Efficient Delivery of Integrated Wired and Wireless Services in UDWDM-RoF-PON Coherent Access Network

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***Abstract*— A high-capacity coherent ultradense wavelength-division multiplexing passive optical network integrated with a 60-GHz radio-over-fiber system has been designed and experimentally demonstrated for the first time. In this proposed architecture, millimeter-wave signal generation is achieved by coherent technology, in place of the optical carrier suppression technique, which requires modulators with large bandwidth and precise optical interleavers. The system fully exploits advantages of coherent access networks to provide both multigigabit wired and wireless access services with high spectral and power efficiencies. Successful wireless transmission of multichannel 3.3-Gb/s quadrature phase-shift keying signals with 10-GHz channel spacing over 50-km single-mode fiber (SMF-28) has been achieved.**

***Index Terms*— Coherent access network, radio-over-fiber (RoF), ultra-dense wavelength-division multiplexing passive optical network (UDWDM-PON).**

I. Introduction

RECENT trends of exponentially growing demand for high-capacity and high-speed information access network drive optical networking research towards coherent access network [1]-[3]. To take full advantages of the 4-THz bandwidth available in C-band that can be shared by thousands of users with a narrow channel spacing of ~0.08 nm is a challenging task without employing coherent technology. High capacity, coherent networks can draw benefits from complex data formats with polarization multiplexing, through increasing the spectral efficiency (SE) by $2\log_2 M$ [4] and reducing the bandwidth requirement of electronics and photonics components. Meanwhile, radio-over-fiber (RoF) technology is considered to be a promising solution to deliver multi-gigabit/s wireless access services [5]-[7]. Integration with existing WDM-PON infrastructure is expected to provide both wired and wireless access services. However, most of the proposed schemes of generating millimeter wave (mm-wave) radio signals at 60 GHz were based on an optical carrier suppression (OCS) technique which occupied large bandwidth and suffered from fiber chromatic dispersion (CD) [8], [9]. Furthermore, the requirement of narrow interleavers (IL) or optical bandpass filters (OBPF), in order to separate the two sidebands for wireless service, become the limitation of SE. To solve this problem, we propose a novel coherent access network architecture that integrates RoF with UDWDM-PON to simultaneously provide both multi-gigabit wired and wireless services with a channel spacing of 0.08 nm. Due to the mm-wave generation in coherent heterodyning technique, it relieves the RoF system from large CD in fiber transmission and large bandwidth requirement of electrical-to-optical (E/O) modulator. Thus the new access system can improve the SE as well as enable a more flexible and low-cost optical line terminal (OLT) structure.

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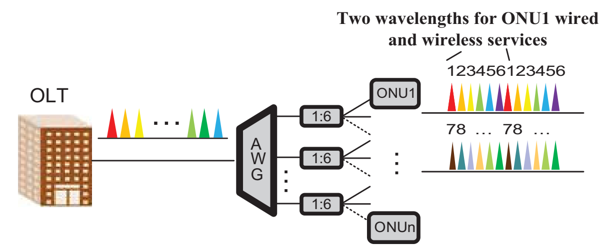

Fig. 1. Network-level system design and wavelength allocation.

II. Operation Principle

As illustrated in Fig. 1, in our UDWDM-RoF-PON architecture, the OLT can provide hundreds of wavelengths in an ultra dense wavelength grid. The optical network units (ONUs) are connected to OLT through an array waveguide grating (AWG) and 1: n optical splitters. Suppose each output of AWG supports 6 ONUs with 10-GHz channel spacing, 12 wavelengths are delivered from each AWG output port. Among the 12 wavelengths ONU1 received, the 1st and the 7th channels, spaced at 60 GHz, are used for wired and wireless services. A local oscillator (LO) with the same wavelength as the 1st channel is designated for both coherent homodyne and heterodyne down-conversions. Similarly, ONU2 utilizes the 2nd and 8th wavelengths for coherent detection. Fig. 2

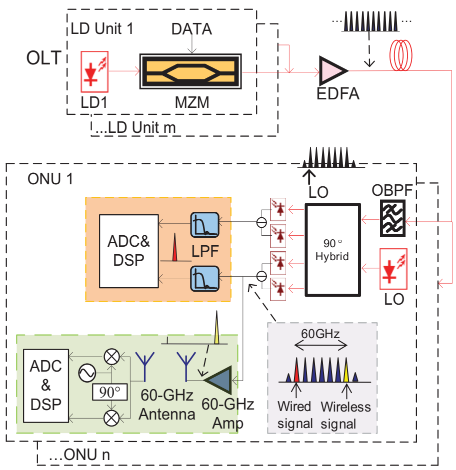

Fig. 2. Conceptual diagram of the proposed UDWDM-RoF-PON for delivering spectral-efficient wired and wireless downlink services, using mm-wave generation at 60 GHz in coherent access network.

illustrates the conceptual diagram of the proposed scheme. The OLT in Fig. 2 is an illustration of a simple and flexible setup where each wavelength carries data for designated users independent of other channels, unlike the optical mm-wave signals generated by OCS modulation method. In our OLT design, the modulators only require a few gigahertz bandwidth and channel spacing can be in the gigahertz range because signals can be filtered electrically. In the ONU, the OBPF roughly filters signals, including the desired wired and wireless channels with bandwidth smaller than 120 GHz, to ensure that only one channel spaced 60 GHz from LO is included. Suppose QPSK signals are modulated in the OLT, the down-link (DL) signals received in ONU can be expressed as:

$$E_r(t) = \Sigma_i \sqrt{P_{r_i}} \exp\{j[\omega_{c_i} t + \theta_{s_i}(t) + \phi_s(t)]\} \quad (1)$$

where P_{ri} and θ_{si} are the average received power and phase of the i^{th} channel, ω_{ci} is the i^{th} carrier frequency, and $\phi_s(t)$ is the phase noise associated with the source laser. After the 90° hybrid and balanced detectors of 60-GHz bandwidth or larger, a series of electric channels is down-converted:

$$\begin{aligned} I_1(t) &= R\mathrm{Re}\left\{\overrightarrow{E_r}(t) \cdot \overrightarrow{E_{LO}}(t)\right\} \\ &= R\Sigma_i \sqrt{P_{r_i} P_{LO}} \cos(\omega_{IF_i} t + \theta_{s_i}(t) \\ &\quad + \phi_s(t) - \phi_{LO}(t)) \quad (2) \\ I_Q(t) &= R\Sigma_i \sqrt{P_{r_i} P_{LO}} \sin(\omega_{IF_i} t + \theta_{s_i}(t) \\ &\quad + \phi_s(t) - \phi_{LO}(t)) \quad (3) \end{aligned}$$

where R is the photo-detector responsivity, P_{LO} is the power of the local oscillator (LO), $\omega_{IF_i} = \omega_{c_i} - \omega_{LO}$, and $\phi_{LO}(t)$ is the phase noise of the LO. Wired users filter the baseband signals out and process them in the conventional way. Wireless users need data carried at frequency of ω_{IF} that equals to 60 GHz. One balanced photodetector serving as part of a coherent heterodyne down-converter [1] is connected to 60-GHz amplifiers and antennae so that desired radio frequency (RF) signal is selected and emitted. Phase information of the signals can be solved by conventional digital signal

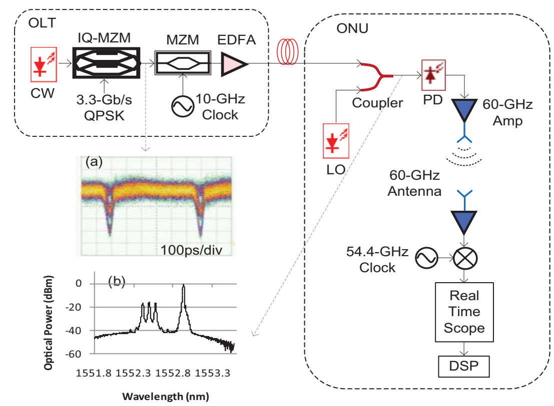

Fig. 3. Experimental setup of delivering RoF wireless service in coherent UDWDM-PON system. (a) Optical eye diagram for QPSK signals. (b) Optical spectrum after the coupler in ONU.

processing (DSP) codes after the down-conversion and analog-to-digital converter (ADC).

Comparing with the RoF network deploying the OCS modulation for 60-GHz signal up-conversion, our design exhibits the following advantages. First, OLT is simple, compact and consuming less power. Second, it's capable to optimize SE since all wavelengths are designated for different users with narrow spacing. Third, coherent detection with DSP allows for flexible operating data rates and modulation formats to support various applications. Fourth, separate wireless services carried at different frequencies in additional to 60 GHz, for example, 40-GHz band can also be implemented by assigning additional wavelengths and adding 40-GHz electrical components in ONUs without changing the infrastructure.

III. Experimental Setup and Results

We have conducted a proof-of-concept experiment to demonstrate the RoF test link integrated in the coherent UDWDM-PON system shown in Fig. 3. At the OLT, an Agilent 81689A tunable laser with 20-MHz linewidth at 1552.91 nm is followed by an in-phase/quadrature Mach-Zehnder modulator (IQ-MZM) driven by 3.3-Gb/s QPSK baseband data, whose symbol rate satisfies the transmit mask defined in the proposed PHY/MAC specification from IEEE 802.11ad [10]. The optical eye diagram for QPSK signal is shown as inset (a) in Fig. 3. The second MZM is driven by a 10-GHz sinusoidal wave, gene-rating neighboring optical subcarriers, which are then boosted and transmitted over a 50-km single-mode fiber (SMF). In the ONU, an Agilent 83433A distributed feedback laser (DFB) with 10-MHz linewidth is employed as the LO at 1552.50 nm and 5.69 dBm. A 3-dB coupler is used to combine the received signals and the LO. The optical spectrum of the LO and three channels is shown as inset (b) in Fig. 3. In this way, 51.6-GHz mm-wave, together with 41.6-GHz and 61.6-GHz subcarriers, are generated after the coupler and 50-GHz photodiode (PD), as a substitution of the 90° optical hybrid and balanced detector. However, the signal strength of the 61.6-GHz channel is weakened through the PD, and the 41.6-GHz channel is impaired through 60-GHz bandpass electrical amplifiers and

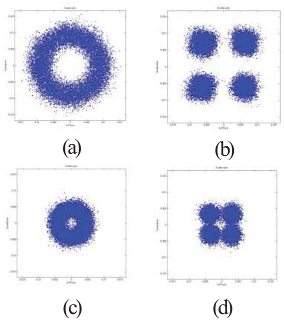

Fig. 4. Constellations plots (a) and (c) before, and (b) and (d) after carrier phase recovery for three-channel QPSK RoF DL with 50-km SMF-28 transmission. The received power of (a) and (b) are −23.8 dBm and BER is 3E-5. The received power of (c) and (d) are −28.9 dBm and BER is 5E-3.

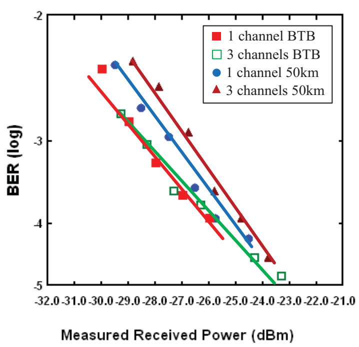

Fig. 5. BER versus received power.

antennae. The amplified 51.6-GHz signal is down-converted to an intermediate frequency (IF) of 2.8 GHz and sent to the 40-GSa/s LeCroy WM818Zi oscilloscope for the offline processing. Channel spacing in our experiment is limited due to the potential overlapping of the adjacent channels after the two-stage heterodyne down-conversion. Ideally, radio signals can be down-converted directly to I and Q baseband channels, then use low-pass filter (LPF) to eliminate the interference.

Fig. 4 shows the constellation plots before and after carrier phase recovery (using the standard Viterbi-Viterbi algorithm) [11] in an experiment where 3 channels are sent and transmitted over 50-km SMF-28. In Fig. 4(a) and (b), the constellation plots are measured for the case when the received power is −23.8 dBm and bit error rate (BER) is 3E-5. Fig. 4(c) and (d) correspond to the case with received power −28.9 dBm and BER 5E-3. The results demonstrate the efficiency in deploying low-cost lasers with rather large linewidth and conventional DSP in the coherent RoF system.

Fig. 5 illustrates the BER performances versus received optical powers for both single- and three-channel system. The power penalty caused by interchannel interference is negligible for back-to-back (BTB) downstream and only a small 0.5 dB penalty for 50-km fiber transmission. The power penalty due to 50-km SMF-28 is less than 1 dB. The received power can be very small without requiring optical amplifiers in the ONU. More importantly, the BER measurement results confirm that, comparing with the OCS scheme, the mm-wave generation by coherent technology is more tolerant to CD [12]. Consequently, the UDWDM-RoF-PON architecture is more suitable for next generation high-capacity and long-reach access networks.

IV. Conclusion

We have proposed and experimentally demonstrated a novel access network architecture for seamless integration of RoF with UDWDM-PON systems based on coherent technology. It is a breakthrough for RoF access network since it remarkably increases SE and allows for advanced modulation formats. Moreover, it eliminates the requirement for both narrow IL and E/O devices with large bandwidth, which are frequently needed in OCS modulation. Our access network design is proved to be robust against signal impairment due to fiber dispersion. The experimental results of the wireless DL show that it is sufficient to employ a conventional DSP for coherent detection by utilizing low-cost lasers with less stringent requirement in linewidth. The power penalty over 50-km SMF-28 is less than 1 dB, while the penalty due to interchannel interference after transmission is 0.5 dB. High receiver sensitivity has been demonstrated in our BER measurement. We believe this new scheme can efficiently deliver integrated multi-gigabit wireless and wired services for next generation ultra-high capacity access networks.

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