000 ONUs serviced by a given optical distribution network (ODN). Increases in the target reach and split ratios are also motivated by potential reductions in capital and operational expenses (CAPEX/OPEX) via node and network consolidation. Furthermore, to capitalize on significant fiber infrastructure investments, maximal reuse of the deployed ODN with passive optical splitters has been identified as highly desirable. Finally, colorless (i.e., wavelength agnostic) ONU-side operation, energy efficiency, open multioperator access, and, of course, low cost, are also among the foremost considerations.

To satisfy the requirements of future PON systems, several multiple-access candidate technologies have been proposed, including time division multiple access (TDMA)-PON, wavelength division multiplexed (WDM)-PON, OFDMA-PON, code division multiple access PON, as well as various hybrid options, formed from one or more of the aforementioned constituent technologies [10], [13], [40]–[44]. While entirely amenable to hybrid operation with both WDM and TDMA overlays, the distinguishing feature of OFDMA-based PON is a pronounced reliance on electronic digital signal processing (DSP) to tackle the key performance and cost challenges [45]. OFDMA-PON thus essentially extends the trend of "software-defined" (DSP-based) optical communications to next-generation optical access. Under this paradigm, performance gains hinge on powerful, yet computationally efficient algorithms tailored to the PON environment, while cost efficiency is enabled by the reuse of legacy fiber, mature optics, and a silicon DSP platform that can be cost-efficiently mass produced. The resulting volume-driven cost profile is indeed the target regime for any technology candidate in this space.

In this paper, a tutorial overview of OFDM-based optical access is presented, covering technology principles and recent progress, different future PON application scenarios and tradeoffs, technology trends for high-speed DSP-based enabling technologies, as well as a techno-economic outlook for practical deployments. The rest of this paper is organized as follows. Section II presents a review of general OFDM principles—including orthogonality-enabled spectral efficiency, fast Fourier transform (FFT)-based digital implementation, the use of the cyclic prefix (CP), single-tap frequency-domain equalization (FDE), and OFDM extension to OFDMA. A system-level comparison is also made between SC transmission with FDE and OFDM in terms of potential application in next-generation optical access. In Section III, three dominant variants of O-OFDM are surveyed, including O-OFDM produced by optical modulation with direct detection (IM/DD), CO-OFDM generated by optical modulation with coherent detection, and AO-OFDM with all-optical field modulation and coherent detection. The tradeoffs between resulting architectures are discussed in light of key requirements for future PON systems. Section III outlines the principles and challenges specific to OFDMA-based PON, including the OFDMA-PON-enabled performance benefits, a summary of the various flavors of optical OFDMA for PON applications, as well as a discussion of important challenges and potential solutions for both downstream and upstream OFDMA-PON transmission. A summary of research advances in the field is provided in Section IV. In Section V, technology requirements for a practical OFDMA-PON implementation are outlined, with a focus on high-speed analog-to-digital and digital-to-analog converter (ADC/DAC) and DSP technologies. A cost-profile analysis for DSP-based access is also included in Section V. Section VI summarizes and concludes this paper.

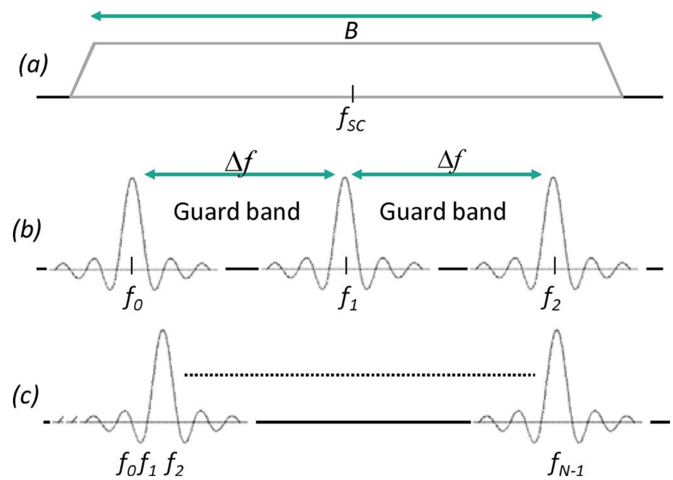

Fig. 1. Frequency-domain spectra for (a) SC, (b) FDM, and (c) OFDM signals.

II. SC Versus FDM Versus OFDM

While OFDM theory is extensive, a compact, intuitive understanding may be gained by contrasting OFDM with SC transmission and conventional frequency division multiplexing (FDM). As shown in Fig. 1, the same overall data rate can be achieved either by serial SC transmission over a broad frequency spectrum, or by parallel transmission on multiple, narrowband spectral tributaries, i.e., via FDM. (It is noted that if the FDM subcarrier frequencies were replaced by wavelengths, a traditional WDM setup would be obtained.) However, at very high symbol rates, the SC approach mandates such short symbol times T that, in any nonideal linear channel, symbols will inevitably become lengthened by the convolution with the channel's nonideal impulse response. The resulting symbol spreading is referred to as dispersion. Dispersion extends data symbols beyond their designated slot and into adjacent symbol times, producing intersymbol interference (ISI) that must be equalized at the receiver. ISI effects moreover worsen with shorter T because a given symbol is spread over more and more adjacent symbols, and increasingly complicated receiver-side equalizers (i.e., filters) with a high number of taps (i.e., coefficients) are needed.

The advantage of the "parallelized" FDM approach is that the symbols on the narrowband tributaries, or subcarriers, have longer durations, making them less vulnerable to linear distortion effects that increase with the symbol rate, such as chromatic dispersion (CD). This principle is also related to time-frequency duality: i.e., the narrower a signal is in frequency, the wider (i.e., longer) it is in time. Consequently, the channel delay (e.g., wireless multipath delay spread, CD-induced delay, etc.) becomes a small fraction of the symbol time, T. As a result, ISI will affect at most one symbol, such that the channel response over each narrowband subcarrier can be approximated as having a constant amplitude and phase. Data symbols can then be recovered via one-tap (i.e., single coefficient) FDE. The tradeoff for this benefit is a loss in spectral efficiency due to the insertion of non-data-carrying spectral guard bands, Δf, which are needed to separate the FDM subcarriers and prevent interference that would otherwise arise from any frequency-domain subcarrier overlap.

A. OFDM

The reason why OFDM boasts a spectral efficiency advantage over conventional FDM is precisely that it eliminates the spectral guard bands Δf by invoking the principle of orthogonality. (Since multilevel modulation, such as M-ary QAM, can be used in SC, FDM, and OFDM, it is not in itself the reason behind OFDM spectral efficiency.) Orthogonality, in turn, can be achieved by judicious selection of the subcarrier frequencies, $f_n, n = 0, 1, 2, \ldots, N-1$. For example, let us assume that f_1 is a sinusoidal carrier that has been modulated with a complex QAM symbol, $A_1 - jB_1$, where the exact values of A_1 and B_1 will depend on the selected QAM constellation. For 16-QAM, for example, $A_1 \in \{\pm 1, \pm 3\}$ and $jB_1 \in \{\pm 1j, \pm 3j\}$. As such, $s_1(t)$ can be expressed as

$$s_1(t) = A_1 \cos(2\pi f_1 t) - B_1 \sin(2\pi f_1 t) \tag{1}$$

wherein the first and second terms, respectively, denote the in-phase and quadrature portions of the signal, produced by the complex nature of M-ary QAM signaling. To now ensure orthogonality between $s_1(t)$ and $s_2(t)$, where $s_2(t)$ is the QAM-modulated signal on subcarrier f_2, it must be the case that

$$\int_0^T s_1(t) s_2(t) dt = 0. \tag{2}$$

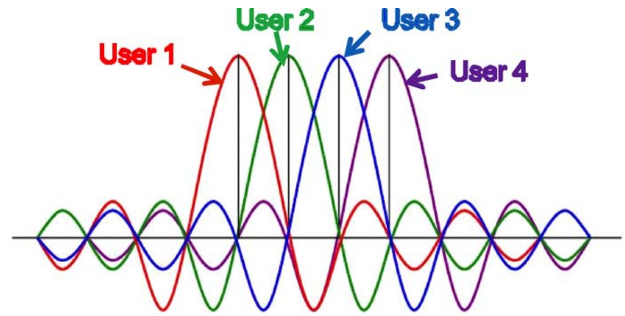

Fig. 2. OFDM(A) spectrum with four orthogonal subcarriers.

Moreover, to generate an OFDM signal, the orthogonality condition of (2) must hold for all $s_n(t)s_m(t), n = 0, 1, 2, \ldots N-1, m = 0, 1, 2, \ldots N-1, n \neq m$. An elegant way to meet this requirement is to define the subcarrier frequencies as integer multiples (i.e., harmonics) over the symbol time T as

$$f_n = \frac{n}{T} + f_{\mathrm{RF}}, \quad n = 0, 1, 2, \ldots, N-1. \tag{3}$$

In (3), the term f_{RF} indicates that the orthogonal subcarrier band may also be upconverted to a different radio frequency (RF); the special case $f_{\mathrm{RF}} = 0$ is, in fact, the distinguishing feature between discrete multitone modulation and OFDM. By substituting (1) into (2) for all $s_n(t)s_m(t), n \neq m$, and exploiting trigonometric identities, it can readily be shown that all N subcarriers will indeed be orthogonal to each other, and can thus occupy the same frequency space without interfering. This result can also be appreciated by recalling that the analog-domain implementation of the optimal (maximum likelihood) receiver in additive white Gaussian noise will essentially perform the correlation of (2) for all combinations of $s_n(t)s_m(t)$, and that its output at the optimal sampling time $t = T$ will, in the absence of time/frequency synchronization errors, either equal zero (when $n \neq m$) or be equal to the energy of the QAM symbol on the nth subcarrier (when $n = m$) [46]. Consequently, owing to the orthogonality principle, all N OFDM subcarriers can partially overlap in frequency without interfering.

Combining (1) and (3), the complete electrical OFDM signal may be expressed as

$$s_{\mathrm{OFDM}}(t) = \sum_{n=0}^{N-1} A_n g(t) \cos(2\pi f_n t) - B_n g(t) \sin(2\pi f_n t) \tag{4}$$

where $g(t)$ denotes the impulse response of any baseband pulse-shaping filter that might be used; the simplest choice is the rectangular pulse given by $g(t) = 1, 0 \leq t \leq T$, and zero elsewhere, which produces the aggregate spectrum of Fig. 2. However, from (4), a practical OFDM implementation difficulty becomes apparent: for an OFDM signal with $N = 256$ subcarriers, for example, directly implementing (4) would require an array of 255 synchronized analog oscillators at both the transmitter and receiver sides. Fortunately, most of (4) can in fact be done digitally. To observe this, we rewrite (4) as

$$s_{\mathrm{OFDM}}(t) = \Re\left\{\tilde{s}_{\mathrm{OFDM}}(t) e^{j2\pi f_{\mathrm{RF}} t}\right\} \tag{5}$$

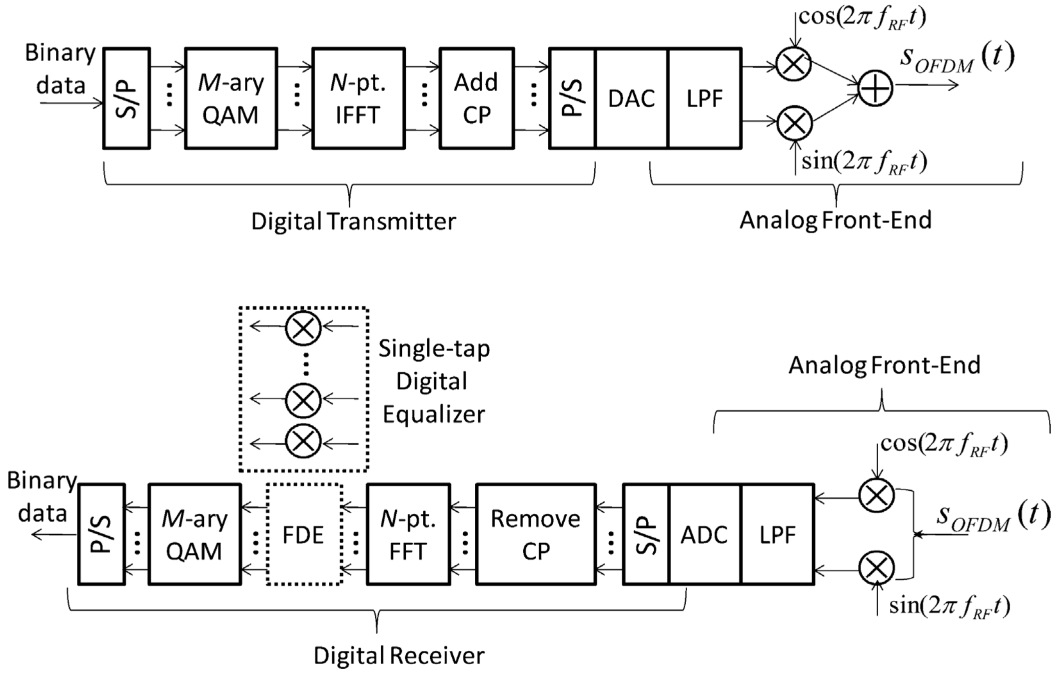

Fig. 3. Block diagram of a generic OFDM communication system.

where

$$\tilde{s}_{\rm OFDM}(t) = \sum_{n=0}^{N-1} (A_n - jB_n) e^{j2\pi nt/T}. \qquad (6)$$

From (5) and (6), we note that if (6) can be generated efficiently, producing (5) becomes a simple task, requiring just one oscillator operating at $f_{\rm RF}$. Converting (6) to the digital domain by sampling (6) at times $t = kT/N$, where the discrete time index is defined by $k = 1, 2, 3, \ldots$, we obtain

$$\tilde{s}[k] = \sum_{n=0}^{N-1} (A_{n,k} - jB_{n,k}) e^{j2\pi nk/N}. \qquad (7)$$

We now observe that, by definition, at each discrete time, k, (7) is in fact the inverse discrete Fourier transform of the complex QAM symbols, $A_{n,k} - jB_{n,k}$, over the N OFDM subcarriers, which can be implemented using the highly efficient inverse fast Fourier transform (IFFT) algorithm. The IFFT and the FFT, therefore, become the baseband OFDM modulator and demodulator, respectively. In other words, (7) states that if we pick any N frequency-domain complex QAM data symbols and take their N-point IFFT, we will get the sampled time-domain version of the corresponding N-subcarrier OFDM signal. Digital-to-analog conversion and upconversion to $f_{\rm RF}$ using a single analog oscillator then complete the RF OFDM signal generation in (5).

The full sequence of operations performed to produce and receive an electrical OFDM signal is illustrated in Fig. 3; as shown in Fig. 3, to recover the transmitted data, the transmitter-side order of operations is simply reversed. Finally, the transition from OFDM to OFDMA is accomplished by treating each OFDM subcarrier as an independent bandwidth resource, which can be assigned to different users (see Fig. 2). Multiple users can thus be accommodated by the OFDM-enabled partitioning of the available frequency spectrum.

B. CP and Single-Tap Equalization

Fig. 3 also illustrates the use of the cyclic prefix (CP) to combat ISI in OFDM and enable efficient N-subcarrier FDE. CP insertion consists of prepending some predefined tail-end portion of an OFDM data frame to its beginning, as shown in Fig. 4. Consequently, the frame begins and ends the same way, acquiring a "cyclic" quality. As long as the CP is at least as long as the dispersive delay of the channel, the CP, rather than the front-end data symbols, will absorb any residual symbol spreading (i.e., ISI). From this perspective, it is only the CP length that matters: the CP content could even be a silent interval. However, the beauty of the CP content as illustrated in Fig. 4 is that it turns the channel's time-domain dispersive effect from a linear convolution into a cyclic convolution, such that no matter how long the impulse response becomes, as long as the CP is as long, data symbols can still be recovered via single-tap equalization in the frequency domain. This is very important because the computational complexity of single-tap FDE scales logarithmically: $N \log_2 N + N$ multiplications are needed per N symbols. By stark contrast, equivalent time-domain equalization scales exponentially: N^2 multiplications are needed to accomplish *the same task* in the time domain. The tradeoff for the computational efficiency gain is the time-domain overhead introduced by the CP [see Fig. 4(c)], which reduces the net data rate. To minimize this penalty, larger FFT sizes can be used, such that the CP-appended symbols make up a small fraction of the total OFDM frame.

By correlation techniques, the CP can also be used to determine the beginning and ending of each data frame, which is crucial in properly aligning the receiver-side FFT window, and

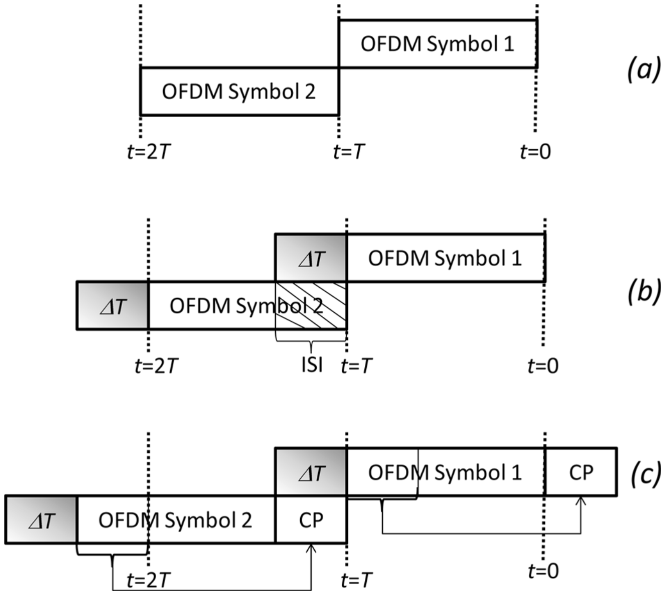

Fig. 4. OFDM symbol transmission in (a) ideal, nondispersive channel, (b) dispersive channel without CP insertion, resulting in ISI, and (c) dispersive channel with CP insertion used to eliminate ISI.

enabling ISI-free and intercarrier interference (ICI)-free operation [1]. Although by the orthogonality property the OFDM subcarriers can spectrally coexist without interference, nonetheless, due to their tight spectral packing, this delicate balance can be upset even by relatively small frequency synchronization or sample timing errors, and/or phase noise, resulting in ICI. This is particularly true for rectangular baseband pulse shaping that results in $|\sin(x)/x|^2$ subcarrier spectra with nonnegligible side lobes that extend over a broad spectral range (see Fig. 2). To reduce ICI sensitivity, a different pulse shaping filter $g(t)$ such as the raised cosine, can be used instead, to better confine the OFDM subcarrier spectral lobes.

To summarize, we can say that the key idea of OFDM is to realize high aggregate data rates through parallel symbol transmission on many narrowband orthogonal subcarriers. By orthogonality, the OFDM subcarrier spectra can partially overlap without interfering, which increases the spectral efficiency compared to conventional FDM. Moreover, the longer time-domain symbol durations and the use of the CP enable high resistance to linear dispersion, while an efficient DSP-based implementation can be realized with the FFT/IFFT. Finally, a natural extension to a multiuser access environment can be made through the OFDMA concept. These key advantages have propelled OFDM(A) into an array of high-speed transmission applications, and can all be exploited in fiber-optic communication as well.

C. SC With FDE Versus OFDM

As any other technology, OFDM also comes with a set of disadvantages, the foremost of these being high sensitivity to time/frequency synchronization errors and phase noise, as well as a high peak to average power ratio (PAPR). The PAPR problem arises from the fact that the sinusoidal signals from many OFDM subcarriers can occasionally constructively add in the time domain, producing sharp amplitude peaks that are significantly higher than the average amplitude value of the signal. This can put a large strain on RF amplifiers, such that either costly devices and/or a power back-off become necessary to ensure linear operation. In optical transmission, a high PAPR has also been shown to potentially increase the vulnerability of the OFDM signal-to-fiber nonlinearity [32], [47]. In SC (e.g., QPSK) transmission with FDE, however, the PAPR problem can be avoided while maintaining the FDE benefits enjoyed by OFDM. Which of these two approaches might thus be better suited for next-generation optical access?

Fig. 5 illustrates a system-level comparison between SC-FDE [see Fig. 5(a)] and OFDM [see Fig. 5(b)] for the case of M-ary QAM signaling. It can be observed that the main difference between the two approaches is the location of the IFFT, which in the case of SC-FDE, is moved to the receiver; the CP requirements and computational complexity are unchanged. However, in the case of future PON access, the absence of the transmitter-side IFFT prevents granular frequency-domain bandwidth partitioning for multiuser access. Consequently, a high-speed, time-domain bandwidth-sharing technique would be necessary, the complexity of which could prove prohibitive at very high data rates. Moreover, in PON systems, it is desirable to centralize complexity as much as possible by moving it out of the ONUs and over to the OLT side. In this way, the cost of an intelligent OLT can be amortized over a large number of simpler, cost-efficient ONUs. The PAPR challenge of OFDM in next-generation optical access is also alleviated by the relatively short transmission distances of PON systems ($\leq$100 km), which are about an order of magnitude lower compared to long-haul applications ($\geq$1000 km). Finally, OFDM flexibility, enabled by a digital transmitter-side platform, could be viewed as another important advantage, as has been observed in earlier applications for which the SC-FDE versus OFDM debate was relevant [17].

III. Optical OFDM(A)

An unmodulated, continuous wave (CW) optical carrier signal offers several options, or dimensions, for data modulation: its amplitude, phase, frequency, polarization, intensity, or a combination thereof can be modulated. Depending on the choice of the modulation dimension(s) at the transmitter, different receiver side detection schemes become possible as well. Bringing OFDM(A) into the optical domain thus generates several new transmitter and receiver architectures compared to purely electronic and/or RF OFDM(A). In this section, three prominent modulation/detection combinations for O-OFDM will be overviewed, with a focus on the resulting transmitter and receiver side architectures. These include optical (intensity or field) modulation with IM/DD, which we will refer to as optical OFDM (O-OFDM), optical modulation with coherent detection, referred to as CO-OFDM, and all-optical field modulation with coherent detection, termed AO-OFDM. Particular emphasis will be placed on implementation aspects that are of unique importance to next-generation optical access. The different flavors of optical OFDMA will also be discussed and classified according to their specific bandwidth sharing mechanisms.

A. O-OFDM: Optical Modulation With Direct Detection

Fig. 6(a) illustrates an O-OFDM system; the functional blocks that may vary with transceiver design are denoted by dashed lines. As shown in Fig. 6(a), the OFDM signal is first

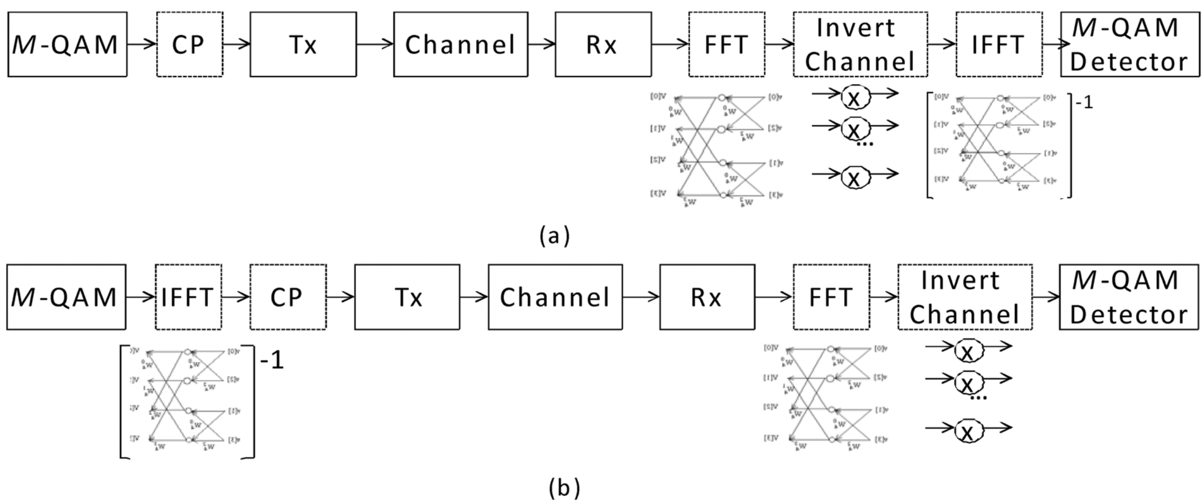

Fig. 5. System-level comparison of (a) SC-FDE and (b) OFDM communication systems.

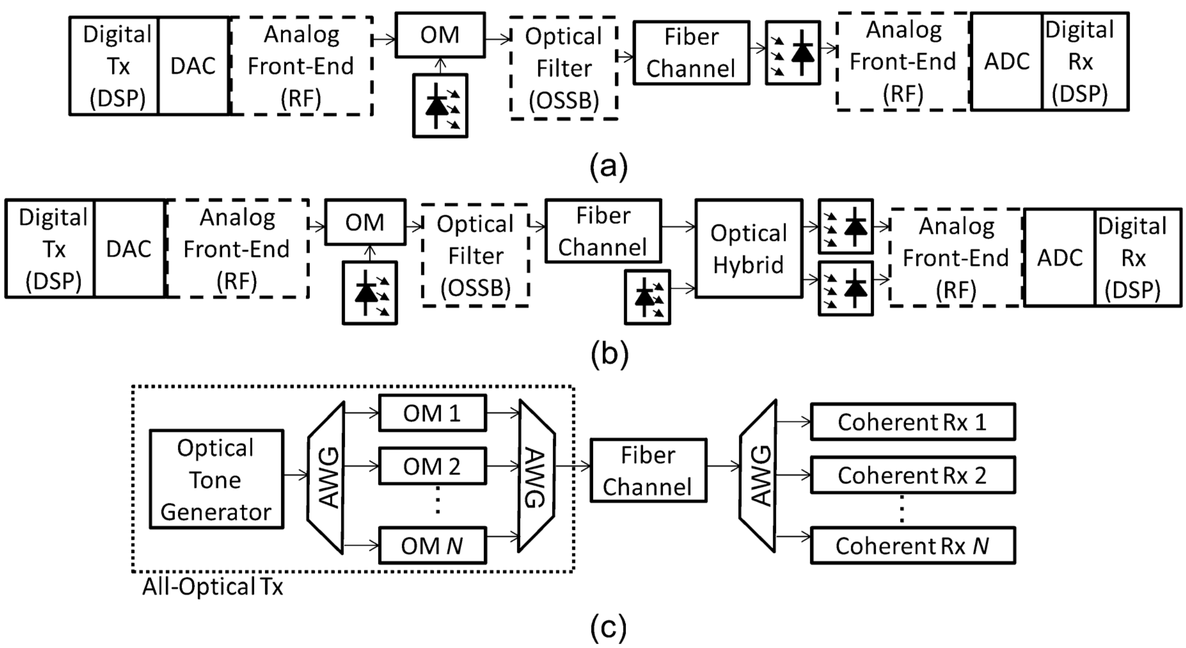

Fig. 6. Block diagram of three variants of O-OFDM. (a) O-OFDM using optical modulation (OM) with direct detection (DD). (b) CO-OFDM using optical modulation with coherent detection. (c) AO-OFDM using an optical IFFT and coherent detection. Functional blocks that may or may not be needed depending on transceiver design are denoted by dashed rectangles. (Tx= transmitter; Rx = receiver; OSSB = optical single sideband; AWG = arrayed waveguide grating).

formed in the electronic domain, using the digital transmitter. Direct-to-RF upconversion may be implemented using a broadband DAC, or a conventional analog RF front-end architecture may also be used, as shown in Fig. 3. For optical modulation, a CW laser and either an intensity modulator (IM) or optical in-phase/quadrature (I/Q) modulator can be used to convert the RF OFDM signal into the optical domain. A directly modulated laser can also be exploited, as in [10] and [48]. The main difference between IM and I/Q modulator use is that the latter directly generates an optical single sideband (OSSB) signal; a separate OSSB filter, such as an optical bandpass filter or interleaver, would thus only be needed if an IM is used.

In the IM case, a signal with optical intensity that is linearly proportional to $s_{\rm OFDM}(t)$ is produced. Because optical intensity is a real, strictly nonnegative quantity, to prevent distortion, the RF OFDM signal $s_{\rm OFDM}(t)$ must be both real and positive. To generate a real signal, electrical in-phase and quadrature (I/Q) multiplexing can be performed, or Hermitian (conjugate) symmetry can be enforced at the IFFT output. The main practical advantage of Hermitian symmetry is that, since neither electrical nor optical I/Q multiplexing is needed, there will be no transmitter or receiver side I/Q imbalances in the system; with all other I/Q multiplexing and demultiplexing methods, this imbalance can be an important practical issue. For more information on I/Q imbalance compensation, the reader is referred to [1], [4]. On the other hand, since Hermitian symmetry requires discarding the second half of the symbol frame and replacing it with the complex conjugate of the first half, it comes at the expense halving the total data rate. Furthermore, to ensure that $s_{\rm OFDM}(t) \geq 0$, a sufficiently large dc bias must be added to the RF OFDM signal, such that the IM operates at its quadrature point. As a result, much of the optical power in the O-OFDM signal will be contained in the transmitted optical carrier, rather than the OFDM signal, increasing the vulnerability of the O-OFDM signal to optical signal-to-noise-ratio (OSNR) degradations. Moreover, as an optical intensity replica of its RF counterpart, the O-OFDM signal will exhibit high PAPR, which can pose a challenge in the presence of fiber nonlinearity. Different types of signal clipping techniques have thus been proposed to reduce PAPR in O-OFDM [1]. It has also been shown that O-OFDM performance can be optimized by equally dividing the optical power between the optical carrier and O-OFDM sideband [5], [7].

Fig. 6(a) also illustrates that, prior to fiber-optic transmission, an OSSB O-OFDM signal must be produced. This is done in order to reduce the required transmission bandwidth and to prevent CD-induced power fading that would occur upon direct detection (DD) of a double-sideband (DSB) O-OFDM signal. Specifically, in the presence of CD, the two optical sidebands of a DSB signal experience opposite phase shifts, but maintain equal magnitudes [49]. Upon DD, the opposite phase shifts would result in destructive interference, i.e., irrecoverable power fading. With OSSB O-OFDM, however, the CD effect reduces to a linear phase shift that can be readily corrected using the CP and FDE techniques described earlier.

After DD with a photodiode, due to incoherent mixing, the output signal will contain both the desirable carrier × sideband RF beating term, and an undesirable sideband × sideband mixing term. This undesirable product will spectrally extend from dc to f_{N-1}, the highest baseband OFDM subcarrier frequency. Consequently, $f_{\rm RF}$ must be sufficiently high to create a frequency guard band between the desirable and undesirable mixing terms [7], [50]. In this way, performance degradation due to noncoherent detection can be avoided at the expense of a reduction in spectral efficiency.

In terms of next-generation optical access, the optical-domain simplicity of the IM/DD O-OFDM and its reliance on mature optics render it most attractive from a cost-efficiency standpoint. The tradeoffs for this benefit compared to CO-OFDM include higher transmitter-side power due to the mandate for a strong optical carrier, as well as a reduction in spectral efficiency stemming from the requirement for a frequency guard band that separates the “good” and “bad” mixing products at the DD receiver output.

B. CO-OFDM: Optical Modulation With Coherent Detection

Unlike in O-OFDM, in CO-OFDM, the optical carrier does not have to be transmitted along with the O-OFDM sideband; a receiver-side local oscillator (LO) can be used instead. Consequently, the transmitter-side optical carrier component in CO-OFDM does not need to be as large as in O-OFDM, such that more power can be allocated to the OFDM sideband. A CO-OFDM signal can thus be made more resilient to OSNR degradations. Moreover, since coherent detection enables the linear capture of the full optical field [51], a frequency guard band to isolate IMD effects is no longer needed. CO-OFDM can thus have higher spectral efficiency than O-OFDM. Finally, coherent detection increases receiver sensitivity, which, in the context of optical access, can be exploited to increase PON reach, ONU splitting ratios, or both.

Fig. 6(b) illustrates a CO-OFDM system exploiting optical modulation with coherent detection. Following the digital transmitter (Tx), in the example architecture of Fig. 6(b), an analog RF front-end (see Fig. 3) can be used for electrical I/Q multiplexing prior to optical modulation. As in O-OFDM, either an I/Q modulator or an IM followed by an optical filter can be used to produce an OSSB O-OFDM signal. It is noted that, in the case of coherent detection, since optical phase information is preserved and CD-induced power fading would thus no longer occur with a DSB O-OFDM signal, the primary motivation for OSSB transmission is a reduction in the required transmission bandwidth. It is also noted that although coherent detection obviates the need for a frequency guard band between the optical carrier and the OFDM sideband, a low-frequency guard band may still be needed if a discrete optical filter is used to generate the OSSB signal, in order to accommodate limitations in the sharpness of the filter passband edges. Following fiber transmission, a CW LO laser, an optical hybrid, and dual photodiodes can be used for coherent reception of the OFDM signal, with the resulting RF OFDM signal downconverted to baseband and processed in the DSP receiver (Rx). Depending on the frequency-domain placement of the LO, the receiver-side RF front end can also be removed, enabling direct downconversion via homodyne optical detection [52].

While the CO-OFDM approach presents several attractive benefits, it also entails an increase in optics complexity and cost compared to O-OFDM. Since this is particularly prominent at the receiver side, it can be a challenge for future PON systems, where the goal is to maximize the cost efficiency of ONU-side hardware. The CO-OFDM approach is also more sensitive to phase noise than O-OFDM. Effective DSP algorithms for phase noise correction are thus a key requirement for CO-OFDM.

C. AO-OFDM: All-Optical Field Modulation With Coherent Detection

An important commonality between the O-OFDM and CO-OFDM approaches of Fig. 6(a) and (b) is that the IFFT and FFT processing is accomplished exclusively in electronic DSP. The extension from OFDM to OFDMA in both O-OFDM and CO-OFDM would thus be performed through adaptive subcarrier assignment in a DSP-based control plane. In the AO-OFDM method illustrated in Fig. 6(c), however, the IFFT is done in an analog fashion directly in the optical domain [12], [15]. As shown in Fig. 6(c), a comb of unmodulated, phase-locked orthogonal subcarriers (i.e., tones) is first produced by a tone generator, such as a pulsed laser or an overdriven Mach–Zehnder modulator . The phase-locked tones are then separated using an arrayed waveguide grating (AWG), with an array of N I/Q optical modulators used to individually modulate each tone with baseband complex symbols, such as M-ary QAM. Following the parallelized modulation, the subcarriers are combined with another AWG and transmitted over fiber. At the receiver, the tones are demultiplexed once again, and processed in parallel by N coherent receivers.

While the AO-OFDM approach has the nice feature of a purely analog transmitter, its overall complexity, particularly on the receiver side, is currently prohibitive for optical access. Nonetheless, by exploiting the same set of receiver-side DSP algorithms, AO-OFDM could prove attractive for smooth upgrades of 100 Gb/s coherent long-haul systems [53], [54].

D. Optical OFDM(A)... in PON?

While flexible allocation of bandwidth resources is a compelling goal for future core networks, for PON, it is a compelling present-day reality; detrimental bandwidth idle times and traffic imbalances already exist in current systems [38]. From a network perspective, future PON generations are envisioned to improve upon their predecessors in this regard, by reducing both bandwidth idleness and improving real-time response to changing demands. The appeal of OFDMA for PON is that it can address these challenges by providing finely granular bandwidth "units" (i.e., subcarriers) that can span the entire per-channel bandwidth; the limitations of the burst-mode TDMA approach, for example, currently restrict the feasible data rates to 10 Gb/s [55]. The wavelength-dedicated WDM approach, on the other hand, can restrict bandwidth granularity and flexibility. Moreover, given that cost is a vital consideration for optical access, it is desirable for emerging technologies to enable *both* advanced features and cost efficiency, rather than enable one at the expense of the other. From this perspective, DSP-based (i.e., software-defined) operation of OFDMA-PON targets both high performance and an attractive volume-driven cost profile.

There exist multiple variants of optical OFDMA; these are illustrated in Fig. 7. The simplest form, shown in Fig. 7(a), consists of assigning different subcarriers from the same OFDM band to different users (see Fig. 2). Adaptive bandwidth provisioning is thus performed by changing the number of subcarriers allocated to a given user/service depending on the real-time traffic demand. The resulting 1-D dynamic bandwidth allocation scheme can be implemented in DSP via MAC layer algorithms [34]. To achieve higher granularity and flexibility, each OFDM subcarrier bandwidth resource can be further subdivided in time, by combining 1-D OFDMA [see Fig. 7(a)] with classic TDMA, as shown in Fig. 7(b). In the resulting 2-D OFDMA scheme (i.e., $\mathrm{OFDMA}+\mathrm{TDMA}$), multiple users can access the same OFDM subcarrier in different time slots. As in 1-D OFDMA, the 2-D $\mathrm{OFDMA} + \mathrm{TDMA}$ approach can be implemented in DSP via MAC layer protocols. Finally, by implementing the DSP-based 2-D OFDMA bandwidth scheduling of Fig. 7(b) on each of W possible WDM wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_W$, a 3-D OFDMA scheme (i.e., $\mathrm{WDM} + \mathrm{OFDM} + \mathrm{TDM}$) can be achieved [see Fig. 7(c)]. In this case, the first step of wavelength assignment can be static, as is the case in conventional point-to-point WDM systems, or dynamic, if tunable optical devices are available at the ONU receivers. In either case, colorless (i.e., wavelength agnostic) ONU-side optics are a key requirement. Following wavelength assignment, OFDM subcarrier and TDM slot scheduling can be implemented in DSP, as discussed for Fig. 7(a) and (b).

Which of the three possible variants of optical OFDMA is selected can be regarded as a function of key network design parameters. For example, the choice between one and 2-D OFDMA depends on the desired bandwidth flexibility, as well as the acceptable MAC layer complexity. Moreover, the adoption of a WDM overlay [see Fig. 7(c)] can be viewed as an effective approach to increase the aggregate capacity and/or achieve access/metro network consolidation while maintaining a last-mile passive optical split [13]. Novel optical OFDMA-PON MAC protocols are also the subject of on-going investigation [56], [57].

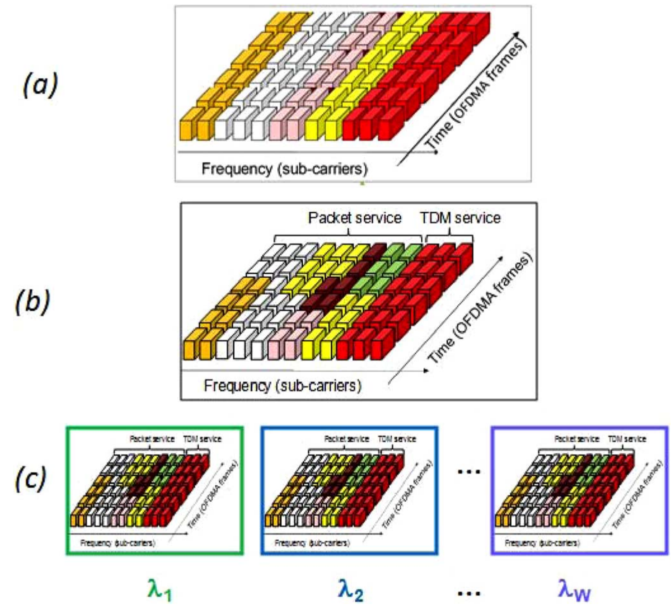

Fig. 7. Different optical OFDMA variants. (a) 1-D OFDMA with different users assigned different OFDM subcarriers. (b) 2-D OFDMA with different users assigned different OFDM subcarriers and TDM time-slots. (c) 3-D OFDMA with different users assigned different OFDM subcarriers and TDM time slots on different WDM wavelengths.

IV. OFDMA-PON Principles and Challenges

Fig. 8 depicts a single-wavelength OFDMA-PON architecture that exploits the principles described earlier; a WDM extension can readily be made by launching multiple wavelengths from the OLT and adopting the single-wavelength architecture of Fig. 8 on each of the launched wavelengths. As shown in Fig. 8, at the OLT, a bandwidth-sharing schedule is formed according to ONU-side demand, and is distributed to all ONUs over prereserved subcarriers and/or timeslots. Different OFDM subcarriers can thus be assigned to different ONUs; each OFDM subcarrier can also be time shared to realize 2-D multiuser bandwidth partitioning. One and 2-D bandwidth provisioning can also be combined. For example, while ONU-2 in Fig. 8 maintains a fixed subcarrier assignment over several frames, ONU-1 and ONU-3 engage in time-domain sharing of the same OFDM subcarriers. Since traffic is aggregated and de-aggregated electronically, the architecture also features the important advantage of a passive last-mile optical splitter, such that the legacy fiber distribution network, which accounts for the majority of PON investment cost, can be reused. At the ONUs, each ONU recovers its preassigned OFDM subcarriers and/or time slots in DSP. An orthogonal OFDMA-based schedule for upstream transmission is likewise generated by the OLT and distributed to the ONUs. At the OLT, a complete OFDMA frame is assembled from the incoming subframes originating at different ONUs. Consequently, for both downstream and upstream OFDMA-PON accurate synchronization is very important to enable multiuser access.

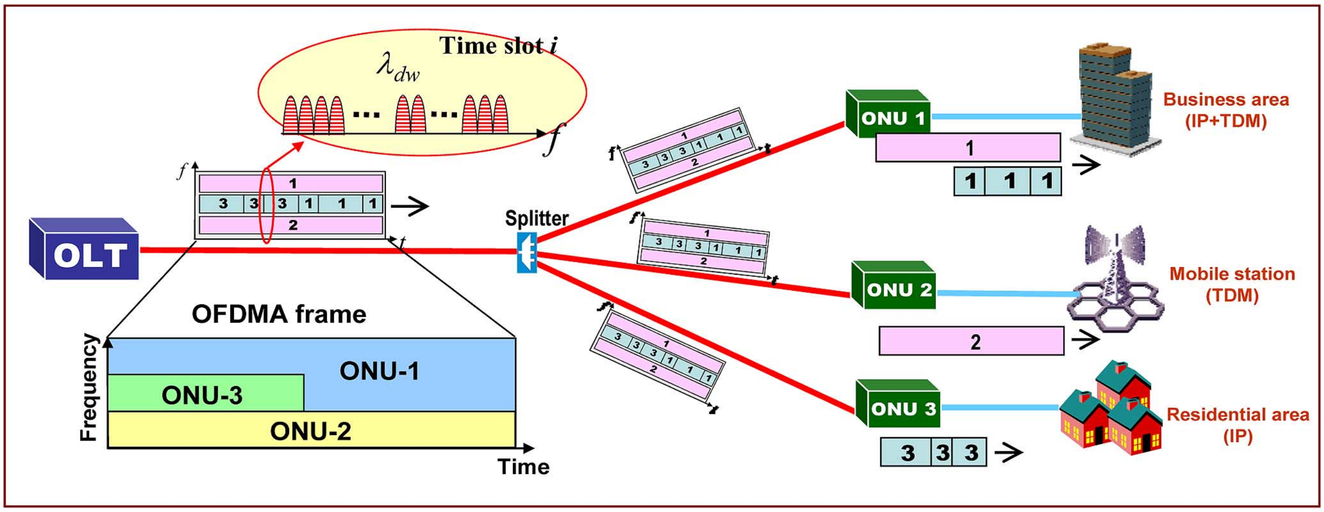

Fig. 8. Single-wavelength optical OFDMA-PON architecture for heterogeneous service delivery.

The OFDMA-PON platform of Fig. 8 can support heterogeneous services because OFDM subcarriers essentially become transparent pipes for the delivery of arbitrary signals (e.g., legacy T1/E1 lines, Ethernet packets, both analog and digitized mobile backhaul, IPTV, VPN, etc.) In terms of implementation, the integrated DSP-based transmission and control planes mean that the MAC protocols can be regarded as simply another functional block of the digital OFDM(A) transceivers. This software-defined approach features high reconfigurability, such that the system can be extended to new and emerging applications in a nondisruptive fashion. Consequently, OFDMA-PON (see Fig. 8) can cost-efficiently coexist with legacy systems and devices on the same fiber ODN by operating in an orthogonal wavelength or frequency band. For example, 1510–1540 nm downstream and 1340–1360 nm upstream OFDMA-PON operation can enable coexistence with G-PON, XG/10 G-EPON, and legacy RF video overlays. For backward-compatible networks, optimal spectral mapping and the required degree of OLT and ONU-side change thus emerge as important challenges. In green-field deployments, which would not involve backward compatibility considerations, a wavelength plan that maximizes mature optical component reuse would be preferred.

Because of a directional asymmetry in the PON topology—i.e., a point-to-multipoint downstream and multipoint-to-point in the upstream—different issues exist for downstream versus upstream transmission in OFDMA-PON. These are surveyed next, along with some potential techniques for mitigating these challenges.

A. Downstream Transmission in OFDMA-PON

A unique feature of OFDMA-PON is that spectrally efficient 40^+ Gb/s downstream transmission can be achieved using a single wavelength [13], [59]. A high degree of statistical bandwidth multiplexing can thus be enabled, since all ONUs in the PON can share the same OFDMA resources. Peak per-ONU rates as high as the full 40^+ Gb/s/λ data rate likewise become possible, and because of the compact OFDM spectrum, multilevel modulation, and polarization multiplexing, this can be realized with very high spectral efficiency. For example, using polarization-multiplexed OFDM with $M = 16$ QAM and direct (noncoherent) detection, a 40 Gb/s/λ data rate was realized in a 5.6 GHz spectrum [59]. ONU-side synchronization, mandated for proper receiver-side alignment of the FFT window, can be viewed as a much simpler version of an equivalent problem in wireless systems [60]; namely, due to the high stability of the fiber channel, downstream synchronization can be accomplished by simply broadcasting a common clock signal from the OLT to the ONUs [61]. Finally, at the expense of minor additional CP overhead, CD also poses no major challenge even for PON reach up to 100 km [13], [62].

However, at 40^+ Gb/s/λ downstream rates, OFDMA-PON transmission can be OSNR-limited. This will especially be true for IM/DD implementations, where much of the transmitted power lies in the optical carrier. In the absence of receiver-side optical amplifiers, as can be the case in highly cost-sensitive residential applications, the OSNR limitation will further reduce to power-limited transmission, which will directly determine the achievable PON reach and passive split ratio. Furthermore, to take advantage of full-range dynamic bandwidth sharing, all ONUs in a 40^+ Gb/s λ OFDMA-PON would have to receive and process the entire 40^+ Gb/s λ OFDMA signal, for which they would need to be equipped with ADC and DSP capability that is comparable to that of the OLT. While VLSI advances can make this a reality for high-performance applications, such as mobile backhaul, enterprise, and/or datacenter connectivity, it is a difficult mandate for residential ONUs.

To overcome the challenges of downstream OFDMA-PON transmission, techniques such as hybrid WDM-OFDMA, multiband OFDMA, and adaptive per-subcarrier modulation/coding have been proposed. With a hybrid WDM-OFDMA approach [63], for example, an aggregate 40^+ Gb/s could be realized with multiple wavelengths, alleviating the power budget and OSNR constraints on each wavelength channel. The tradeoff for this benefit would be the requirement for a colorless ONU receiver that could select and process one or more wavelengths. In the multiband OFDMA approach [13], a 40^{+} Gb/s/λ signal would be realized via multiple OFDMA sub-bands separated by frequency-domain guard bands. At the ONU side, a tuning mechanism, either analog or digital, could be used to select and process a target sub-band, reducing ADC and/or DSP complexity. In this case, the peak per-ONU speeds would be restricted to the data rate of the selected OFDMA sub-band(s). Finally, as in wireless OFDMA systems where different modulation and/or coding formats are used for users that are closer or further away from the base station, a similar solution could be adopted in OFDMA-PON [10], [11]. For example, for ONUs that are closer to the OLT, symbols could be drawn from larger M-ary QAM constellations and low coding overhead could be employed; this would be reversed for more remote ONUs, where smaller, more resilient constellations and higher coding overhead could be exploited to improve performance.

B. Upstream Transmission in OFDMA-PON

Since the cost and complexity of an OLT can be amortized over a number of ONUs, the use of receiver-side optical amplification, and sophisticated optics and electronics can more easily be justified for upstream OFDMA-PON transmission. Consequently, upstream OSNR and received power limitations can be overcome with the proper OLT-side hardware upgrades.

The main challenge for high-speed, single-wavelength upstream OFDMA-PON arises from the fact that colorless transmission is achieved by transmitting decorrelated optical signals from multiple ONUs over the same nominal wavelength. This situation will occur both in lightwave-centralized architectures—where a single upstream carrier is broadcasted from the OLT to the ONUs [62], [64]—and in systems where all ONUs have their own upstream laser source, operating at a common wavelength. Namely, due to fiber path differentials between the OLT and different end users, the broadcasted carrier components at N ONUs can become just as decorrelated as if they originated from N discrete optical sources. Consequently, the actual wavelength of each upstream carrier will exhibit random fluctuations around its nominal value. The mixing of N such carriers upon photodetection would produce strong optical beating noise that could easily overwhelm the weaker OFDMA signal terms [64]. Upstream optical carrier decorrelation also complicates the upstream OFDMA synchronization problem, since the OLT must correctly assemble an OFDMA frame from N frequency-shifting subframes.

To overcome these upstream transmission challenges, different techniques, including hybrid WDM-OFDMA transmission, and/or single-wavelength optical carrier suppression with coherent OLT-side detection can be used. In the hybrid WDM-OFDMA approach [63], the beating noise problem is directly solved by wavelength orthogonality. However, multiple optical sources—either broadcasted from the OLT, or included in the ONUs—as well as a mechanism for wavelength tunability would be needed to realize this approach. Alternately, optical carrier suppression with OLT-side coherent detection can also be exploited [13], [62], [64]. In this method, each of the N de-correlated optical carriers is suppressed via proper biasing of the transmitter-side optical modulator and/or receiver-side optical filtering. A single OLT-side optical carrier reference is then used as the coherent receiver LO. As shown in [64], the beating noise will be eliminated by this approach, enabling coherent recovery of the OFDMA signals. To absorb larger frequency shifts that would lead to ICI, as well as to relax upstream synchronization requirements, frequency guard bands can be inserted between the upstream signals of different ONUs, resulting in an upstream multiband OFDMA configuration. Correlation techniques can then be exploited to properly align the FFT window and jointly process upstream data from multiple ONUs [65].

V. Summary of Advances in OFDMA-PON

OFDM transmission using low-cost optics for optical access was demonstrated at 4 Gb/s in [58], while the OFDMA-PON concept was first proposed in [10], where the first bidirectional experimental demonstration of 10 Gb/s OFDMA-PON and WDM-OFDMA-PON was also made. An extension to OFDMA-PON-enabled heterogeneous service delivery was shown in [63], where a 40 MHz analog WiMAX signal centered at 3.4 GHz was successfully embedded into a 5 GHz OFDMA band carrying digital traffic. Adaptive per-subcarrier modulation for OFDMA-PON was first demonstrated in [11] for a cost-efficient 10 Gb/s IM/DD architecture. The first 40 Gb/s/λ downstream OFDMA-PON was achieved by introduction polarization multiplexing with direct detection, which, in conjunction with novel 4×4 multiple-input multiple-output (MIMO) DSP equalization was also used to achieve record 108 Gb/s/λ downstream OFDMA-PON transmission [65]. Lightwave-centralized, or carrier-distributed, OFDMA-PON was proposed in [66], and extended to source-free colorless upstream transmission with OLT-side coherent detection in [65]. A 100 km upstream OFDMA-PON reach was demonstrated by this approach in [62], while a novel OLT-side architecture was exploited in [67] to achieve a record 108 Gb/s/λ upstream data rate. Polarization-insensitive ONU-side operation for source-free OFDMA-PON was shown in [68] and [69]. End-to-end real-time O-OFDM transmitter and receiver-side processing was achieved in [70]–[72]. Several real-time O-OFDM transmitter demonstrations have also been made in [73]–[75], with record 101.5 Gb/s real-time operation recently shown [76]. On the receiver side, a record 41.25 Gb/s real-time single-band WDM-OFDMA-PON receiver was implemented in [77]. A hybrid electronic CDM-OFDM-PON was exhibited in [78], while a physical-layer encryption technique for OFDM-based PON using chaos scrambling was demonstrated in [79]. The use of OFDMA-PON for wired/wireless convergence has been examined in [63], [80], and [81]. Advanced modulation formats for spectrally efficient long-reach OFDMA-PON, including 128 QAM [82], have also been shown. The first Terabit PON based on WDM-OFDMA was also recently demonstrated, featuring a 90 km reach and support for up to 800 ONUs with 1.25/10 Gb/s dedicated/peak data rates [13], while a 1.92 Tb/s coherent DWDM-OFDMA-PON serving up to 2048 ONUs over 100 km was demonstrated in [52]. Other recent progress in the research area of OFDM-based optical access includes efficient real-time synchronization implementations [61], [83], reduced-overhead and efficient MIMO DSP equalization algorithms [84], [85], low-cost optical component optimization [86], and higher-layer (i.e., MAC) protocol design [56], [57]. With several international OFDM(A)-PON research initiatives underway, continued advances in the field are expected.

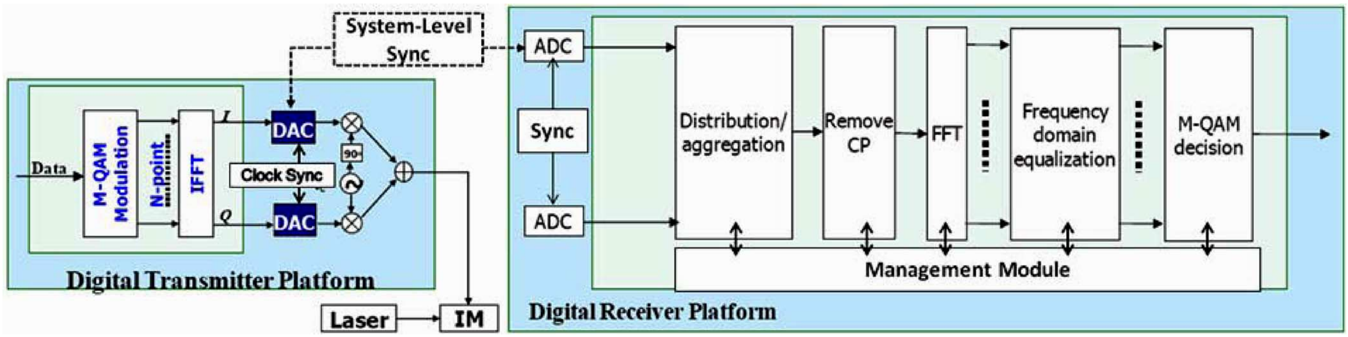

Fig. 9. Digital transmitter and receiver architectures for OFDMA-PON.

VI. DSP Requirements for OFDMA-PON

The contention that OFDM is a "great technology" is generally not viewed as controversial. In the context of PON-based access, optical OFDMA has been shown to be advantageously flexible, nondisruptive to the legacy ODN, and capable of record transmission rates and distances. However, the implicit reliance of a practical OFDMA-PON implementation on advanced ADC, DAC, and DSP technologies has often been regarded as a liability. The primary reason for this is that an optical OFDMA-based system would require DSP-based components that are at least one order of magnitude faster than those of any other successfully commercialized OFDM(A)-based application. The decisive question is thus whether VLSI technologies could keep up with optical OFDMA. To address this, the key DSP requirements and technology trends related to a practical OFDMA-PON implementation are overviewed next.

A. DSP Components for Real-Time OFDMA-PON Transceivers

Fig. 9 illustrates a DSP-based transceiver architecture for application in OFDMA-PON. The overarching goal of such transceivers is real-time, multi-Gb/s operation. From the transmitter side, the required DSP-based components include a digital processor, which performs the vital IFFT computation, and a two-channel DAC module used to convert the digital in-phase (I) and quadrature (Q) OFDMA signal components into the analog domain. According to Nyquist theory, to avoid distortion, the DAC bandwidth (GHz) should be at least as large as the OFDM signal bandwidth, while the DAC per-channel sampling rates (GS/s) should be at least twice the OFDM(A) signal bandwidth (GHz). It is also noted that if the DAC bandwidth is sufficiently large, the two-channel DAC can also replace the analog RF front end of Fig. 9. Direct digital-to-RF conversion is feasible in this case. In both scenarios, the two DAC channels must be synchronized, and the DAC resolution as measured by the effective number of bits (ENOB) must be sufficiently high to accurately represent the rapidly changing, "noise-like" time-domain analog OFDM signal. Since ENOB is also related to the achievable signal-to-noise ratio, a higher ENOB value is generally preferred, albeit more difficult to realize in practice. In terms of the DSP processor, its most demanding task is the real-time, high-speed IFFT, the complexity of which fortunately scales logarithmically with respect to the IFFT size, N. The remaining functional blocks of the digital transmitter (see Fig. 3) feature relatively low complexity.

At the receiver side, following photodetection and I/Q demultiplexing, a two-channel ADC is required to digitize the I and Q components, respectively (see Fig. 9). In terms of required ADC bandwidth, sampling rates, and ENOB, the same general requirements as those outlined previously for DAC operation apply. However, as shown in Fig. 9, in terms of synchronization, sample-level accuracy is required both between the two ADC channels, and between the transmitter-side DAC and receiver-side ADC. Incoming samples must also be parsed and organized into parallelized segments via real-time distribution/aggregation before becoming input to the receiver side FFT module, and subsequent digital equalizers and symbol detectors. As in the transmitter-side DSP processor, the real-time FFT can be regarded as the most computationally intensive digital receiver operation.

In laboratory demonstrations, high-speed arbitrary waveform generators and real-time digital oscilloscopes are typically used as high-speed DACs and ADCs, respectively, while DSP processors are emulated by software programmed for off-line data generation and recovery. For early stage prototyping, field programmable gate arrays (FPGAs) offer an attractive way to upgrade to real-time DSP functionality, while maintaining sufficient flexibility for iterative design. Real-time IFFT/FFT implementations in FPGAs can range from highly customized approaches [75] to those based on generic modules, such as the Xilinx LogiCORE for FFT that was exploited in [77]. In both cases, important design tradeoffs emerge, involving achievable throughput, FFT size, and resource utilization. In implementations involving multiple FPGAs, the combination of FFT size, FFT core clock frequency, and the number of FFT cores becomes an extremely important factor in determining overall throughput and performance. As an example, Table I illustrates the resource utilization tradeoffs that were involved in the implementation of the 41.25 Gb/s real-time receiver of [77]. In [77], it was essential to parallelize the real-time FFT in order to achieve sufficiently high throughput, by using multiple FFT cores with an optimized FFT size. As shown in Table I, different combinations of FFT sizes, clock frequencies, and total FFT cores were studied. From the comparison in Table I, it can be seen that the FPGA logic slice consumption was related to the number of FFT cores. Moreover, the primary driver of higher FPGA resource utilization was in fact higher logic slice usage. Consequently, to lower the FPGA resource utilization for the parallelized FFT module, the combination of six FFT cores operating at a 215 MHz clock frequency with FFT size of 32 was selected as optimal. Consequently, in [77],

TABLE I
RESOURCE COMPARISON FOR DIFFERENT FFT CORE/SIZE

	Slices	RAM	DSP
8 FFT cores/ FFT size 16 @ 192MHz	2461 (17%)	6 (2%)	24 (3%)
12 FFT cores/ FFT size 16 @ 156MHz	3736 (26%)	10 (3%)	36 (5%)
6 FFT cores/ FFT size 32 @ 215MHz	2363 (16%)	5 (2%)	36 (5%)

Based on XC5VSC95T FPGA, data width: 8 bits, Phase factor width: 8 bits, unscaled, truncation rounding, bit reverse order output.

data were parsed into 192-sample I/Q segments for real-time FFT processing (i.e., 6 FFT cores × 32 points per FFT results in a 192-point FFT). The optimal solution in a given real-time application must thus strike an acceptable balance among several key parameters.

Given the large form factor and rather high power consumption of FPGA-based implementations, the ultimate goal is to realize a digital OFDMA-PON transceiver as an application specific integrated circuit (ASIC) chip. With Moore's Law still holding, as attested to by the commercial viability of DSP chips for 100 Gb/s long-haul fiber transmission [29], it is reasonable to assume that an ASIC implementation of an OFDM(A)-based DSP processor for next-generation PON is feasible. Perhaps less certain, at least until recently, was the commercial availability of *both* high-speed ADCs and DACs. Although high-speed ADC chip development was spurred by the emergence of the 100 Gb/s digital coherent receiver, the adoption of all-optical POLMUX-QPSK modulation seemed to obviate the need for a digital transmitter. Indeed, in previous papers [34], we have issued practical guidance for DAC-side undersampling and ADC-side oversampling as a way of offsetting the potential unavailability of DACs capable of satisfying high Nyquist rates. However, the potential for high flexibility and digital precompensation of transmission impairments enabled by high-speed digital transmitters has increased the industry momentum toward ASIC implementations of high-speed DACs. Recent high-speed ADC/DAC technology trends and their relevance to future optical access are thus discussed next.

B. High-Speed ADC/DAC Technology Trends

Fig. 10 illustrates the growth in the sampling rates (GS/s) in commercially available high-speed ADCs and DACs in recent years. (It is noted that Fig. 10 is intended to be illustrative rather than exhaustive, in order to highlight steady trends rather dynamic, short-term developments.) From Fig. 10, it can be observed that prior to 2007–2008, the highest speed commercial data converter operated in the 20 Gs/s range, and it was an ADC [87]. DAC-side sampling rates were substantially lower, in the ∼5 Gs/s range. However, fueled by market demand in adjacent areas, including 100 Gb/s long-haul fiber-optic transmission, there has been a dramatic increase in the sampling rates of commercially available DAC/ADCs since 2008 [88], [89]. At present, 50^{+} GS/s single-chip ADC *and* DAC ASICs represent the state of the art. Furthermore, the 100^{+} GS/s mark has recently been reached by laboratory equipment (i.e., real-time oscilloscopes.) This suggests that still higher sampling rates could be realized in ASIC chips in the future.

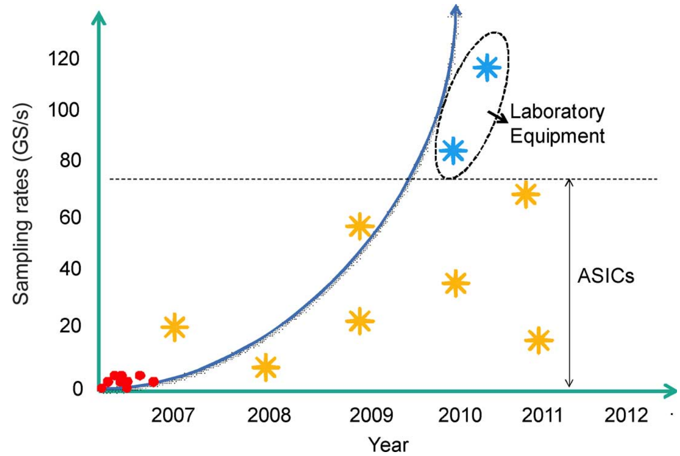

Fig. 10. Summary of recent high-speed ADC/DAC sampling rate trends.

While discrete ADCs and DACs can be implemented using different materials, it has been shown that high-performance implementations are feasible on a purely silicon platform [88]. Due to the material simplicity of silicon and its amenability to on-chip component integration, an integrated ADC/DAC/DSP ASIC that can readily be mass produced can be viewed as a highly attractive commercial solution for a high-speed digital transceiver. To reduce the power consumption that stems from the high computational power of such chips, advances in complementary metal–oxide–semiconductor (CMOS) can be exploited. For example, by implementing the same high-speed ADC or DAC in 40 nm CMOS rather than 65 nm CMOS, its power consumption can be approximately halved [88]. Even more advanced 28 and 20 nm CMOS processes have also been announced; however, the tradeoff between increasingly marginal power reductions and increasingly higher cost does need to be taken into consideration when selecting the optimal CMOS process. This holds particularly true for cost-sensitive optical access. Nevertheless, aggressive ADC/DAC developments initially targeted for long-haul fiber systems are expected to have beneficial effects on next-generation DSP-based optical access.

C. Cost-Profile Ramifications of DSP-Based Access

It bears repeating that for optical access, cost efficiency is quite a strict requirement. A highly effective way to achieve the desired cost efficiency is to leverage the high-volume nature of PON deployments by exploiting mass-market technologies, the cost of which significantly reduces on a per-unit basis for high unit counts. Silicon-based technologies, such as advanced DSP, are perhaps the best example of this cost-profile model, which has been very successfully adopted in wireless handheld devices, for example. It is envisioned that advanced DSP could play an analogous role in future PON systems [90], [91], while also providing some PON-specific benefits: i.e., the ability to simplify optical components and maximally reuse the costly legacy ODN.

In order for the mass market model to hold for future PON, several key criteria must be met: first, the pricing of ASICs for PON applications must be exclusively volume based. In other words, ASIC cost must not be determined by the reliance on exotic materials, expensive packaging techniques, etc. From this perspective, it is helpful that next-generation optical access will operate at data rates notably lower than 100 Gb/s, such that more cost-efficient options can be used. Second, ASICs for DSP-based access must not create a power consumption bottleneck neither at the OLT nor at the ONUs. This challenge can be addressed by a well-designed synergy between advanced CMOS and computationally efficient DSP algorithms [92], [93]. Finally, deployed PON volumes must be sufficiently high. While it is not expected that these will reach the stratospheric numbers of mobile devices in the near future, a rough estimate suggests that PON volumes comparable to those of wireless base station deployments could bring about important benefits.

VII. Conclusion

A comprehensive overview of OFDM-based optical access has been presented in this paper, covering technology principles, practical advantages and challenges, as well as recent progress and application scenarios in future PON. The techno-economic prospects for DSP-based enabling technologies, including high-speed digital processors and data converters, have also been discussed.

In summary, the fundamental motivation for using optical OFDM(A) in optical access can be regarded as threefold: 1) OFDM enables multilevel modulation and efficient dispersion compensation to achieve spectrally efficient, high-speed, long-reach access over a legacy PON fiber plant; 2) OFDMA subcarriers can be used as finely granular bandwidth resources for highly dynamic multiuser traffic aggregation in point-to-multipoint optical access networks; and 3) OFDM(A) implementation is largely DSP based and can thus be realized in silicon to achieve a cost-efficient, volume-driven cost profile. Moreover, with the advent of efficient high-speed DSP and data converters in recent years, and an increasing momentum of R&D activity in the field, the progress in this area is expected to continue.

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