# Emerging Optical Access Network Technologies for 5G Wireless [Invited]

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***Abstract*—With the advancement of radio access networks, more and more mobile data content needs to be transported by optical networks. Mobile fronthaul is an important network segment that connects centralized baseband units (BBUs) with remote radio units in cloud radio access networks (C-RANs). It enables advanced wireless technologies such as coordinated multipoint and massive multiple-input multiple-output. Mobile backhaul, on the other hand, connects BBUs with core networks to transport the baseband data streams to their respective destinations. Optical access networks are well positioned to meet the first optical communication demands of C-RANs. To better address the stringent requirements of future generations of wireless networks, such as the fifth-generation (5G) wireless, optical access networks need to be improved and enhanced. In this paper, we review emerging optical access network technologies that aim to support 5G wireless with high capacity, low latency, and low cost and power per bit. Advances in high-capacity passive optical networks (PONs), such as 100 Gbit/s PON, will be reviewed. Among the topics discussed are advanced modulation and detection techniques, digital signal processing tailored for optical access networks, and efficient mobile fronthaul techniques. We also discuss the need for coordination between RAN and PON to simplify the overall network, reduce the network latency, and improve the network cost efficiency and power efficiency.**

***Index Terms*—5G; C-RAN; Fixed-mobile convergence; Mobile fronthaul; Optical access network; PON.**

## I. Introduction

Optical networks have been continuously evolving to address the ever-increasing communication demands in the cloud era. To support diverse applications such as fiber-to-the-home (FTTH), fiber-to-the-building (FTTB), and fourth-generation (4G)/fifth-generation (5G) wireless, optical transmission over optical access networks, metro networks, and core networks is needed, as illustrated in Fig. 1. Optical access networks are becoming ultrabroadband in order to provide first fiber connections to the end users [1–3]. Due to widespread deployment of cloud data centers (DCs) in metropolitan areas, traffic within metro networks is experiencing significant growth [4]. For core networks, ultrahigh-speed wavelength channels, such as terabit/second superchannels [5], are being used to provide high spectral efficiency and long-haul transmission capabilities. Transport software-defined networking (T-SDN) is applied across the optical networks to provide global network optimization, ease of network management, and fast response to new network demands.

For wireless applications, optical networks have been used to support mobile fronthaul and mobile backhaul [6,7]. The cloud radio access network (C-RAN) is expected to play an important role in next-generation mobile networks [8] by improving network performance via coordinated multipoint (CoMP) and increasing network energy efficiency via capacity sharing and optimization [9,10]. Mobile fronthaul is a key network element in the C-RAN architecture, as it connects centralized baseband units (BBUs) with remote radio units (RRUs). On the other hand, mobile backhaul connects BBUs with the core networks to transport the baseband data streams to their respective destinations. Mobile fronthaul could also be used to support massive multiple-input multiple-output (M-MIMO), which is considered a key technology for 5G wireless networks [10].

To better meet the stringent optical communication demands imposed by 5G wireless, such as high capacity, low latency, and low cost and power per bit, optical access networks need to be improved and enhanced. Here, we review emerging optical access network technologies for supporting future 5G wireless networks. This paper is organized as follows. In Section II, we briefly describe the optical communication demands of 5G wireless networks, especially those for fronthaul transmission. In Section III, we present recent advances in optical access networking. In Section IV, we discuss advanced modulation and detection techniques for achieving low cost and power per bit. In Section V, we present recent results on the efficient mobile fronthaul (EMF) technique for achieving high transmission throughput and low processing latency. In Section VI, we discuss the need for enhanced convergence between the RAN and passive optical network (PON) to simplify the overall network, reduce the network latency, and improve the network cost efficiency and power efficiency. More specifically, coordination in the media access control (MAC) layer between RAN-MAC and PON-MAC, as well as accelerated burst scheduling of the PON, is suggested. Finally, concluding remarks are made in Section VII.

## II. Demands of 5G Wireless

Figure 2 illustrates the use of optical-fiber-based mobile fronthaul to support CoMP and M-MIMO, as well as mobile

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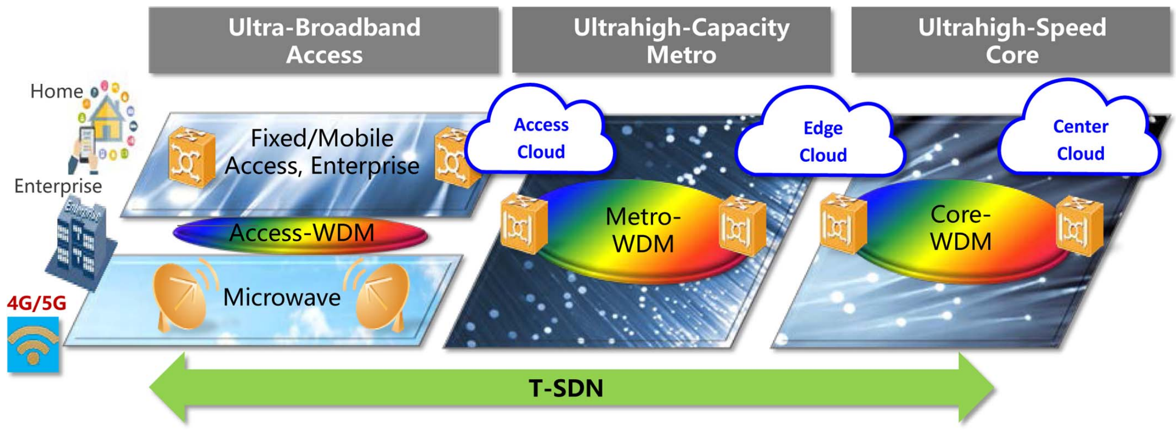


Fig. 1. Illustration of cloud-era optical networks supporting diverse applications such as FTTH, FTTB, and 4G and 5G wireless.

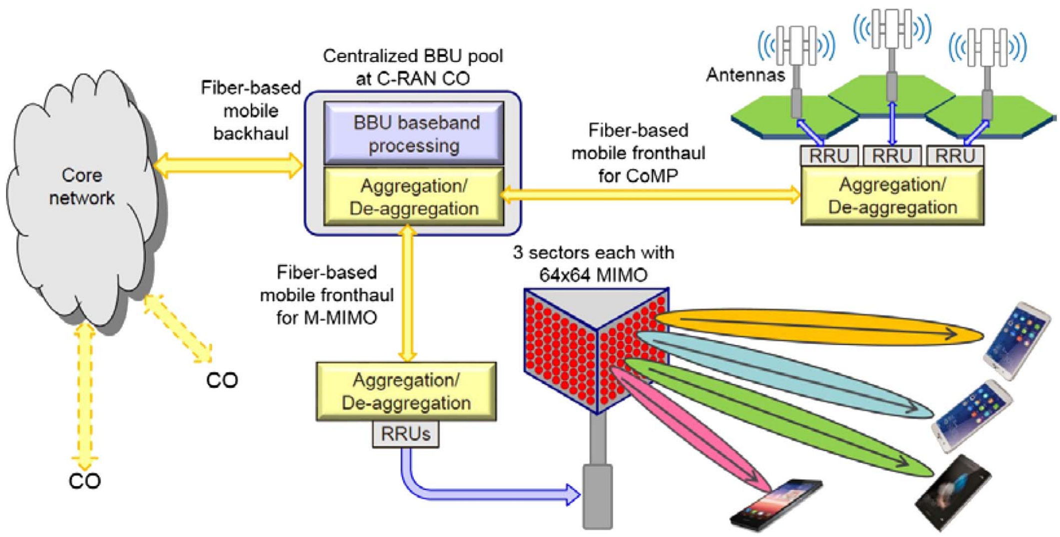


Fig. 2. Illustration of optical-fiber-based mobile fronthaul supporting CoMP and M-MIMO, as well as mobile backhaul transporting the baseband data to/from the core networks. CO, central office.

backhaul to transport the baseband data to/from the core networks. Currently, the interface used for mobile fronthaul is primarily based on the common public radio interface (CPRI) [11]. CPRI uses binary on–off keying (OOK) as the modulation format, leading to a key drawback of bandwidth inefficiency. For a potential 5G M-MIMO scenario with carrier-aggregated 200 MHz signals, $64 \times 64$ M-MIMO, and three directional sector antennas (to cover a 360° angle geographically), 240 CPRI Option 7 (9.8304 Gbit/s) interfaces would be required, corresponding to a total fronthaul data rate of about 2.4 Tbits/s. If 10 Gbit/s optical transceivers are used, this scenario requires 240 optical transceivers, which would be forbiddingly expensive. Recently, a CPRI-compatible EMF technique was demonstrated to substantially increase the bandwidth efficiency of fronthaul transmission [12,13], which we will describe in more depth in Section V.

In addition to high capacity, low processing latency is also required in mobile fronthaul. The commonly suggested end-to-end latency in a 5G wireless network is 1 ms, and the latency allocated to fronthaul is about 200 μs, which corresponds to the round-trip delay caused by a 20 km standard single-mode fiber (SSMF) link. Considering that the fronthaul coverage may be up to 20 km, the processing latency needs to be a small fraction of the fiber propagation delay, e.g., <10 μs. With a novel (to our knowledge) digital signal processing (DSP)-based channel aggregation and de-aggregation approach, round-trip processing latency of <4 μs has been achieved [14].

Furthermore, low cost and power per bit is of crucial importance in mobile fronthaul and backhaul applications. This calls for low-cost, low-power-consumption optical transceivers running at high speed, e.g., 50 Gbits/s or 100 Gbits/s. One attractive approach is to use advanced modulation and detection techniques, enabled by DSP, to support high-speed transmission with low-cost narrow-bandwidth optics [15]. For example, 20-GHz-class lasers were used to generate 100 Gbit/s signals via discrete multitone (DMT) [16,17]. More detailed discussion on DSP-assisted modulation and detection techniques will be given in Section IV.

To further reduce the overall cost, it would be beneficial to share the same optical infrastructure among multiple RRU sites. This may be realized in a time-domain-multiplexed (TDM) PON with an accelerated PON burst scheduling to achieve the needed low processing latency and small timing jitter. Also, coordination between the RAN-MAC and the PON-MAC is needed to reduce the processing latency. These aspects will be discussed in Section VI.

## III. Advances in Optical Access Networks

Bandwidth-consuming services required by emerging applications such as 4K/8K HD television have been driving optical access network to evolve continuously. 2.5 Gbit/s gigabit PON (GPON) and Ethernet PON (EPON) systems are currently being widely deployed around the world, 10 Gbit/s symmetric/asymmetric EPON has been standardized by IEEE, and 40 Gbit/s time- and wavelength-division-multiplexed (TWDM) PON has been standardized by the Full Service Access Network [1,2]. Recently, IEEE has initiated the 100G-EPON task force, aiming to achieve a per-channel data rate of at least 25 Gbits/s [3]. DSP has been actively studied to enable a high-throughput PON using low-bandwidth optics [18–24]. 25 Gbit/s downstream transmission was recently demonstrated by using 10G optics together with DSP-assisted 4-ary pulse-amplitude modulation (PAM-4) [19,20] and non-return-to-zero (NRZ) [21]. DMT is a well-studied modulation format for DC communications and for PON [16]. A flexible-PON delivering adaptive data rates between 25 and 40 Gbits/s, respectively, supporting link loss budgets of 30 and 21.5 dB, has recently been demonstrated using 10G optics [22].

Figure 3 illustrates a futuristic flexible-PON architecture with software-defined networking and network function virtualization implemented to optimize the network in terms of throughput, energy efficiency, and control and management. Multiple virtual PON (VPON) units are interconnected to better address various applications, such as FTTH and FTTB, through software-defined routing and capacity sharing. Flexible optical line terminals (OLTs) are used to realize software-defined transmission with flexible data rates and link loss budgets, depending on network topology and dynamics.

## IV. Advanced Modulation and Detection Techniques

As briefly mentioned in the previous section, advanced modulation and detection techniques are promising for realizing a high-speed PON with lower cost per bit than previous generations of PON systems. Table I compares five major options of downstream modulation and detection schemes for a PON in terms of implementation complexity and performance. In all these options, the receivers at the optical network unit (ONU) sites are based on single-detector direct detection (DD) in order to make the overall system cost low. The first option is based on conventional NRZ OOK, which is the simplest to implement, as shown in Fig. 4(a). However, it has the drawback of being bandwidth inefficient. Also, it has low dispersion tolerance, and can only work in the O-band (around 1310 nm) for $25^{+}$ Gbit/s applications. The second option is based on optical duobinary modulation [23], as shown in Fig. 4(b).

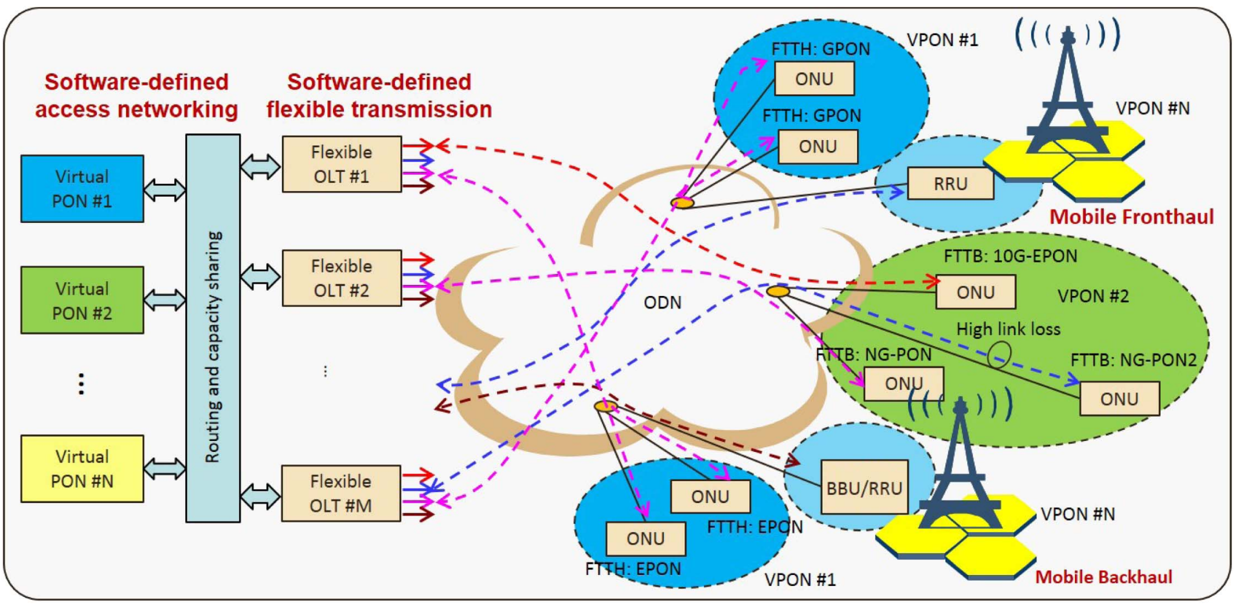


Fig. 3. Schematic of a futuristic PON that addresses demands such as customer-specific data rates, network optimization and virtualization, and fiber/wireless convergence. OLT, optical line terminal; ODN, optical distribution network; ONU, optical network unit; VPON, virtual PON; FTTH(B), fiber-to-the-home(business); RRU, remote radio unit; BBU, baseband unit; NG-PON, next-generation PON.

TABLE I
Comparison of Downstream Modulation and Detection Options for PON

| Option | Modulation at OLT | Detection at ONU | Pros | Cons |
|---|---|---|---|---|
| 1 | NRZ (EML, DML)[a] | Analog DD (APD) | + Cost effective | – Low bandwidth efficiency<br>– Low dispersion tolerance<br>– O-band operation only for $25^{+}$ Gb/s |
| 2 | Optical duobinary (Laser+MZM) | Analog DD (APD) | + Higher dispersion tolerance than Option 1 (by ∼2.5×) | – MZM needed (more expensive)<br>– High modulation loss (optical booster amplifier needed) |
| 3 | DSP-assisted NRZ/ PAM-4 (EML, DML) | DSP-assisted DD (linear APD) | + Higher dispersion tolerance than Option 1 (by ∼2.5×)<br>+ Higher bandwidth efficiency than Option 1 (by ∼2×) | – High-speed DAC/ADC/ DSP needed<br>– Linear APD needed<br>– DSP power consumption an issue |
| 4 | DSP-assisted DMT | DSP-assisted DD (linear APD) | + Higher dispersion tolerance than Option 1 (by ∼2.5×)<br>+ Higher bandwidth efficiency<br>+ Flexible modulation formats | – High-speed DAC/ADC/ DSP needed<br>– Linear APD needed<br>– DSP power consumption an issue |
| 5 | IQ modulation (IQ-MZM) | DD (APD) | + Dispersion precompensation<br>+ Bandwidth-efficient modulation | – High cost due to IQ-MZM<br>– DAC/ADC/DSP needed for advanced formats |

[a]EML, electro-absorption modulated laser; DML, directly modulated laser.

It has the advantage of improved dispersion tolerance, but requires the use of a Mach–Zehnder modulator (MZM) for external modulation to realize the $0/\pi$ optical phase shifts needed for generating an optical duobinary signal, which adds cost and loss. The third option is based on DSP-assisted single-carrier formats such as NRZ and PAM-4, as shown in Fig. 4(c). It has the advantages of being dispersion tolerant and bandwidth efficient, but requires the use of a high-speed digital-to-analog converter (DAC), analog-to-digital converter (ADC), and DSP. It is also necessary to simplify the DSP implementation to keep the power consumption at an acceptable level. The fourth option is based on DSP-assisted multicarrier formats such as DMT, as shown in Fig. 4(d). Due to the use of training symbols (TSs) and pilot subcarriers, the fourth option offers the additional benefits of being flexible in terms of subcarrier modulation format. The fifth option is based on dispersion precompensation via optical in-phase and quadrature (IQ) modulation [24]. With the use of the optical IQ modulation, the complex E-field of a suitably dispersion-precompensated optical signal can be generated, such that the signal becomes dispersion free after fiber transmission. This scheme has the advantages of being highly dispersion tolerant and bandwidth efficient, but requires a complex transmitter that is currently both costly and lossy.

Table II compares five major options of upstream modulation and detection for PON in terms of implementation complexity and performance. In all these options, the transmitters at the ONU sites are based on simple intensity modulation (IM) in order to make the overall system cost low. The first option is based on conventional NRZ, as shown in Fig. 5(a). It has the same pros and cons as in the downstream case. The second option is based on electric duobinary modulation, as shown in Fig. 5(b). An electric duobinary signal is basically a NRZ signal with a strong bandwidth limitation such that the received electric signal is a three-level duobinary-like signal. It allows for relaxed transmitter bandwidth requirement, but suffers in receiver sensitivity [25]. The third option is based on DSP-assisted single-carrier formats such as NRZ and PAM-4, as shown in Fig. 5(c). It has the same pros and cons as those in the downstream case. The fourth option is based on DSP-assisted multicarrier formats such as DMT, as shown in Fig. 5(d), which also has the same pros and cons as those in the downstream case. The fifth option is based on dispersion postcompensation via digital coherent detection [26]. It has the advantages of being highly sensitive, dispersion tolerant, and bandwidth efficient. However, it requires a coherent receiver that is much more complex than a single-detector DD receiver. In addition, the ONU laser frequency wandering due to temperature changes and burst-mode operation is an issue that needs to be addressed, as the optical local oscillator used in the coherent receiver needs to be sufficiently aligned with the center frequency of the incoming signal (preferably within a few gigahertz). Nevertheless, the potential benefits offered by coherent detection make it worthwhile to explore elegant designs of low-cost digital coherent detection suitable for upstream detection in future PON systems. Note that unlike the downstream transmission, the upstream transmission in a TDM-PON is operating in the burst mode, so fast channel synchronization and tracking techniques need to be further researched and developed.

## V. Efficient Mobile Fronthaul

Recently, a CPRI-compatible EMF technique was proposed and demonstrated [12–14]. Figure 6 shows the

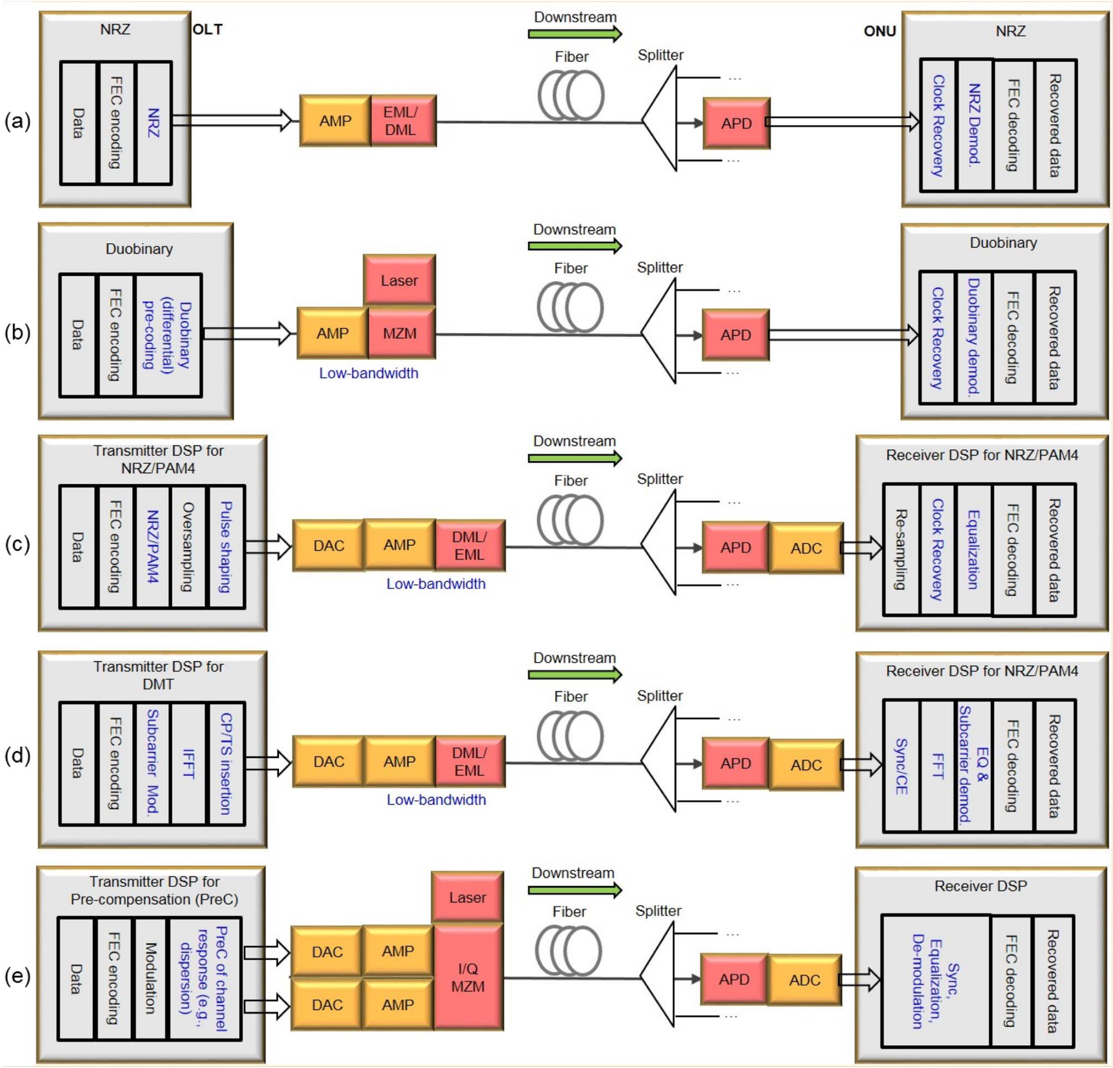


Fig. 4. Schematic of downstream modulation and detection options based on (a) NRZ, (b) optical duobinary, (c) DSP-assisted NRZ/PAM-4, (d) DSP-assisted DMT, and (e) DSP-assisted dispersion precompensation. AMP, RF driver amplifier; APD, avalanche photodetector; CP, cyclic prefix; FFT, fast Fourier transform; IFFT, inverse FFT; TS, training symbol; EML, electro-absorption modulated laser; DML, directly modulated laser; CE, channel equalization.

principle of the EMF technique. CPRI input channels are first processed so that the wireless IQ bits are separated from the control word (CW) bits. TDM is then applied to aggregate the IQ bits and CW bits separately. As the CW bits need to be transmitted without errors, we use low-level quadrature amplitude modulation (QAM), e.g., 16-QAM, to carry the CW bits. For the IQ bits, we use pulse-code modulation (PCM) in order to achieve high bandwidth efficiency. The PCM signal is quantized to 9 bits for each of the I and Q components of the complex waveform of the signal. Due to the finite effective number of bits of the transmission link, the received PCM signal will have nonzero error-vector magnitude (EVM), which is acceptable as long as it is below a given value, e.g., as specified by the Third Generation Partnership Project. The PCM signal is downsampled by a factor of ¾, and the QAM signal is inserted with periodic TSs for synchronization purposes. The two signal streams are then multiplexed in the time domain, Nyquist pulse shaped, and frequency upconverted to generate a real-valued TDM-EMF signal for IM-DD. In the receiver, the input signal is downconverted to the baseband, and TS-based synchronization and time-division demultiplexing are performed to separate the PCM signal stream from the QAM signal stream. The QAM signals are used to train an equalizer, which then performs channel equalization for both the PCM and the QAM signals [12]. With the use of the equalizer, the signal-to-noise ratio (SNR) performance of the fronthaul can also be accurately estimated.

In CPRI, each time-domain sample of a wireless signal is typically digitized to 15 bits for each of the I and Q components of the complex waveform of the signal. The ratio between the bits used for CWs and the IQ bits is 1:15. For optical transmission, binary OOK is used. 8 bit/10 bit line coding is used to facilitate OOK clock recovery and error detection. As a typical example, the line rate needed for aggregating eight 20 MHz Long Term Evolution (LTE) signals

TABLE II
COMPARISON OF UPSTREAM MODULATION AND DETECTION OPTIONS FOR PON

| Option | Modulation at ONU | Detection at OLT | Pros | Cons |
|---|---|---|---|---|
| 1 | NRZ (DML, EML)[a] | Analog DD (APD) | + Cost effective | – Low bandwidth efficiency<br>– Low dispersion tolerance<br>– O-band operation only |
| 2 | Electrical duobinary (DML, EML) | Analog DD (APD) | + Cost effective | – Worse receiver sensitivity than NRZ |
| 3 | DSP-assisted NRZ/ PAM-4 (DML, EML) | DSP-assisted DD (linear APD) | + Higher bandwidth efficiency<br>+ Higher dispersion tolerance than Option 1 (by ~2.5×)<br>+ Higher bandwidth efficiency than Option 1 (by ~2×) | – High-speed DAC/ADC/ DSP needed<br>– Linear APD needed<br>– DSP power consumption an issue |
| 4 | DSP-assisted DMT | DSP-assisted DD (linear APD) | + Higher dispersion tolerance than Option 1 (by ~2.5×)<br>+ Higher bandwidth efficiency<br>+ Flexible modulation formats | – High-speed DAC/ADC/ DSP needed<br>– Linear APD needed<br>– DSP power consumption an issue |
| 5 | NRZ/PAM-4/DMT (DML, EML) | Coherent detection (coherent RX) | + Highly sensitive<br>+ Dispersion postcompensation<br>+ Bandwidth-efficient modulation | – High cost due to coherent RX<br>– DAC/ADC/DSP needed<br>– ONU laser frequency wandering an issue |

[a]EML, electro-absorption modulated laser; DML, directly modulated laser.

(with a 30.72 MHz sampling rate) in CPRI Option 7 is as high as $9.8304\ \text{Gbits/s}(= 8 \times 2 \times 16 \times 30.72 \times 10/8\ \text{Mbits/s})$, within which 491.52 Mbits/s is dedicated to CWs. In the proposed TDM-EMF scheme, CWs can be modulated by 16-QAM, which leads to a bit error rate (BER) of well below $10^{-12}$ for a typical SNR of ~24 dB. Assuming that 4:3 downsampling is applied to the PCM signal, the spectral bandwidth needed to transmit the IQ and CW bits in CPRI Option 7 (supporting eight 30.72 MHz sampled LTE signals) is only 0.3072 GHz $(= 491.52\ \text{MHz}/4 + 8 \times 30.72\ \text{MHz} \times 3/4)$. This indicates that the proposed TDM-EMF approach is 32 $(= 9.8304/0.3072)$ times as high as that of the typical CPRI approach [12]. The EMF approach we took here can be regarded as the combination of analog transmission for wireless signals (via PCM) and digital transmission for CW bits (via QAM). In addition, the analog PCM transmission is also implemented with the assistance of high-speed DAC, ADC, and DSP to realize useful features such as channel equalization and flexible channel aggregation/de-aggregation.

Figure 7(a) shows the recovered spectra of an 8 Gbaud TDM-EMF signal, generated by a 10G directly modulated laser (DML) and received by a 10G linear avalanche photodetector (APD) in the optical back-to-back case ($L = 0$ km) and after 1 km SSMF transmission ($L = 1$ km) [12]. The corresponding CPRI data rate is 256 Gbits/s. Figures 7(b) and 7(c), respectively, show the SNR of the CW signal and the EVM of the wireless 64-QAM optical frequency-division multiplexing (OFDM) signal versus $P_{RX}$. For the CW signal, BER $< 10^{-12}$ is obtained without forward-error correction (FEC) (or SNR $> 23.9$ dB) at $P_{RX} \geq -4$ dBm. For the wireless 64-QAM-OFDM signal, EVM $< 8\%$ is achieved at $P_{RX} \geq -8$ dBm. Moreover, a negligible fiber transmission penalty is observed by comparing the cases of $L = 0$ km and $L = 1$ km. When operating in the O-band, a 20 km transmission distance is expected to be supported. It is possible that future PON systems would widely use similar 10G-class linear optics (such as DML and APD), making it possible to use a common optical transceiver platform to cost-effectively support both optical access and mobile fronthaul applications.

## VI. RAN–PON COORDINATION

A PON has a point-to-multipoint architecture, which is uniquely suited to cost-effectively carry RAN traffic via the sharing of most of the common fiber infrastructure with multiple RRU sites. There is a clear need for coordination between the RAN and PON to simplify the overall access network, reduce the network latency, and improve the network cost efficiency and power efficiency. To meet the stringent latency requirements of 5G mobile fronthaul and backhaul, joint MAC scheduling between the RAN-MAC and PON-MAC is needed. For example, wireless scheduling can be shared with the PON scheduling in advance, such that the upstream traffic from wireless user equipment (UE) can be seamlessly carried over by the TDM-PON system without having to wait for negotiation between the ONU and OLT, as illustrated in Fig. 8. This concept has been recently proposed and described in Refs. [27–32]. With this coordination and future advances in fast burst-mode channel tracking (e.g., via advanced burst-mode DSP), accelerated burst scheduling of PON may be realized.

Figure 9 illustrates accelerated burst scheduling in TDM-PON upstream transmission for timing-critical mobile fronthaul applications. Preferably, the cycle time

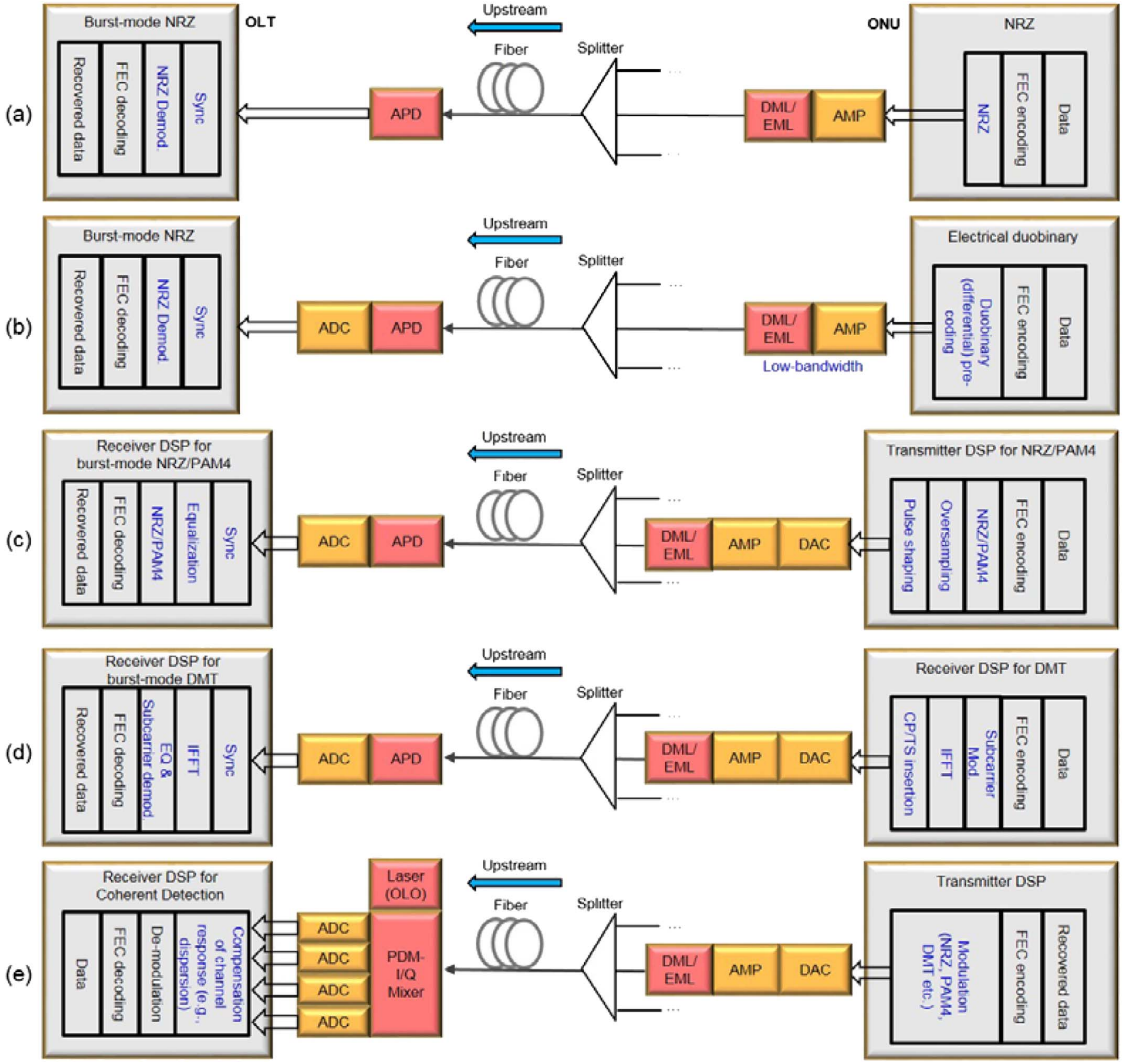


Fig. 5. Schematic upstream modulation and detection options based on (a) NRZ, (b) electric duobinary, (c) DSP-assisted NRZ/PAM-4, (d) DSP-assisted DMT, and (e) DSP-assisted coherent detection. Sync, burst synchronization; EQ, channel equalization; AMP, RF driver amplifier; APD, avalanche photodetector; CP, cyclic prefix; IFFT, inverse fast Fourier transform; EML, electro-absorption modulated laser; DML, directly modulated laser.

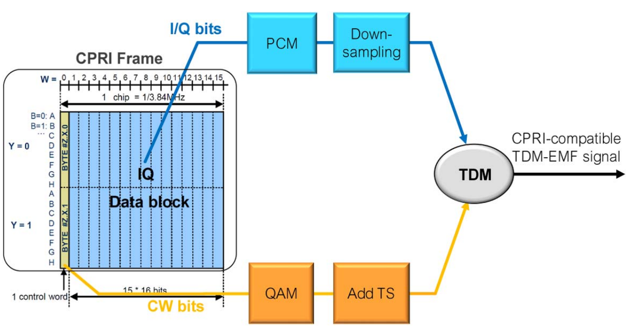


Fig. 6. Principle of the CPRI-compatible TDM-EMF scheme.

period ($T_{\mathrm{cycle}}$), during which the OLT scans through all the ONUs once, is a multiple of the CPRI basic frame period, 260.416667 ns (or 1/3.84 MHz), so that multiple CPRI frames can be transported per cycle. $T_{\mathrm{cycle}}$ needs to be shorter than the processing latency specified. For example, the preferred $T_{\mathrm{cycle}}$ is less than 20 μs for fronthaul applications. Each ONU transmits CPRI frames on a burst-by-burst basis with a predetermined burst period, $T_{\mathrm{burst}}$. Flexible bandwidth allocation can be realized by assigning each ONU a given number of bursts per cycle. A suitable gap period, $T_{\mathrm{gap}}$, is allocated between adjacent bursts to avoid implementation of imperfection-induced burst collision. Thus, $T_{\mathrm{cycle}}$ can also be expressed as $T_{\mathrm{cycle}} = (T_{\mathrm{burst}} + T_{\mathrm{gap}}) \cdot \sum_{i=1}^{N} NB_i$, where $N$ is the total number of ONUs in the PON and $NB_i$ is the number of bursts per cycle assigned to the $i$th ONU. Assuming the use of the

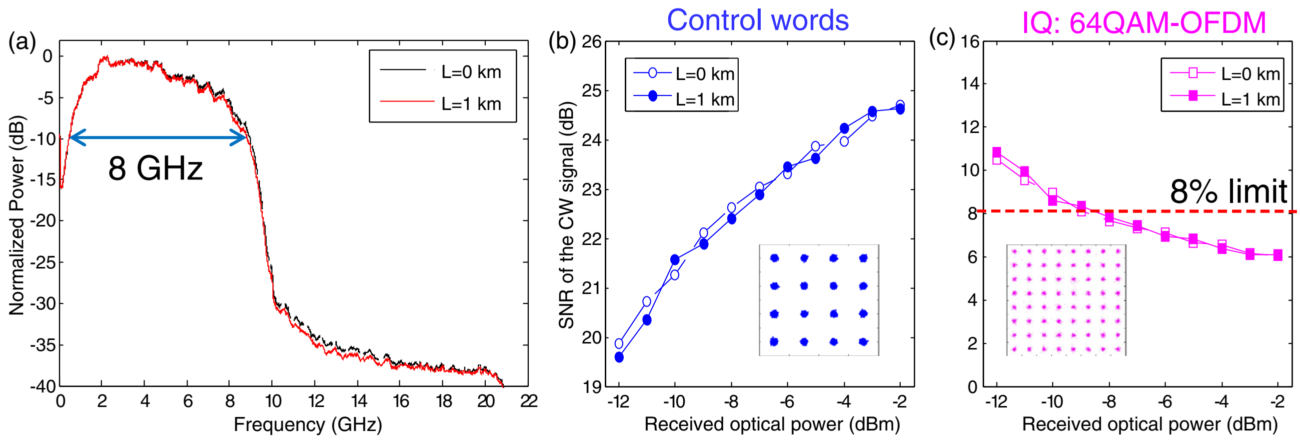


Fig. 7. (a) Measured RF spectra of an 8 Gbaud CPRI-compatible TDM-EMF signal after optical modulation and detection, (b) SNR of the CW signal versus received optical power, and (c) EVM performance of the 64-QAM-OFDM signal versus received power. Insets: typical recovered constellations of (b) the CW signal (with 16-QAM) and (c) the LTE signal (with 64-QAM) at $P_{RX} = -10$ dBm (after Ref. [12]).

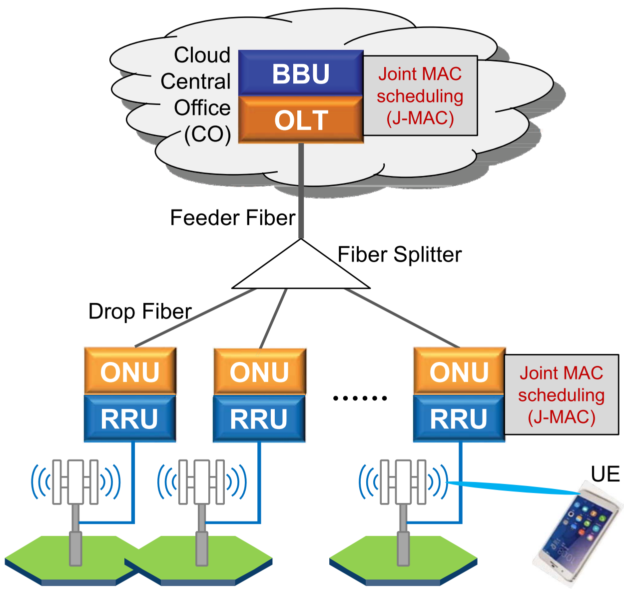


Fig. 8. Illustration of a TDM-PON-based mobile fronthaul/backhaul network with RAN–PON coordination for joint MAC shceduling to reduce overall network latency.

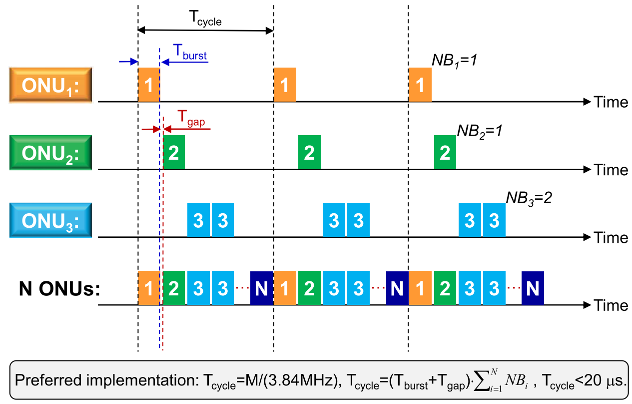


Fig. 9. Illustration of a low-latency synchronous burst scheduling design in TDM-PON upstream transmission for timing-critical mobile fronthaul applications.

EMF technique reported in Ref. [12], 10G-class optics can be used to support a 256 Gbit/s CPRI-equivalent data rate, or about 10 CPRI Option 10 (24.33024 Gbit/s) connections. Thus, an EMF-assisted PON system using 10G-class optics could enable the sharing of the PON system with eight RRU sites, each running at the highest CPRI speed so far, the Option 10 rate, thereby achieving high cost-effectiveness on the network level. More wavelength channels may be used, e.g., via TWDM-PON [1–3], to further increase the throughput per fiber.

Note that in this specific PON architecture, the OLT and all the ONUs have a common clock frequency that is locked to the source clock of the BBU pool. In the case of CPRI, a fundamental frequency is the CPRI basic frame rate (or the basic Universal Mobile Telecommunications System chip rate), 3.84 MHz. In essence, it is beneficial for a PON and RAN to share both the MAC-layer scheduling and the physical-layer clock to achieve low-latency, synchronous forwarding of mobile signals through the low-cost PON system. By doing so, timing-critical mobile communication demands can be effectively supported. This type of PON system may coexist with the current generation of PON systems by using different wavelength plans.

## VII. Conclusion

We have reviewed emerging optical access network technologies for their ability to support 5G wireless with high capacity, low latency, and low cost and power per bit. More specifically, we have discussed advanced modulation and detection techniques, DSP techniques tailored for optical access networks, and CPRI-compatible EMF techniques. We also discussed the need for coordination between a RAN and PON to meet the dynamic wireless traffic demands in a very responsive manner. Particularly, it is beneficial for a PON and RAN to share both the MAC-layer scheduling and the physical-layer clock to achieve low-latency, synchronous forwarding of mobile signals through the low-cost PON system, effectively meeting the timing-critical mobile communication demands in future 5G wireless networks.

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