Electrical code divided multiplexing orthogonal frequency division multiplexing-based 60-GHz radio-over-fiber system with extended wireless transmission and optical beating interference noise mitigation in upstream link

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Abstract. This paper proposes an electrical code divided multiplexing orthogonal frequency division multiplexing (ECDM-OFDM) modulation-based radio-over-fiber (ROF) system at the 60-GHz band. Compared with conventional OFDM ROF system, it can increase the distance of wireless links as well as suppressing the optical beating interference noise in the upstream link. The 4.68 Gb/s ECDM-OFDM signal at 60 GHz with a 25-km fiber and 8-m air transmission is experimentally demonstrated. The wireless distance of the ECDM-OFDM signal has been extended 3 m with the same transmitted power. For the upstream signal, no significant receiver power penalties are observed after transmission. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.53.11.116103]

1 Introduction

The breath-taking growth of wireless and mobile communications has fueled renewed interest in the development of various architectures and technologies that offer an enhanced bandwidth and mobility. The radio-over-fiber (ROF) system, which distributes RF signals from a central office (CO) to the base station (BS) over an optical fiber, has become a promising technology to provide high throughput wireless and wired signals.[1–4] In particular, an ROF system centered at 60-GHz band or higher is necessary to provide high capacity wireless links because it offer Gigahertz of available bandwidth. The wide bandwidth will lead to channel-wide nonuniformity such as group delay and fading effect.[5] Orthogonal frequency division multiplexing (OFDM) technology, which has been widely utilized in current wireless communication, has become more and more popular in an ROF system due to its high spectral efficiency and resistance to fiber dispersion and fading effect.[6–8] Moreover, the uneven channel response of a 60-GHz ROF system can be compensated by a simple digital equalization.

Usually, both the optical frequency multiplication method and the scheme of a centralized light source have been employed for bidirectional OFDM-ROF links, which could reduce the cost and complexity of the system.[9,10] However, the higher carrier frequency of 60 GHz will lead to a significantly higher loss, resulting in a limited cell radius especially for hotspot places such as airports and conference halls. Although the wireless link can be extended through increasing the transmitted signal power, the RF power is restricted due to the high peak to average power ratio (PAPR) of the

OFDM signal. Additionally, a high RF power might be harmful to the human body. Electrical code division multiplexing (ECDM) technology has many attractive advantages such as high code gain and low interference noise between different subscribers.[11] It can be utilized to improve the sensitivity of the receiver and to increase the distance of the wireless link. For an upstream OFDM signal, it would suffer a lot due to the optical beating interference (OBI) noise at the CO. The ECDM technology can also be employed to reduce the interference between user channels.

In this paper, we propose a new 60-GHz ROF system based on ECDM-OFDM modulation. Compared with a normal OFDM-ROF system, it can extend the distance of a wireless link due to the code gain. It can also suppress the interference between different base stations (BSs) in a wavelength-based colorless upstream link. A 4.68-Gb/s ECDM-OFDM ROF system is successfully demonstrated over a 25-km fiber and 8-m air-link in the experiment.

2 System Configuration

The proposed configuration of an ECDM-OFDM-based ROF system is illustrated in Fig. 1. In this scheme, a couple of optical carriers spaced at 60 GHz serve as the millimeter-wave (mm-wave), which is shown as green arrows in Fig. 1. The mm-wave can be generated by the optical carrier suppression method. The central blank carrier is reserved for the upstream signal. The aggregated data at the central station (CS) are first mapped into quadrature amplitude modulation symbols, and then assigned with dedicated code chips and OFDM subcarriers. The BSs share the total bandwidth of the OFDM signal, and the spectrum spreading by code chips is executed accompanying with the subcarrier modulation of the OFDM symbol in the electrical domain. At the BS, the
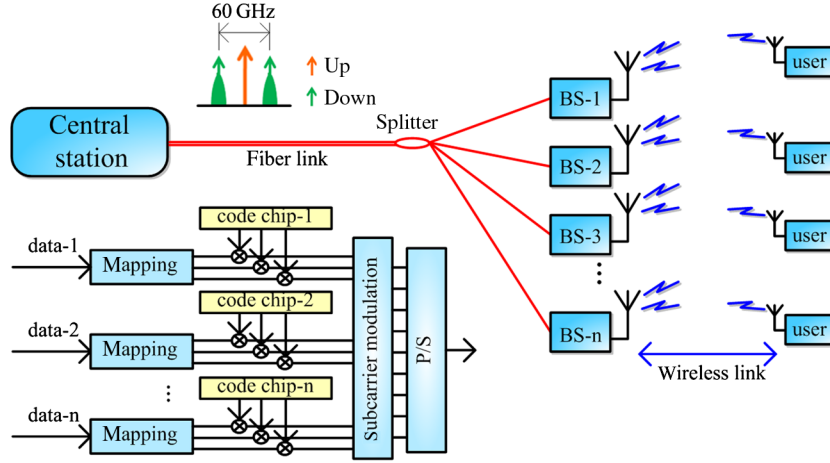

Fig. 1 Schematic configuration of the electrical code divided multiplexing orthogonal frequency division multiplexing (ECDM-OFDM) based radio-over-fiber (ROF) system (BS: base station).

ECDM-OFDM RF signals at 60 GHz can be generated by optical beating in a photodiode (PD). The generated RF signals are transmitted out to the subscribers through an air-link, and the central blank carrier is modulated by the upstream ECDM-OFDM signals.

The m'th sample of the baseband ECDM-OFDM signal can be expressed as

$$s(t) = \sum_{q=1}^{Q} s_q(t)$$
$$= \sum_{q=1}^{Q} \sum_{k=1}^{N} [u_{qk} \times C_q + j v_{qk} \times C_q] \cdot \exp(j2\pi kt/T_s),$$
$$t = mT_s/N, \tag{1}$$

where k is the index of the OFDM subcarriers, q is the index of the BS, N is the total number of subcarriers, u_{qk} and v_{qk} are the in-phase and quadrature components of the symbols of q-th BS, T_s is the time duration of each sample, and C_q is the code chip for the q'th BS which is satisfied with

$$C_p \bigoplus C_q = \begin{cases} 0, & p \neq q \\ G, & p = q \end{cases}. \tag{2}$$

Here G is a constant number proportional to the code gain. A longer code chip would result in higher code gain. The optical ECDM-OFDM ROF signal can be expressed as

$$E(t) = [A_{+1} e^{j(\omega_0 + \omega_{RF}/2)t} + A_{-1} e^{j(\omega_0 - \omega_{RF}/2)t}] \times [1 + \gamma s(t)], \tag{3}$$

where ω_0 is the optical central frequency, ω_{RF} is the heterodyning frequency, $A_{\pm 1}$ is the amplitude of the optical carrier and γ is the modulation index. The linearity of the optical modulator is important for the OFDM signal due to its high PAPR. In the following experiment, we have executed clipping for an OFDM signal and adopted modulator with a large linear work area, which could suppress the nonlinearity at the optical modulation. At the BS, the square-law photo-detector acts as an envelope detector and the photocurrent with ignorance of the double frequency can be represented by

$$I(t) = \xi |E(t)|^2$$
$$= \left[\frac{1}{2} \xi (A_{+1}^2 + A_{-1}^2) + \xi A_{+1} A_{-1} \cos(\omega_{RF} t) \right] \cdot [1 + \gamma s(t)]^2. \tag{4}$$

Here ξ is the responsivity of the detector. The first part is the baseband signal which will not be transmitted out and the second part is the ECDM-OFDM RF signal. The current of the RF signal can be written as

$$I_{RF}(t) = \underbrace{\frac{\xi A_{+1} A_{-1} \cos(\omega_{RF} t)}{\text{pure RF}}} + \underbrace{\frac{2\gamma \xi A_{+1} A_{-1} \cos(\omega_{RF} t) \cdot s(t)}{\text{signal}}}$$
$$+ \underbrace{\frac{\xi \gamma^2 A_{+1} A_{-1} \cos(\omega_{RF} t) \cdot s^2(t)}{\text{ISI}}}. \tag{5}$$

From Eq. (5), we can see that the intersubcarrier interference (ISI) is the main noise. It is caused by optical sideband and OFDM subcarriers around the other sideband in a square-law PD, which would degrade the mm-wave OFDM signal. There, we assume $\xi = 1$, $\gamma = 1/2$ and $A_{+1} = A_{-1} = 1$, therefore, the down-converted signal at the BS can be expressed as

$$I_{rec}(t) = I_{RF}(t) \cdot \cos(\omega_{RF} t + \varphi)$$
$$= \frac{\cos \varphi}{2} \left[1 + s(t) + \frac{1}{4} s^2(t) \right]. \tag{6}$$

Here φ is the phase noise of the local oscillator (LO) and $\cos \varphi \approx 1$. In Eq. (6), the DC component can be removed by DC blocking. For the q'th BS, it will extract data with a dedicated code chip C_q, which can be expressed as

$$I_{rec-q}(t) = \left[\frac{1}{2} \sum_{p=1}^{Q} s_p(t) + \frac{1}{8} \sum_{p=1}^{Q} s_p^2(t) \right] \cdot C_q$$
$$= \left[\frac{1}{2} + \frac{1}{8} s_q(t) \right] \times s_q(t) \cdot C_q$$
$$+ \left[\frac{1}{2} + \frac{1}{8} \sum_{p \neq q}^{Q} s_p(t) \right] \times \sum_{p \neq q}^{Q} s_p(t) \cdot C_q. \tag{7}$$
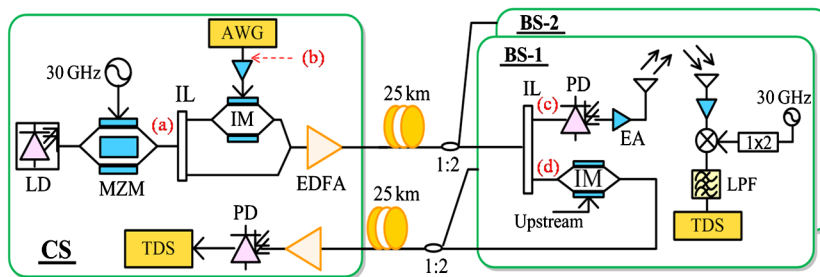
Fig. 2 Experimental setup (PD: photodiode).

The first part of Eq. (7) is the desired signal and the second part is the ISI term. In normal OFDM, the ISI term cannot be removed and remains as noise for the downstream signal. However, this term is suppressed after using ECDM-OFDM. Due to the correlation gain of the code chip, the interference from the other BSs and the signal-to-noise (SNR) can be improved to increase the distance of the wireless link.

3 Experiment and Results

Figure 2 depicts the experimental setup for the bidirectional ECDM-OFDM ROF system at 60-GHz band. The experiment is carried out in the laboratory. The wavelength of a distributed feed back laser at the CS is 1560.32 nm. A Mach–Zehnder modulator (MZM) and a cascaded 25-GHz interleaver (IL) are employed to generate the mm-wave carrier while providing the light source for the upstream signal. The MZM is driven by a radio frequency (RF) source at 30 GHz. The optical spectrum is shown in Fig. 3(a). The mm-wave carrier is modulated by an intensity modulator (IM), which is driven by the downstream ECDM-OFDM signal. In our experiment, the ECDM-OFDM signal is generated offline by MATLAB®. We adopt quadrature phase shift keying mapping for the bit stream data and the Walsh code chip is a 16 bit-length, which could theoretically provide a 12-dB gain. The total number of
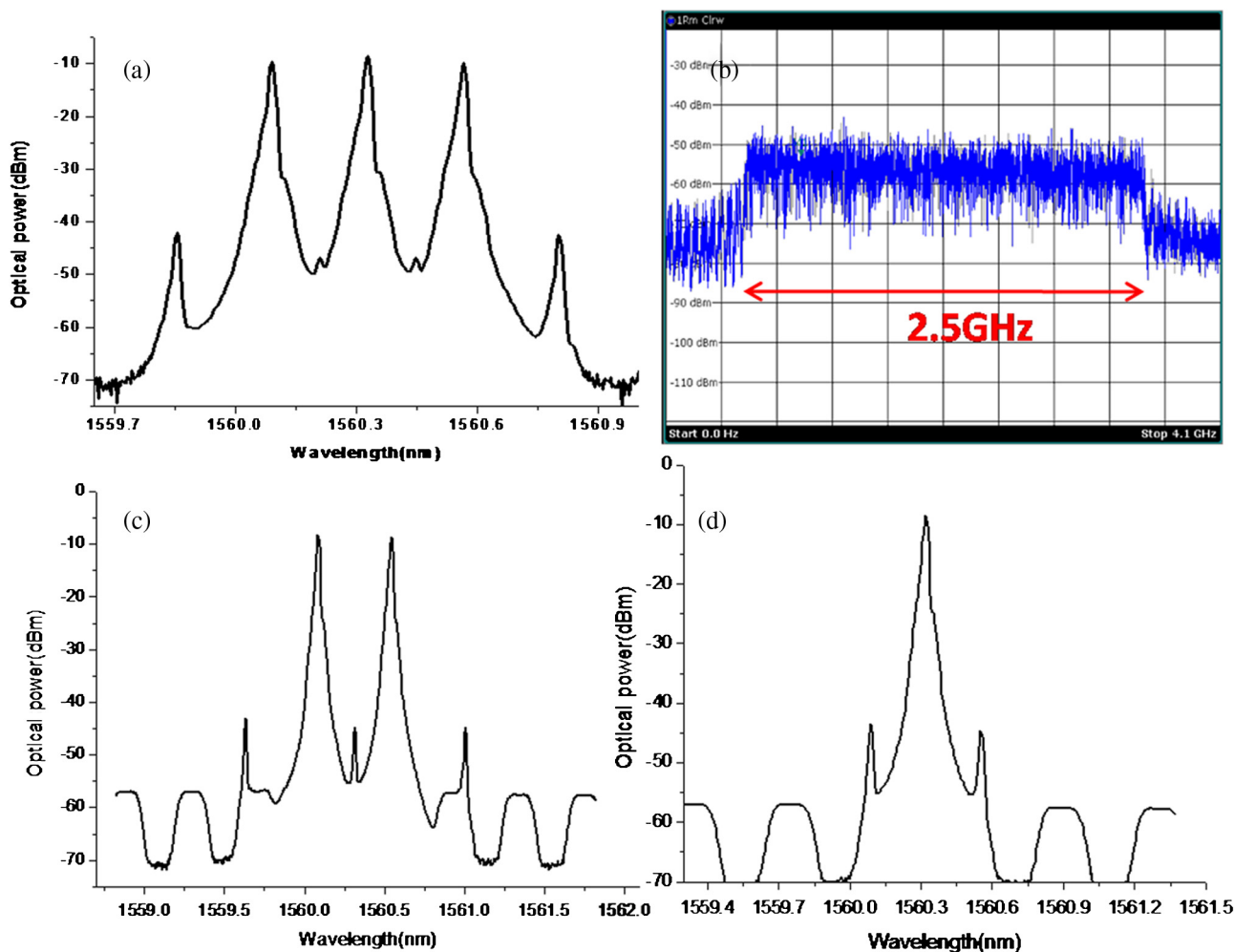

Fig. 3 Spectra at corresponding points in Fig. 2: (a) after the MZM at CS; (b) electrical ECDM-OFDM signal; (c) and (d) after the IL at the BS (optical resolution: 0.01 nm).

OFDM subcarriers is 256 where 8 subcarriers are unfilled and the signal is upconverted by digital I-Q modulation to 2.1 GHz. The length of the cyclic prefix is 1/16 and a training sequence is added every 60-OFDM symbols. An arbitrary waveform generator (AWG7122B) with a 10 Gs/s sample rate and 8 bits resolution is employed to execute the D/A conversion, which produces a data rate of 4.68 Gb/s occupying a 2.5-GHz bandwidth. The signal from the AWG gets a V_{pp} of 500 mV and the electrical spectrum is shown in Fig. 3(b). The output signal is amplified by an electrical amplifier with a 16-dB gain and then used to drive the MZM. The measured error vector magnitude of the amplified signal is about 10%. The modulated ECDM-OFDM ROF signal is combined with the central blank carrier by a 3-dB optical coupler. The combined signal is amplified by a commercial Er-doped fiber amplifier (EDFA) before being launched into the 25-km single-mode fiber. The EDFA has a noise figure of 4.2 dB and the measured optical signal-to-noise ratio (OSNR) is about 30.5 dB with a bandwidth of 0.1 nm for the sideband signal.

At the BS, a 25-GHz IL is used to separate the ECDM-OFDM ROF signal and the central blank carrier, and the optical spectra are shown in Figs. 3(c) and 3(d). The optical ROF signal is detected by a 67-GHz PD. The generated ECDM-OFDM RF signal at 60 GHz is amplified by a low noise electrical amplifier (EA) with a 35-dB gain and then sent into the air-link through a standard 20-dBi antenna. After air transmission, the RF signal is received by another antenna and downconverted by an RF clock with a frequency of 60 GHz. The 60-GHz LO is produced by a 1×2 frequency multiplexer with a 30-GHz clock. After being filtered by a 3.9 GHz low pass filter, the obtained ECDM-OFDM signal is captured by a real-time digital scope with a 20 Gs/s sample rate and 8 bits resolution. Offline processing is carried out to demodulate the ECDM-OFDM signal.

Figure 4 compares the measured bit error ratio (BER) curves of the ECDM-OFDM signal and normal OFDM signal after transmission over different air-link distances. The two signals have the same subcarriers and mapping format.
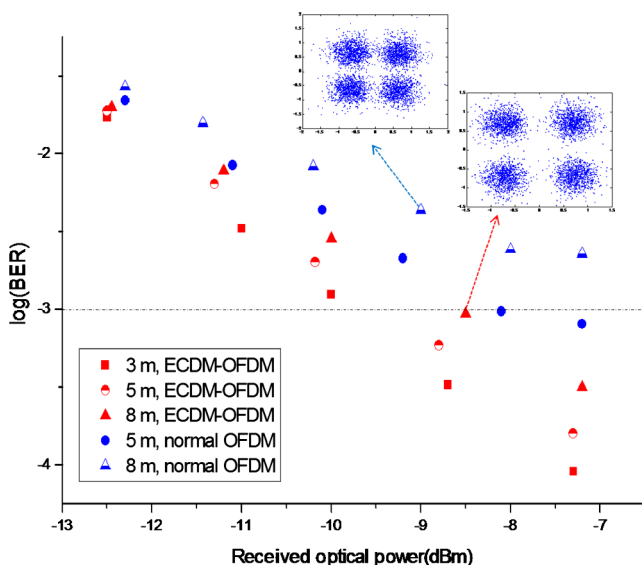
For the ECDM-OFDM signal, a received optical power of at least −8.8 dBm is needed to achieve a BER of 1×10^{-3}. The corresponding SNR is about 13 dB for the ECDM-OFDM radio signal. However, the BER of the normal OFDM signal with a 5-m air-link seems saturated at an error floor of 1×10^{-3}. When the wireless distance extends to 8 m, the BER of the normal OFDM signal is beyond the forward error correction limit of 1×10^{-3}. The constellations are also shown as insets in Fig. 4.

For the upstream link, the central blank carrier serves as the light source, which can simplify the BS and reduce the cost. The same ECDM-OFDM signal modulation is adopted for the upstream signal, and the two BSs share the same OFDM subcarriers. Because the improvement of wireless distance has been demonstrated in the downstream link, we mainly focus on the mitigation of OBI noise for the upstream signal. The signal is directly modulated onto the central blank carrier without a wireless channel. Because the observed performances are almost the same for the two upstream signals, we have taken one signal for analysis. The measured BER curves are illustrated in Fig. 5. It can be seen that the performance of the upstream signal is better than that of the downstream signal. Although the quality of the optical carrier is worse than that of the downstream signal, there is no wireless channel and the dispersion influence can be ignored for an ECDM-OFDM signal with the additional 25-km fiber length. Furthermore, there is a pre-EDFA at the CS for the upstream signal. The power penalties for both the ECDM-OFDM and normal OFDM signals are less than 0.2 dB after transmission. The required SNR at BER of 1×10^{-3} is about 11.5 dB for the upstream signal. Compared with the ECDM-OFDM signal, the BER of the normal OFDM signal is deteriorated due to the OBI noise. The received sensitivity is improved by about 3.7 dB at a BER of 1×10^{-3} after ECDM-OFDM modulation was adopted. As the number of BS increases, the BER deterioration would be more severe.

The ECDM-OFDM is easy to implement into the ROF access system using convenient DSP technology. It provides
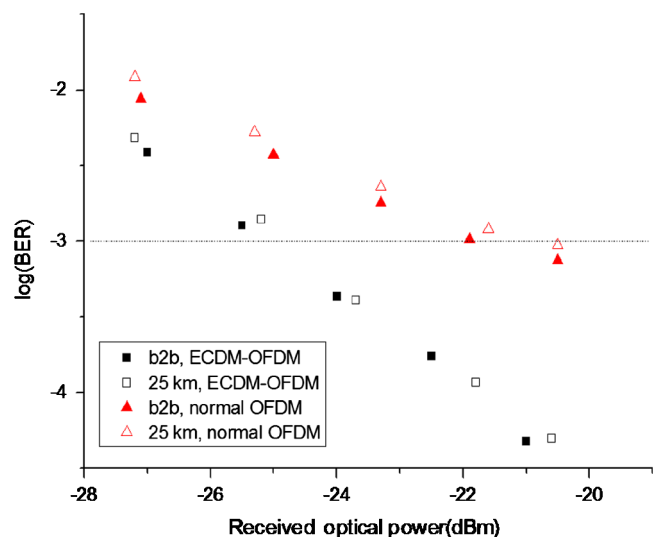

Fig. 4 The measured bit error ratio (BER) curves for different wireless distances.

Fig. 5 The measured BER for the upstream signal at a rate of 4.68 Gb/s.

a further wireless transmission distance and mitigates the OBI noise without any channel estimation algorithm, which can reduce the cost for future ROF access. The received sensitivity can be improved by ECDM, which endows the system with more subscribers under the same transmitted power. Besides, it can be well merged with wireless communication based on ECDM.

4 Conclusion

This paper proposed and experimentally demonstrated an ECDM-OFDM-based ROF system over a 25-km fiber and 8-m wireless distance at 60 GHz. Compared with a normal OFDM signal, the wireless distance of the ECDM-OFDM signal has been extended 3 m with the same transmitted power. For the upstream signal, the ECDM-OFDM signal shows a better performance against OBI noise, which is attributed to the code gain. The experimental results underscore the potential of ECDM-OFDM in application for ROF systems.

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