Adaptively Modulated OFDM RoF Signals at 60 GHz Over Long-Reach 100-km Transmission Systems Employing Phase Noise Suppression

Chia-Chien Wei, Chun-Ting Lin, Ming-I Chao, and Wen-Jr Jiang

***Abstract*—We experimentally demonstrated the transmission performance of orthogonal frequency-division-multiplexing (OFDM) signals in a 60-GHz radio-over-fiber system over up to 100-km standard single-mode fiber employing an adaptive bit-loading algorithm. Considering dispersion-induced phase noise, the maximum capacities after different fiber distances are investigated with and without a phase noise suppression (PNS) algorithm for the first time. When a distributed-feedback (DFB) laser with the linewidth of 1.3~4.1 MHz is modulated to carry the radio signals, the PN will result in more than 21.5% capacity decrease after 100-km fiber and 3-m wireless link, and the PNS algorithm which needs no bandwidth-consuming pilot tones can accomplish more than 15.3% capacity increase.**

***Index Terms*—Orthogonal frequency-division multiplexing (OFDM), phase noise (PN), radio-over-fiber (RoF).**

I. Introduction

WITH the continuously growing demand for wireless communication capacity, millimeter-wave has caused much attention due to its multi-GHz bandwidth. In particular, since 60-GHz wireless band provides 7-GHz unlicensed band [1], it is expected to satisfy the future bandwidth-hungry wireless applications. Nevertheless, owing to the high air-link loss at 60-GHz band, the radius of the cell size is limited to $\sim$ 10 m [2]. To extend the coverage, radio-over-fiber (RoF) technologies provide a most promising choice [3]–[5]. Moreover, since both an optically-amplified long-reach passive optical network (PON) and a hybrid RoF/PON system have been proposed to form efficient multiservices networks, the required reach of a 60-GHz RoF signal is up to 60~100 km [6].

Furthermore, orthogonal frequency division multiplexing (OFDM) has been widely used in wireless communications and considered as a visible scheme in 60-GHz applications. While double sideband (DSB) RoF signals will encounter power fading induced by fiber chromatic dispersion (CD) [3], and DSB modulation with carrier suppression will cause serious intermixing interference among OFDM subcarriers after photo-detection (PD) [4], single sideband (SSB) modulation is free from the above issues [5]. However, a 60-GHz OFDM RoF system with SSB modulation still suffers from some technique challenges owing to its high carrier frequency and wide channel bandwidth. One of them is the uneven frequency responses of 60-GHz components with $>$ 10-dB deviation within the 7-GHz spectrum resulting in irregular subcarrier performance [7]. Thus, subcarriers with poorer performance will dominate the performance. Another issue is the CD-induced phase noise (PN) [8]. To eliminate laser PN, an OFDM-modulated signal and an RF-tone with 60-GHz frequency difference are generated by modulating the same laser [8]. However, the phase coherence between them is decreased after transmission over dispersive fiber. Namely, CD will induce differential PN after PD. While earlier works have shown transmission performance of OFDM RoF systems [5], [9], the CD-relevant maximum capacity over up to 100-km fiber has not been explored.

In this letter, the Levin–Campello (LC) [10] bit-loading algorithm is adopted to cope with uneven frequency responses and to maximize the capacity of OFDM RoF systems at 60-GHz band. Considering the CD-induced PN, we experimentally demonstrated the maximum capacity within 7-GHz band with various laser linewidths and fiber distances for the first time. Moreover, the CD-induced PN is suppressed by a PN suppression (PNS) algorithm [11] to achieve a higher capacity, and no bandwidth-consuming pilot tone is required in the PNS scheme. Using the laser of 1.3~4.1-MHz linewidth, more than 21.5% capacity decrease is caused by the PN after 100-km fiber and 3-m wireless transmission, and applying the PNS algorithm can increase the capacity by more than 15.3%.

II. Concept of Adaptive Bit-Loading and PNS

While the frequency response of the 60-GHz RoF system is not flat and shows the deviation of up to 10 dB, the subcarriers with worse error performance will deteriorate the performance of the whole system [7]. Fortunately, the performances of subcarriers can be equalized to optimize the system performance by adjusting the powers and/or modulation levels of individual subcarriers independently. For instance, to reach a universal target bit-error rate (BER), higher power and/or lower modulation level can be allocated to a subcarrier with low signal-to-noise ratio (SNR), and vice versa. Therefore, giving a target

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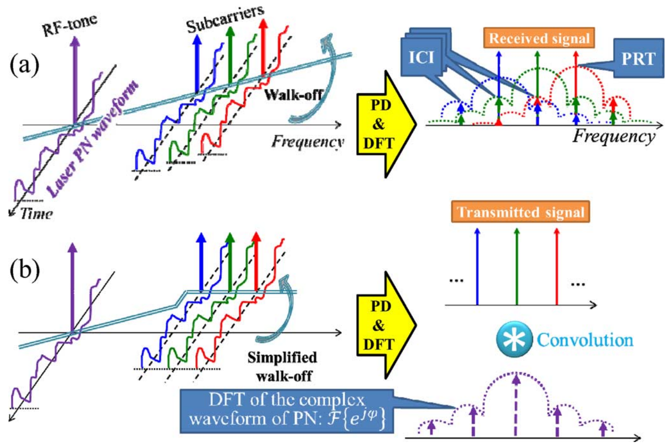

Fig. 1. Schematic plots of (a) dispersion-induced walk-off and the corresponding received signal, (b) the simplified case.

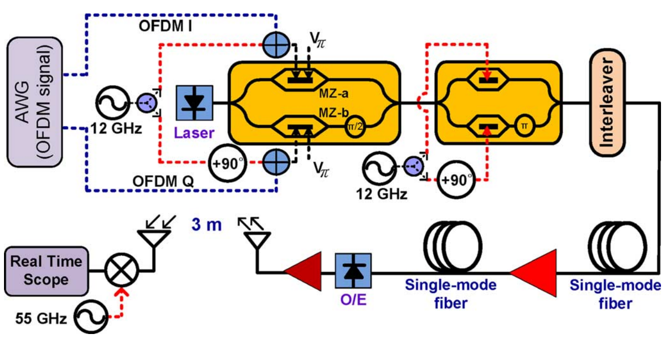

Fig. 2. Experimental setup of the 60-GHz RoF transmission system.

BER and measured SNRs, a maximum capacity can be achieved via applying the LC algorithm to allocate specific power and modulation levels to subcarriers. Notably, since the power of PN depends on CD, the SNRs of subcarriers would vary with fiber distances. Hence, the allocation needs to be modified at different distances, resulting in different capacities.

Furthermore, as a commercial DFB laser is used as light source, unfortunately, its several MHz linewidth has been shown to inevitably degrade an OFDM RoF signal at 60 GHz within 100-km standard single-mode fiber by the CD-induced PN [8], [10]. After PD and discrete Fourier transform (DFT) at the receiver, Fig. 1(a) schematically shows the CD-induced PN generates not only phase rotation (PRT) on each subcarrier but also intercarrier interference (ICI) among subcarriers [8]. To estimate and suppress both of PRT and ICI, the CD-induced walk-off could be simplified by assuming perfect correlation among subcarriers, as shown in Fig. 1(b). This approximation is reasonable owing to the much smaller frequency difference of $<$ 7 GHz among subcarriers, compared with $\sim$ 60-GHz frequency difference between the RF-tone and a subcarrier. Consequently, the effect of CD-induced differential PN, φ, in the time domain can be viewed as multiplying each electrical subcarrier by the same complex waveform of PN, i.e., $\exp(j\varphi)$. After DFT, the received signal is approximated as the discrete convolution of the transmitted signal and the DFT of $\exp(j\varphi)$, as shown in Fig. 1(b). Hence, the iterative steps of the PNS algorithm are [11]:

i. making hard decision on the received signal to "guess" what the transmitted signal is;
ii. estimating the PN from the received signal and the guessed transmitted signal by deconvolution processing;
iii. removing the PN from the received signal by the estimated PN to get a PN-suppressed signal.

The PN-suppressed signal obtained in the last step could be utilized to achieve better guess in the first step iteratively to result in a lower BER. Nevertheless, the decision error occurred in the first step will propagate among subcarriers and iterative steps by the error-involved PN estimation to fail the algorithm. Accordingly, to lower error propagation, the PN bandwidth is assumed to be limited and truncated in the algorithm [11].

III. Experimental Setup and Results

Fig. 2 shows the experimental setup of an OFDM RoF transmission system at 60-GHz band [5]. To investigate the linewidth-dependent transmission performance, the bias current of a DFB laser is adjusted to obtain different linewidths. When the laser output powers are set as 10.5 dBm, 8.5 dBm, 6.5 dBm, and 4.5 dBm, the corresponding linewidths are 1.3 MHz, 1.8 MHz, 2.5 MHz, and 4.1 MHz, respectively. The first Mach–Zehnder modulator (MZM) in the transmitter generates an optical single-sideband OFDM signal and an RF-tone with 12-GHz frequency difference, and the second one up-converts their frequency difference to 60 GHz. Hence, the bandwidth requirement of the transmitter is only 12 GHz [5]. The baseband OFDM signals are generated by a Tektronix AWG7102 arbitrary waveform generator (AWG). The sampling rate and D/A resolution of the AWG are 10 GS/s and 8 bits, respectively. After optimization, the OFDM signal contains 176 subcarriers to occupy 7-GHz bandwidth with the fast Fourier transform size of 256 and the CP of 1/16. The data format is m-ary quadrature amplitude modulation (m-QAM), and both of the power level and the modulation level (m) of each subcarrier are determined by the LC bit-loading algorithm with the target BER of 10^{-3}. After transmission over standard single-mode fiber with an EDFA inserted in the middle, the optical RoF signal of a fixed -6-dBm received power is detected by a 67-GHz photodiode. The generated RF signal at 60 GHz is then amplified by a low noise amplifier with 38-dB gain, before being fed into a rectangular waveguide-based standard gain horn antenna. After 3-m air-link, the signal is received by another horn antenna and down-converted by a local oscillator with frequency of 55 GHz. The obtained 7-GHz wide OFDM signal at 5 GHz is captured by a Tektronix DPO 71254 with the 50-GS/s sampling rate and the 3-dB bandwidth of 12.5 GHz. The offline program is used to demodulate the OFDM signal and carry out the PNS. 1024 OFDM symbols composed of nonrepeated random binary data with the sequence length of $4 \times 10^5 \sim 7 \times 10^5$ are captured to calculate BER by error counting for each case. In the PNS algorithm, after optimization by long training symbols in advance, the truncated bandwidth of PN depends on the system parameters and is set between 20 and 32 times of the subcarrier bandwidth. Since the 4th iteration shows little improvement, the iteration time is 3 throughout this work.

For the back-to-back case (only 3-m air-link), the maximum capacity with the bit-loading algorithm is 29 Gbps irrelevant to the laser linewidth. Nevertheless, after fiber transmission, the received SNR decreases due to the linewidth-relevant PN.

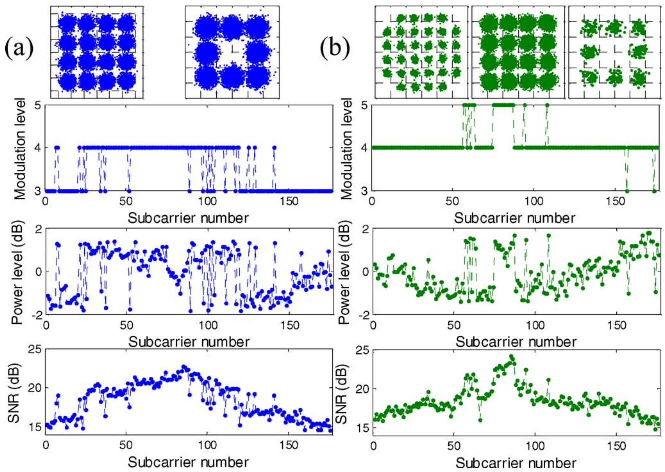

Fig. 3. After 100-km fiber with 1.3-MHz laser linewidth, the modulation levels, the relative power levels, and the SNR (a) without and (b) with PNS, and the corresponding constellation diagrams.

Therefore, the modulation levels must be lowered to reach the target BER of 10^{-3}. Fig. 3(a) shows the modulation levels, the relative power levels, and the SNR of subcarriers with 1.3-MHz linewidth and 100-km fiber transmission. The total data rate is only 22.76 Gbps. The unequal power levels of subcarriers with the same modulation level are mainly caused by uneven frequency responses of electrical components at 60-GHz band. For comparison, while all subcarriers are encoded by the same format without bit-loading, 8-QAM is the highest level to achieve the BER of $< 10^{-3}$ with the result of 19.4-Gbps capacity. Furthermore, because the PNS algorithm can lower BER, the target BER of the LC algorithm can be set higher to achieve the same BER of 10^{-3} after PNS. Hence, compared with Fig. 3(a), the results with PNS in Fig. 3(b) show very different modulation and power levels, and its capacity is up to 26.54 Gbps. Notably, due to the intermodulation distortion of electronics and MZMs, the SNR will deviate from the expected levels. As a result, the SNRs in Fig. 3 are not step-like, but their trends approximately correspond to their modulation levels.

With the bit-loading algorithm, the maximum transmission capacities with and without PNS are plotted in Fig. 4 as functions of laser linewidths and fiber distances. The PNS algorithm does not improve the transmission capacity with the fiber distance of less than 25 km due to the relatively small contribution of the CD-induced PN to total noise at the concerned BER [11].

However, after longer transmission, more PN is induced to result in lower capacity, but more improvement can be accomplished by the PNS. After 100-km transmission, the capacities without the PNS are decreased by 21.5%, 23.8%, 32.8%, and 41.3% for the linewidths of 1.3 MHz, 1.8 MHz, 2.5 MHz, and 4.1 MHz, respectively. Compared with the cases without PNS, applying the PNS can increase the capacities by 16.6%, 15.7%, 17.6%, and 15.3%.

IV. Conclusion

This work experimentally demonstrated the capacity of an adaptively modulated OFDM RoF signal at 60-GHz band over up to 100-km standard single-mode fiber transmission for the first time. When both the bit-loading and the PNS algorithms are employed to obtain the maximum transmission capacity, a 26.54-Gbps OFDM RoF signal can achieve the BER of 10^{-3} over 100-km fiber and 3-m wireless transmission. Furthermore, compared with the cases with only the bit-loading algorithm, the PNS can increase the acceptable modulation levels with the result of higher capacities. As the laser linewidth is 1.3~4.1 MHz, due to the CD-induced PN, the capacity is reduced by more than 21.5% after 100-km fiber, and using the PNS scheme can enhance it by more than 15.3%.

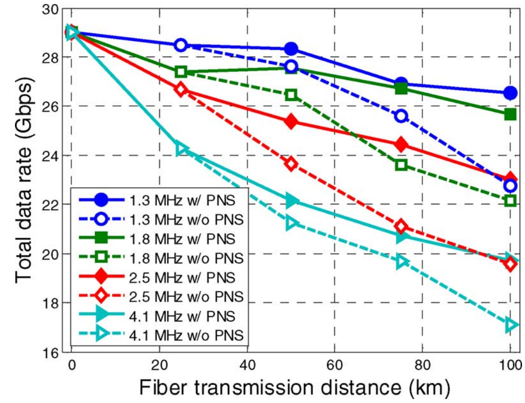

Fig. 4. Maximum data rates with and without PNS as functions of laser linewidths and fiber distances.

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