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Full-duplex link with a unified optical OFDM signal for wired and millimeter-wave wireless accesses based on direct detection

Ruijiao Zhang, Jianxin Ma*

State key laboratory of Information photonics and optical communications, School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

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ABSTRACT

This paper proposes a full-duplex link with a downlink unified optical orthogonal frequency division multiplexing (OFDM) signal, to support wired and 60 GHz band wireless accesses alternatively based on direct detection. At the optical line terminal (OLT), the downlink unified optical signal is produced via $LiNbO_3$ Mach-Zehnder modulators (MZMs) and an interleaver. At hybrid optical network unit (HONU), it is detected by a high-speed photoelectric diode (PD) to generate a 10 GHz IF-OFDM and a 60 GHz RF-OFDM signals as well as an additional RF clock at 50 GHz. Since the uplink optical carrier is abstracted from downlink, the HONU is free from the light source; and because part of the 50 GHz RF clock is abstracted and used as the wireless uplink local RF carrier, the wireless terminal is free from the RF source. This reduces the system complexity and cost. Moreover, only one tone of the downlink unified optical signal carries the OFDM signal, which makes it suffers little from the fiber chromatic dispersion and laser phase noise. A proof-of-concept full-duplex access link over 25 km fiber is conducted by simulation to demonstrate the feasibility of our proposed scheme and the link performance are assessed.

1. Introduction

Recently, the bandwidth demand for the access network has witnessed a sharp increase driven by various high-definition interactive multimedia services like business IP traffic, Ultra-HD video, mobile traffic backhaul and social networking [1]. Consequently, the next-generation access networks, including wired and wireless accesses, need to significantly increase their current capacities. With respect to wired access, the cost-effective passive optical network (PON) is persistently considered to meet the demand of broadband and high-speed transmission with extreme data throughput, but it is still limited in applications due to the lack of mobility. On the other hand, although the wireless access technologies can provide flexible access to the users, they do not have the abundant bandwidth for high-definition video transmission. The millimeter-wave at V band with 7 GHz license-free spectrum, has been considered as a strong candidate for high-capacity data transmission [2], multi-Gb/s wireless access [3], next-generation very high throughput (VHT) wireless personal area networks (WPANs) and wireless local access networks (WLANs) [4]. Nevertheless, its coverage is limited by high air propagation loss. Therefore, radio-over-fiber (RoF) system, comprising a fiber distribution network with low propagation loss, has been identified as a potential solution to extend wireless coverage. Moreover, it leads to a combination of the flexibility and mobility of wireless access networks with the high capacity of optical networks [5]. The convergence of RoF and PON technologies on an integrated platform is promising to provide broadband and ubiquitous access with cost-effective configuration. Several convergent network architectures have been proposed [6–11]. However, the wired and wireless channels are independent and merely bonded together in [6,7], which makes insufficient use of the equipment and sources. In [8–10], the proposed schemes can provide the wired and wireless accesses simultaneously, but the wired and wireless data are modulated on different optical carriers, which induces lower spectrum efficiency. Moreover, the services supported by the wired and wireless accesses are different, so that they are poor shared. The scheme based on heterodyne beating technology, reported in [11], has realized the multi-band wireless and wired accesses. But it needs an assistant light source at remote node and the uplink transmission is not considered. In our previous study [12], we have proposed a full-duplex hybrid fiber-wireless link to support the alternative wired or wireless access. Even though the uplink transmission is considered, a tunable laser is also needed to provide the coherent optical local oscillator at hybrid optical network unit (HONU), which makes HONU complex and expensive.

Thanks to the advancement of digital signal processing (DSP) technologies, optical orthogonal frequency division multiplexing (O-OFDM) is becoming a promising candidate for the high-speed optical

* Corresponding author.

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access networks. Moreover, for seeking higher spectral efficiency and multipath tolerance, the combination of OFDM and quadrature amplitude modulation (QAM) has been employed in both wired and wireless access networks [13,14].

A full-duplex link is proposed in [15], in which the uplink signal is intensity modulated onto the downlink optical signal via an electric absorption amplifier (EAM). So, there will exist these issues: lossy splitter is required, and the uplink signal performance is limited by EAM nonlinearity and residual chirp. Moreover, the bit rates of the downlink and uplink are low, and this link only can provide wired access. Even though the carrier recycling technique for uplink is reported in [16], the uplink optical carrier is abstracted from the downlink using a fiber Bragg grating (FBG) and the system only can realize mm-wave access. A 60-GHz millimeter-wave OFDM transmission, using two dual-parallel modulators along with an interleaver to generate the optical mm-wave signal which consists of two tones with the frequency spacing of 60 GHz, is proposed in [17]. Its system structure is very complex and after wireless transmission, a 55 GHz local oscillator is needed to down-convert the generated 60 GHz OFDM signal, which makes the wireless terminal complex and costly. Moreover, it shares the same limitation of [16], that it can only provide mm-wave access.

In this work, a full-duplex link with a downlink unified optical OFDM signal based on direct detection for alternatively supporting wired or millimeter-wave wireless access is proposed. At HONU, the downlink optical OFDM signal is opto-electrically converted to a 10 GHz IF-OFDM for wired access and a 60 GHz RF-OFDM with a pure RF clock at 50 GHz for wireless access via a photodiode (PD). At wireless receiver, the 50 GHz RF clock is used to down-convert the OFDM-modulated signal at 60 GHz into a 10 GHz IF-OFDM-modulated signal based on power detection [18,19]. For uplink, the reserved optical carrier abstracted from downlink optical signal is intensity-modulated by the wired or wireless access uplink data via an optical modulator. Through the uplink fiber, the uplink optical signal is transmitted back to optical line terminal (OLT) and then opto-electrically converted by a PD. To verify the feasibility, a full-duplex link for alternative wired or wireless access is built up based on the simulation platform. The calculated error vector magnitude (EVM) curves of the downlink and the bit error rate (BER) curves of the uplink show that the proposed full-duplex fiber-wireless link has good performance for both the wired and wireless accesses.

The paper is organized as follows. Section 2 presents the operational principle of the proposed scheme. Section 3 presents and discusses the simulation results. Finally, Section 4 concludes the paper.

2. Principle of the proposed full-duplex link

Fig. 1 illustrates the basic structure of our proposed full-duplex link with a downlink unified optical OFDM signal based on direct detection. The downlink unified optical signal, consisting of three optical tones, is generated by two MZMs based on the optical carrier suppression (OCS) and single sideband (SSB) modulations at the OLT, respectively. As shown in Fig. 1, the lightwave from the continuous wave (CW) laser diode (LD), represented by $E_c(t)=E_c exp(j\omega_c t)$, is directly injected into the first MZM (MZM1). The MZM1 is biased at its OCS modulation point with the relative DC bias voltage of V_π. Its two arms are driven in a push-pull pattern by the local oscillator (LO1) at ω_{RF}. Here, V_π is the half-wave voltage. Hence, all the even-order sidebands are suppressed and the generated two first-order sidebands at $\omega_c \pm \omega_{RF}$ are main output because the other higher-order odd-sidebands are smaller to be neglected. The output of the MZM1 can be expressed as

$$\begin{aligned} E_{OCS}(0,t) &= \frac{\gamma_1}{2}E_c(t)\left[e^{-j\frac{\pi}{V_\pi}V_{RF}\cos(\omega_{RF}t)+j\pi} + e^{j\frac{\pi}{V_\pi}V_{RF}\cos(\omega_{RF}t)}\right] \\ &\approx \gamma_1 E_c m_{h1}\left(e^{j\left[(\omega_c+\omega_{RF})t+\frac{\pi}{2}\right]} + e^{j\left[(\omega_c-\omega_{RF})t+\frac{\pi}{2}\right]}\right) \\ &= B_1\left(e^{j\left[(\omega_c+\omega_{RF})t+\frac{\pi}{2}\right]} + e^{j\left[(\omega_c-\omega_{RF})t+\frac{\pi}{2}\right]}\right) \end{aligned} \quad (1)$$

Here, E_c and ω_c are the amplitude and central angular frequency of the lightwave electrical field, respectively. V_{RF} is the amplitude of the RF LO1, and γ_1 and m_{h1} are the insertion loss and modulation index of the MZM1, respectively. $B_1=\gamma_1 E_c m_{h1}$. Fig. 1(a) shows the optical spectrum of the generated OCS optical signal. An interleaver (IL1) is used to separate the generated positive and negative first-order sidebands. Then the positive first-order sideband is injected into the second dual-electrode MZM (MZM2). Fig. 2 shows the generation procedure of the IF-OFDM driving signal. It needs three steps: digital signal processing (DSP), digital to analog conversion (DAC) and frequency up-conversion. The DSP processes the transmitted signal in digital domain and is performed off-line using MATLAB software. The detailed DSP mainly consists of the QAM mapper, serial-parallel conversion, inverse fast Fourier transform (IFFT) and parallel-serial conversion.

Firstly, the binary digital signal is mapped into QAM symbols, expressed as

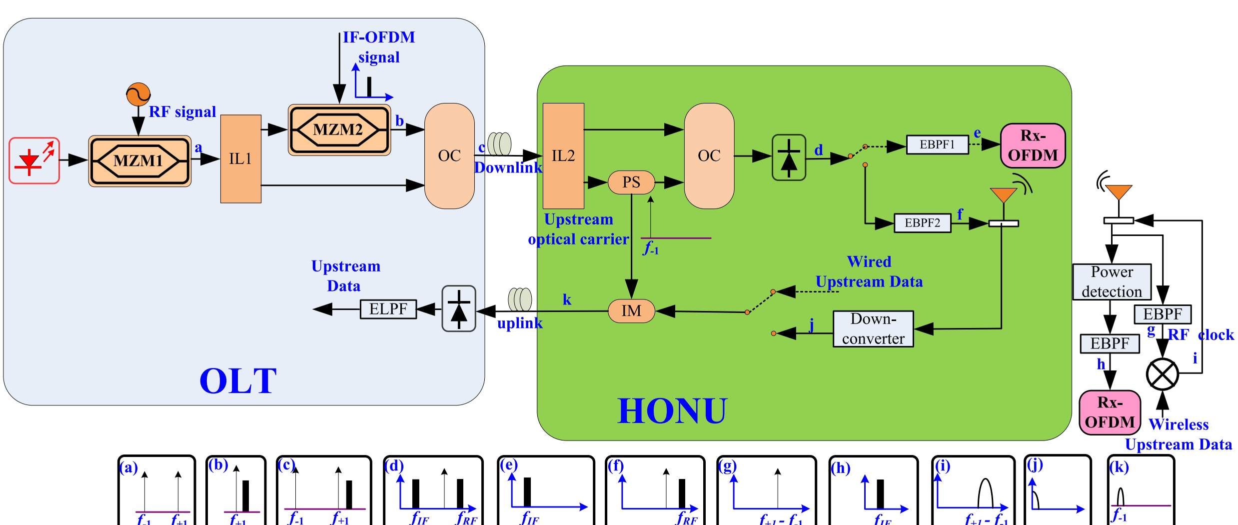

Fig. 1. Schematic diagram of the proposed full-duplex link based on direct detection. (a)-(k) examples of the spectrum evolution of location a-k. MZM, Mach-Zehnder modulator; IL, interleaver; OC, optical coupler; PS, power splitter; EBPF, electrical band-pass filter; IM, intensity modulator; ELPF, electrical low-pass filter.

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