Simultaneous Generation and Transmission of 60-GHz Wireless and Baseband Wireline Signals With Uplink Transmission Using an RSOA

Wen-Jr Jiang, Chun-Ting Lin, Po-Tsung Shih, Li-Ying Wang He, Jyehong Chen, and Sien Chi

Abstract—**This study presents a novel hybrid access network for 60-GHz wireless and wireline applications using a frequency quadrupling technique. Both 1.2-Gb/s eight phase-shift keying and 1.25-Gb/s quadruple phase-shift keying radio-frequency (RF) signals for radio-over-fiber (RoF) links are demonstrated. A 1.25-Gb/s baseband (BB) on–off keying (OOK) signal for fiber-to-the-x services is simultaneously generated and transmitted using the same modulator. The proposed system does not suffer from RF fading and needs no narrowband optical filter at the remote node to separate the RF and BB signals. A frequency quadrupling method for RoF link is realized to reduce the bandwidth requirement of the transmitter. Following 25-km single-mode fiber transmission, the observed receiving power penalty is negligible for both RF and BB signals. Wavelength reuse for a 1.25-Gb/s OOK signal via a reflective semiconductor optical amplifier for uplink transmission is also demonstrated.**

Index Terms—**Fiber-to-the-home (FTTH), frequency multiplication, hybrid access networks, radio-over-fiber (RoF).**

I. Introduction

SINCE the capacity requirement for wireless communications continues to increase, high spectral efficiency modulation and a high carrier frequency are required for the next generation of ultrahigh capacity wireless systems [1]. Many standards have been proposed concerning the delivery multigigabit-per-second services for 60-GHz wireless system in the 7-GHz license-free band. They include IEEE 802.15.3c, ECMA TC48, wireless HD/HDMI, WiGig, and IEEE 802.11 VHT. High path loss and high attenuation through walls [2] allow 60-GHz wireless signals to be used only over relatively short distances (<10 m). The radio-over-fiber (RoF) approach technique is an effective means of extending the coverage of 60-GHz wireless signals [3]–[6].

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Because of the required high bandwidth, high flexibility, high mobility, and low cost in the next-generation access networks, an optical distributed infrastructure that hosts both fiber-to-the-x (FTTx) and RoF systems is greatly desired. Recently, the simultaneous generation and transmission of FTTx and RoF systems that use a single wavelength have attracted significant interest because of sharing the same distributed infrastructure [5], [6]. However, the bandwidth of a typical commercially available $LiNbO_3$ modulator is limited to 40 GHz, and electrical components and equipment with an operation frequency range of up to 60 GHz are very expensive. Additionally, since the available wireless spectrum is limited, high spectral efficiency modulation formats are very desirable for wireless systems. Therefore, the development of a cost-effective optical 60-GHz vector signal generation approach that integrates FTTx service is of great interest.

This work presents a simple hybrid access network architecture for generating and transmitting a 60-GHz radio-frequency (RF) phase-shift-keying (PSK) signal, a baseband (BB) on–off keying (OOK) signal, and an upstream signal. A dual-parallel Mach–Zehnder modulator (MZM) with a 16-GHz bandwidth is employed to support both wireless and wireline downstream services. The frequency quadrupling scheme is used to yield a bandwidth of the transmitter of only 15 GHz. Both 1.2-Gb/s 8 PSK and 1.25-Gb/s quadruple phase-shift keying (QPSK) signals for wireless services and the 1.25-Gb/s OOK signal for wireline services are demonstrated. The proposed approach neither requires a narrowband optical filter at the remote nodes to separate the RF and BB signals, nor does it suffer from RF fading. After 25 km of single-mode-fiber (SMF) transmission, the observed receiving power penalties for both RF and BB signals are negligible. Additionally, a 1.25-Gb/s OOK upstream link employing a reflective semiconductor optical amplifier (RSOA) is demonstrated.

II. Concept

Fig. 1 schematically depicts a proposed hybrid access network system that uses a dual-parallel MZM. The MZ-a driving signal is an RF PSK signal with a frequency of f for wireless application. When the MZ-a is biased at full point, only even-order optical subcarriers are generated, as presented in inset (i) in Fig. 1. The original optical carrier can be completely suppressed by adjusting the bias point of MZ-b and introducing a 180° phase shift between MZ-a and MZ-b, indicating that the output optical carrier field of MZ-a, $J_0[m_a]$, equals the output carrier field of MZ-b, $\cos[m_b]$, where m_a and m_b are $\pi V_a/2V_\pi$ and $\pi V_b/2V_\pi$, respectively. However, when an OOK signal is sent to

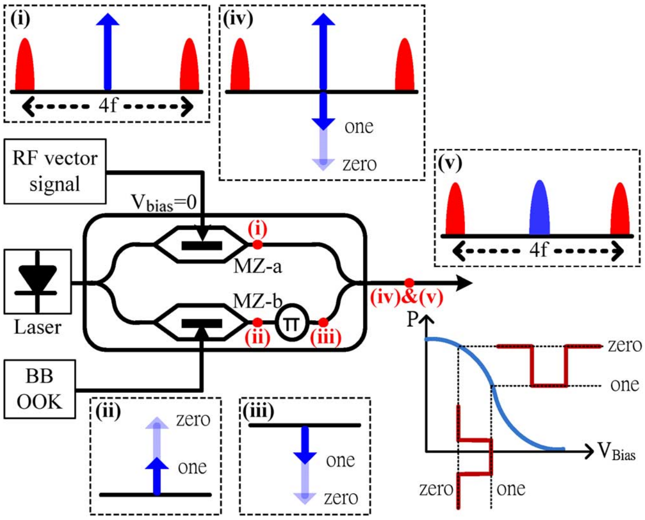

Fig. 1. Concept of proposed hybrid access network system.

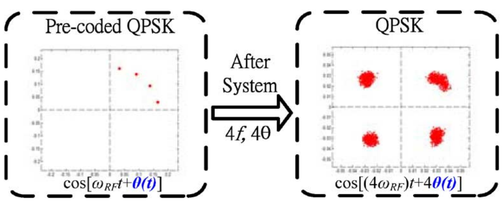

Fig. 2. Concept of precoded method.

MZ-b in a wireline applications, $J_0[m_a]$ does not always equal $\cos[m_b]$. The optical carrier reappears, as presented in the insets (ii)–(iv) in Fig. 1. This phenomenon implies that an RF signal with a frequency of $2f$ will appear at the receiver, but this signal can be easily filtered out by an electrical bandpass filter that is centered at $4f$. Inset (v) in Fig. 1 presents the generated optical spectrum, which includes two optical sidebands and optical carrier at the output of the modulator. After square-law photodetection, the beating terms of the two optical sidebands generate the desired electrical RF PSK signal, as presented in Fig. 2. Since the amount of frequency and phase information for the generated RF signal is four times that in the original electrical RF signal, precoded data are needed to ensure that the generated RF signal is regular PSK [7]. For FTTx applications, the square terms of the optical sidebands and optical carrier contribute to the BB signal. When the precoded data represent a precoded PSK signal, the square terms of the optical sidebands contribute only the dc term to the BB signals, causing only negligible interfering with the BB OOK signal after being suppressed by an electrical dc block. Therefore, the BB OOK signal can be easily recovered using a typical low-speed receiver, whereas the RF PSK signal can be recovered using a high-speed receiver with no interference from the BB signals. Therefore, no optical filter is required to separate the BB and RF signals. Since no additional narrowband optical filter is required, the proposed structure is compatible with the existing wavelength-division-multiplexing passive optical network (WDM-PON).

III. Experimental Setup and Results

Fig. 3 depicts the experimental setup to verify the feasibility of the proposed hybrid access network system. A tunable laser

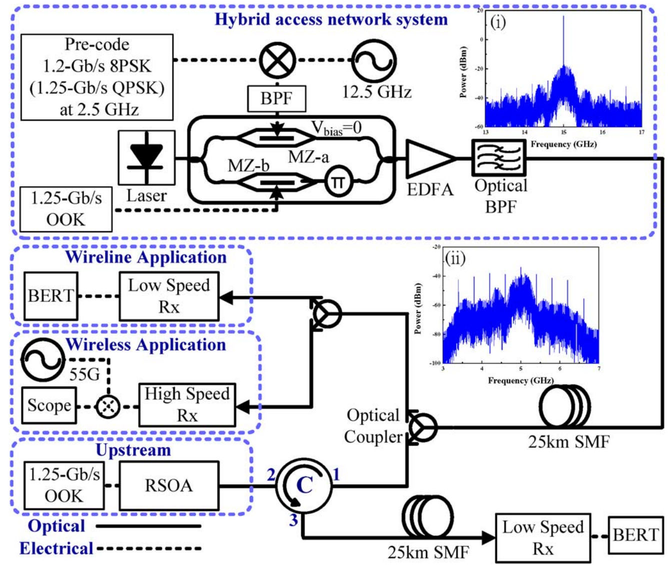

Fig. 3. Experimental setup of the proposed system. (MZ: Mach–Zehnder; EDFA: erbium-doped fiber amplifier; BPF: band pass filter; SMF: single-mode fiber; RSOA: reflective semiconductor optical amplifier; BERT: bit-error-rate tester.)

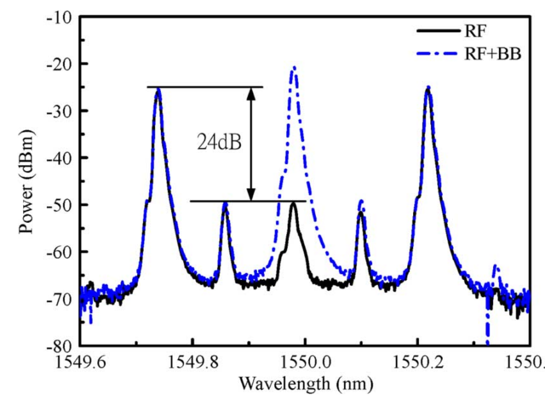

Fig. 4. Optical spectra of the RF signal before and after combing.

with linewidth of 10 kHz is utilized as the optical source. The laser output power is 3.8 dBm centered at 1550 nm. The precoded 1.2-Gb/s 8 PSK and 1.25-Gb/s QPSK signals at 2.5 GHz are generated using a Tektronix AWG7102 arbitrary waveform generator (AWG) with a Matlab program. The sampling rate and digital-to-analog converter resolution of the AWG are 10 GS/s and 8 bits, respectively. After the signal from the AWG, the signal is up-converted to 15 GHz using an electrical mixer with a 12.5-GHz local oscillator signal and an electrical bandpass filter that is centered at 15 GHz with a 4-GHz passband, as presented in inset (i) in Fig. 3. The generated RF signal is then applied to the MZ-a with bias at the full point. The modulation index (MI $\triangleq V_{p-p}/2V_\pi$) is set at one to maximize the undesired sideband suppression ratios. The generation of optical carrier is suppressed by adjusting the bias voltage of the MZ-b. Fig. 4 shows the optimal optical spectrum, and the optical powers of the two desired second-order sidebands are 24 dB higher than those of the other sidebands. The BB OOK signal is a 1.25-Gb/s pseudorandom binary sequence (PRBS) signal with a word length of $2^{11}-1$. Fig. 4 also plots the optical spectra of the OOK signal. Second-order sidebands and optical carrier are clearly shown. Since the losses of the dual-parallel MZM and 25-km

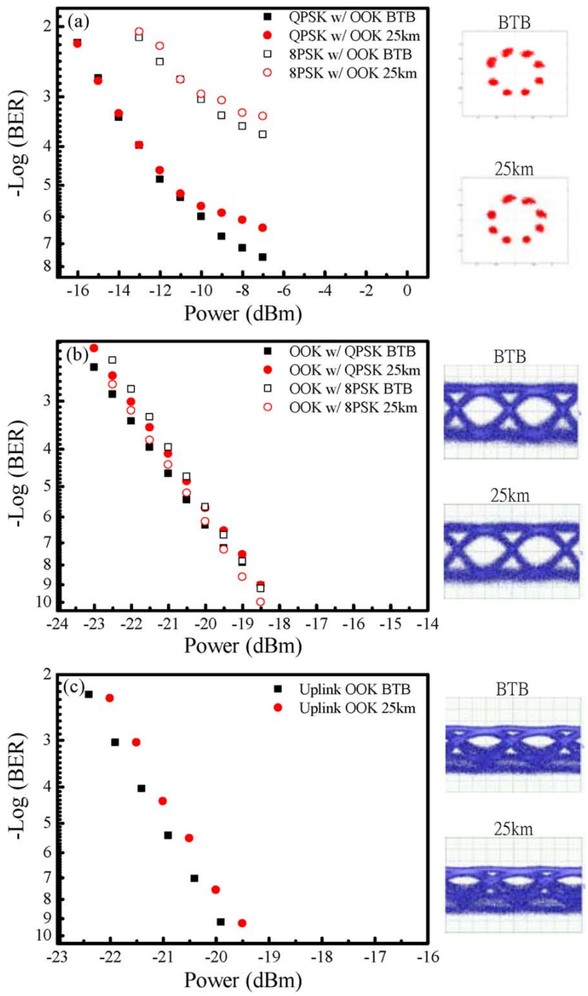

Fig. 5. BER curves of (a) RF PSK, (b) BB OOK, and (c) uplink OOK signals.

SMF are about 14 and 5 dB, respectively, the generated optical signal is amplified using an erbium-doped fiber amplifier (EDFA) to compensate for this loss. At the receiver end, an optical coupler is adopted to separate the optical power to deliver it to various applications. For wireless applications, the 60-GHz 8 PSK or QPSK signal is generated by square-law photodetection (beating term of two second-order sidebands) and down-converted to 5 GHz using a 55-GHz sinusoidal signal, as shown in inset (ii) in Fig. 3. Five thousands symbols of 8 PSK (QPSK) waveforms are captured using a digital scope at a 50-GHz sampling rate for offline signal processing. The bit-error rate (BER) is estimated from the error vector magnitude [8]. For wireline applications, the optical signal is directly detected using a commercial 1.25-Gb/s photoreceiver and the performance is evaluated using a BER tester. For uplink applications, wavelength reuse is achieved via an RSOA, and a 1.25-Gb/s OOK signal is directly applied to the RSOA. For the RSOA, the electrical bandwidth is 1.2 GHz, the bias voltage is set at 4 V, and the driving voltage of the OOK signal is 2 V. To reduce the effect of the original optical signal, the input power of the RSOA is set to -8 dBm to ensure that the RSOA operates in the saturation region.

Fig. 5(a) and (b) shows the BER curves for the RF and BB signals for back-to-back (BTB) and a transmission length of 25 km. No significant receiver power penalties are observed following the transmission. Fig. 5(a) also presents the tradeoff between the spectral efficiency and the receiving power sensitivity. The 8 PSK signal has 1.5 times the spectral efficiency of the QPSK signal, but it has the worse receiver sensitivity. Whether the RF signal data format is 8 PSK or QPSK does not significantly affect the sensitivity of the receiver to the OOK signal. Fig. 5(c) plots the BER curves for the upstream signal. After transmission over 25-km SMF, the sensitivity penalty at a BER of 10^{-9} is less than 0.5 dB. Fig. 5 also presents the constellations of the RF 8 PSK signals, the eye diagrams of the downstream OOK signals, and the eye diagrams of the upstream OOK signals. Following the transmission, all of the diagrams are observed without significant distortion.

IV. Conclusion

A novel hybrid access network architecture was demonstrated using one dual-parallel MZM; a 60-GHz RF signal, a 1.25-Gb/s downstream BB signal, and a 1.25-Gb/s upstream signal are transmitted on a single wavelength. The 1.2-Gb/s 8 PSK and 1.25-Gb/s QPSK signals are produced by 15-GHz RF components of the transmitter by frequency quadrupling and precoding. After transmission over 25-km SMF, the power penalties for both RF and BB signals are negligible. The proposed system exhibits no RF fading; no narrowband optical filter is required at the remote node to separate the RF and BB signals; uplink services are provided, and vector signals are carried. In summary, the proposed system provides a simple and cost-effective solution for hybrid access networks.

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