Hybrid Access Network Integrated With Wireless Multilevel Vector and Wired Baseband Signals Using Frequency Doubling and No Optical Filtering

Po-Tsung Shih, Chun-Ting Lin, Wen-Jr Jiang, Yu-Hung Chen, Jason (Jyehong) Chen, and Sien Chi

***Abstract*—This letter experimentally demonstrated a hybrid access network which supports both radio-over-fiber and fiber-to-the-x systems. A 20-GHz radio-frequency (RF) 312.5-MSymbol/s M-ary phase-shift keying (PSK) signal and a baseband (BB) 1.25-Gb/s on–off keying signal are simultaneously generated and transmitted over an identical distributed infrastructure. The wired BB signal is compatible with the existing passive optical network (PON) system, and the wireless RF PSK signal can also share the same distributed infrastructure. The proposed system has no RF fading issue, no narrowband optical filter at remote node to separate the RF and BB signals, and can carry vector signals. Moreover, a frequency doubling for optical RF signal generation is achieved to reduce the bandwidth requirement of the transmitter. After transmission over 25-km standard signal-mode fiber, the receiver sensitivity penalties are less than 0.5 dB for both the RF and BB channels.**

***Index Terms*—External modulation, fiber-to-the-home, optical access networks, optical communication, radio-over-fiber (RoF).**

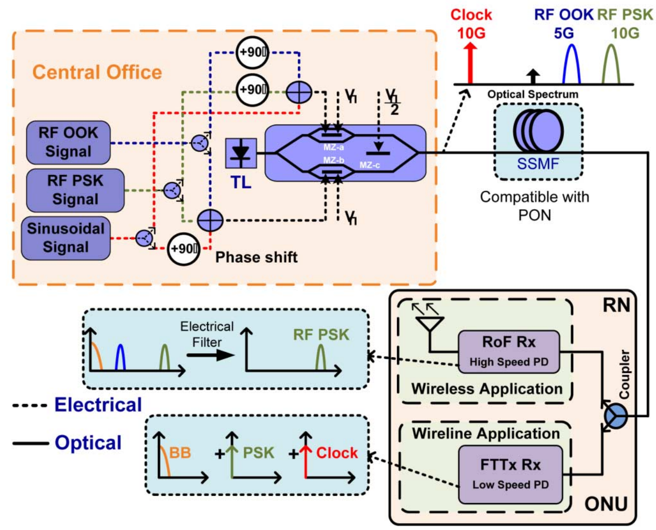

Fig. 1. Conceptual diagram of the proposed system.

I. Introduction

FIBER-TO-THE-x (FTTx) have been widely constructed for high data rate wired services to provide triple-play services including voice, data, and video [1]. On the other hand, radio-over-fiber (RoF) techniques have become a potential candidate for the future broadband wireless system. Due to the requirement of high bandwidth, high flexibility, and high mobility in next-generation access networks, the convergence of FTTx and RoF systems on an identical optical distributed infrastructure to provide wired and wireless access services at the same time are highly desired. Recently, simultaneous generation and transmission of FTTx baseband (BB) and RoF radio-frequency (RF) vector signals using external modulators have been intensively investigated [2]–[6]. However, narrowband optical filters at remote nodes are required in these proposed systems to separate BB and RF signal for wired and wireless applications [2], [6], which severely hinders the implementation in wavelength-division-multiplexing (WDM) systems and is not compatible with the existing passive optical network (PON) system. Moreover, double-sideband with carrier suppression modulation schemes have been utilized in most of the proposed systems for RF signals [2], [6], [7]. As a result, only on–off-keying (OOK) modulation format with lower spectral efficiency can be used for RF wireless signals.

In this work, hybrid access networks with a 1.25-Gb/s BB OOK signal and a 312.5-MSymbol/s RF M-ary phase-shift keying (PSK) signal on a single wavelength using a dual-parallel Mach–Zehnder modulator (MZM) are experimentally demonstrated. Both quadrature PSK (QPSK) and 8PSK RF signals with higher spectral efficiency are demonstrated for wireless services in this work. No narrowband optical filter is required at remote node to separate the BB and RF signal for wired and wireless applications, respectively. To recover the wired BB signal, only a low speed photodetector which is compatible with the existing PON FTTx system is required. Since the wired and wireless services share an identical optical network, the construction and maintenance costs can be reduced. Furthermore, there is no RF fading issue because a modified single-sideband with carrier suppression (SSB-CS) modulation scheme is used in the proposed system. Moreover, a frequency doubling for optical RF signal generation is achieved to reduce the bandwidth requirement of the transmitter, which is very important for RoF systems at millimeter-wave band.

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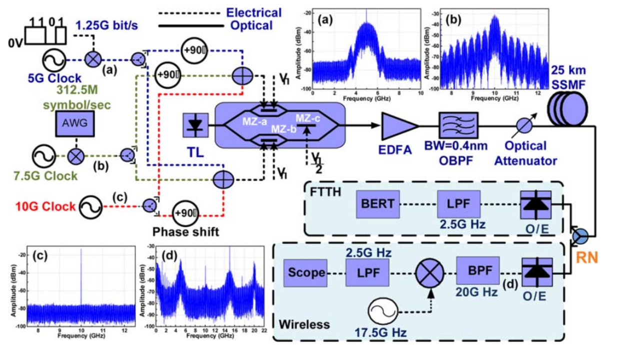

Fig. 2. Experimental setup of the proposed system. (AWG: arbitrary waveform generator; EDFA: erbium-doped fiber amplifier; OBPF: optical bandpass filter; RF: remote node; BPF: bandpass filter; LPF: low pass filter; BERT: BER tester.)

II. Experimental Setup and Results

Fig. 1 shows the conceptual diagram of the proposed system. A dual-parallel MZM (Sumitomo, T.SBX1.5–10-P-FK), which is composed of three sub-MZMs, is employed. MZ-a and MZ-b of the dual-parallel MZM are biased at null point and MZ-c is biased at quadrature point. The driving signals consist of an RF OOK, an RF M-ary PSK, and a sinusoidal signal. Additional 90° phase delays are added on the upper path of the OOK, PSK signal, and the lower path of the sinusoidal signal. The generated optical spectrum consists of two upper sidebands (USBs) modulated with data and a lower sideband (LSB) with a sinusoidal carrier. The original optical carrier is inherently suppressed using the proposed system [8]. At remote node, no optical filter is required to separate the BB and RF signals. For FTTx BB applications, the square terms of the RF M-ary PSK subcarrier and new optical carrier contribute only dc terms to the BB signals after photodiode square law detection and cause negligible interference on the BB OOK signal after being removed by an electrical dc block. Thus, the BB OOK signal can be easily recovered with a typical low-speed receiver, whereas the RF M-ary PSK signal can be recovered using a high-speed receiver with no interference from the BB signals. Since no additional narrowband optical filter is required, the proposed structure is compatible with the existing WDM PON.

Fig. 2 shows the experimental setup. A distributed-feedback (DFB) laser is used as the optical source. Both 8PSK and QPSK modulation formats with 312.5-MSymbol/s symbol rates are demonstrated for the RF signals. The M-ary PSK signals are generated form an arbitrary waveform generator with 2.5-GHz carrier frequency and up-converted to 10-GHz using an electrical mixer with a 7.5-GHz local oscillator (LO) signal. The 1.25-Gb/s OOK pseudorandom binary sequence (PRBS) signal with a word length of $2^{31}-1$ is generated using a pattern generator and up-converted to 5 GHz. A 10-GHz sinusoidal signal is also employed for the generation of a new optical subcarrier. The signals are separated using 90° hybrid couplers. The 90° phase delays are added on the upper path of OOK and PSK to generate USB signals, and the 90° phase delay is added on the lower path of the 10-GHz sinusoidal signal to generate LSB signal. The half-wave voltages (V_π) of MZ-a and MZ-b in the dual-parallel MZM are 2.9 V. In addition, the modulation indices (V_m/V_π, V_m is the amplitude of the driving signal) for all the driving signals are about 0.1.

At the output of the modulator, an erbium-doped fiber amplifier is utilized to boost the optical power and adjust to 0 dBm before being sent into the fiber. After transmission over 25-km standard single-mode fiber (SSMF), only an optical coupler is employed to separate the optical power of the hybrid signal for different applications. For FTTx BB application, the OOK BB signal is directly detected using a commercial 1.25-Gb/s photoreceiver and sent into a bit-error-rate (BER) tester for performance analysis. For RoF applications, the 20-GHz M-ary PSK signal are detected using a high-speed photoreceiver, down-converted with a 17.5-GHz sinusoidal signal, and then sent into a real time scope to capture the time domain waveform for off-line analysis. In this work, 1024 symbols of PSK signals are captured. The BERs of the Gray-coded M-ary PSK are calculated using $\mathrm{BER} = (1/\log_2 M) * \mathrm{erfc}\left[(E/N_0)^{1/2} * \sin(\pi/M)\right]$ [9], [10], where M is the order of the M-ary PSK signal, E is the error sum, and N_0 is the signal sum.

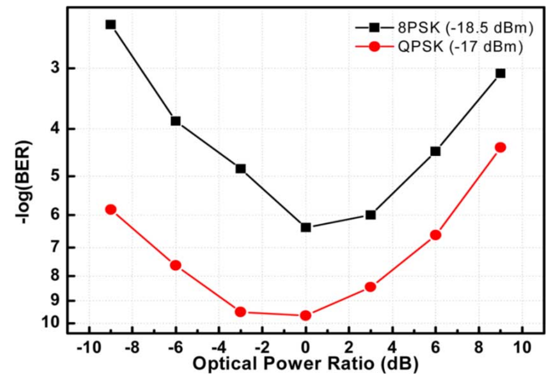

Fig. 3. Log(BER) versus optical power ratio between PSK optical sideband and new carrier.

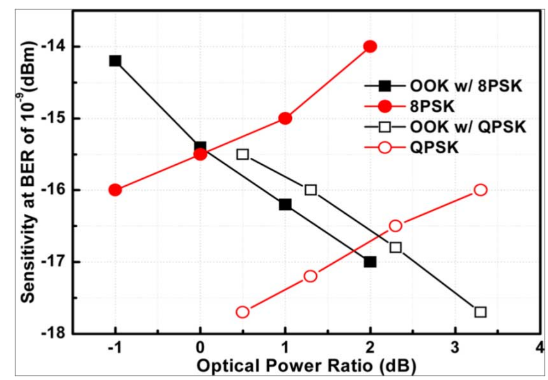

Fig. 4. Optical power ratio between 8PSK and new carrier.

The optical power ratio between the PSK optical sideband and the new optical carrier is an important factor which influences the receiver sensitivity required to recover the RF PSK signal. To optimize the RF PSK signal, the RF OOK signal is turned OFF first. Only PSK and the 10-GHz sinusoidal signals are sent into the dual-parallel MZM. Fig. 3 illustrates the -log(BER) of both the 8PSK and QPSK signals with different PSK optical sideband to optical carrier optical power ratio. The BER values of RF 8PSK and QPSK signals are obtained with −18.5- and −17-dBm optical power, respectively. The best receiver sensitivity of both the 8PSK and QPSK signals are obtained when the optical power ratios are 0 dB.

After optimization of the optical power ratio between PSK and new optical carrier sidebands, the optical power ratio between the RF OOK and optical carrier sidebands are also needed

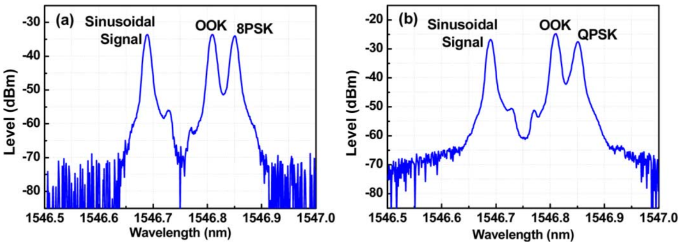

Fig. 5. Optical spectra of the optimized systems (OSA resolution 0.01 nm). (a) 8PSK system; (b) QPSK system.

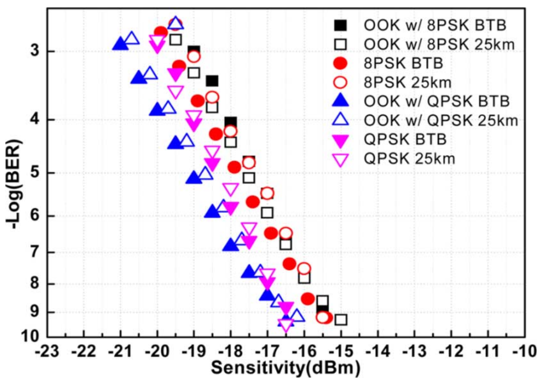

Fig. 6. BER curves of OOK (with 8PSK), 8PSK, OOK (with QPSK), and QPSK.

to be optimized. Compared with wired transmission media, the wireless signal is more sensitive to the transmission environment. Therefore, system operators need to be able to freely adjust the power ratio between wired and wireless services according to geographic variation. Since all of the optical sidebands are generated using independent driving signals, the proposed system can freely adjust the power ratio between wired and wireless services for various requirements. Fig. 4 illustrates the receiver sensitivity of both RF PSK and BB OOK signals at a BER of 10^{-9} with different new carrier to OOK signals optical power ratio. The receiver sensitivity tradeoff between the RF PSK and BB OOK signals are observed. In this work, RF and BB signals with equal receiver sensitivities are set as the optimal condition, where the 8PSK and QPSK to OOK optical power ratio are about 0 and 2 dB as the optical spectrum shown in Fig. 5.

Fig. 6 shows the -log(BER) curves of both the 8PSK-OOK and QPSK-OOK systems at back-to-back (BTB) and following 25-km transmission of SSMF. No significant receiver power penalties of both the RF and BB signals in 8PSK-OOK and QPSK-OOK systems are observed after the transmission. The constellations of the RF 8PSK and QPSK signals, the eye diagrams of the BB OOK signals in 8PSK-OOK and QPSK-OOK systems are also shown in Fig. 7. After the transmission, no significant distortions are observed in both the RF and BB signals.

III. Conclusion

In this work, simultaneous generation and transmission of wireless RF M-ary PSK vector signal and FTTx BB OOK signals for hybrid access networks are experimentally demonstrated. No additional narrowband optical filter is needed in

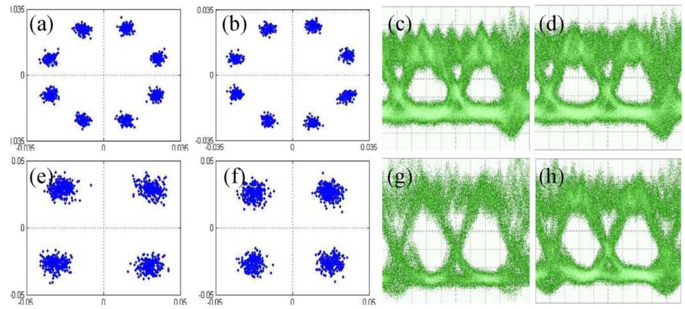

Fig. 7. Constellations and eye diagrams. (a) 8PSK BTB; (b) 8PSK 25 km; (c) OOK with 8PSK BTB; (d) OOK with 8PSK 25 km; (e) QPSK BTB; (f) QPSK 25 km; (g) OOK with QPSK BTB; (h) OOK with QPSK 25 km. (Eye diagrams 100 mV/div; 200 ps/div.)

the proposed system to separate the RF and BB signals. Only a typical low-speed photo receiver is required to recover the BB OOK single. Therefore, the proposed system is compatible with the existing WDM PON system.

In addition, frequency doubling is also achieved in the proposed system. Generations of 20-GHz RF signals are experimentally demonstrated using 10-GHz RF components in this work. Moreover, high spectral efficiency QPSK and 8PSK modulation formats can be used in the proposed system which is compatible with the existing wireless communication system. After the transmission over 25-km SSMF, no significant receiver penalties are observed in both RF and BB signals. In summary, the proposed system provides an attractive and cost-effective solution for the next generation hybrid access networks.

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