

# 100-GHz DD-OFDM-RoF system over 150-km fiber transmission employing pilot-aided phase noise suppression and bit-loading algorithm

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**Abstract:** This study extended the transmission distance of a 100-GHz DD-OFDM-RoF system through the reduction of chromatic dispersion-induced phase noise. The implementation of a pilot-aided phase noise suppression (PPNS) scheme enabled the transmission of distance-insensitive 16.97-Gbps QPSK OFDM over 0~150-km fiber and 2-m air transmission via a DFB laser with linewidth of 1~10-MHz. We applied a bit-loading algorithm in conjunction with PPNS to maximize spectral efficiency, resulting in a 93% improvement in the data rate from 11.53 to 22.27 Gbps at a fiber transmission of 150 km.

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## 1. Introduction

W-band (75-110 GHz) has attracted considerable interest among researchers seeking unlicensed bandwidth to meet the growing demand for data transmission in wireless systems. Unlike V-band (57-64 GHz) [1], the applications of W-band can be extended to outdoor

communications due to its reduced air attenuation. Radio-over-fiber (RoF) technology combines the advantages of fiber with wireless techniques to overcome limitations in the transmission distance at mm-wave radio frequencies. It is also viewed as an efficient means to simplify remote units through infrastructural sharing [2]. The need for spectral efficiency and multipath tolerance has led numerous researchers to combine OFDM modulation with quadrature amplitude modulation (QAM) as a means to increase capacity within wireless bands of limited bandwidth.

Currently, coherent detection (CO) and direct detection (DD) are the primary methods used for the implementation of 100-GHz RoF systems [3–5]. The use of an optical local oscillator (LO) in the CO scheme requires an additional laser and an optical hybrid coupler at remote nodes, which increases complexity and costs. In addition, the linewidth of both the transmitter laser and LO must be in the sub-MHz range to resist the influence of phase noise (PN), and the frequency difference of common DFB lasers has to be precisely controlled to generate mm-wave signals at the desired 100 GHz. Therefore, the CO scheme is not a suitable choice to simplify remote units. In contrast, the DD scheme requires only a simple photo-detector (PD) at a remote unit, making it a far simpler and cost effective solution for RoF schemes. Generating the desired beating signal involves the production of both a beating tone and a modulated signal with 100-GHz frequency difference at the optical transmitter. Theoretically, if they are both generated by modulating the same laser, the desired RF signal will not be affected by laser PN following photo-detection. However, after fiber transmission, fiber chromatic dispersion (CD) can produce walk-off in the time domain between the signal and the beating tone, resulting in degraded signal performance after photo-detection due to differential PN [6]. In fact, the walk-off time is proportional to the difference in frequency between the beating tone and the signal; therefore, this issue is of greater consequence in W-band RoF systems than in lower frequency RoF systems. Several approaches have been proposed for the elimination of PN in wireless and optical OFDM systems [7–11]; however, CD-induced PN has not been studied in a W-band DD-RoF system.

This is the first study to investigate the transmission performance of a 103-GHz RoF system degraded by CD-induced PN. Using a 10.3-MHz linewidth DFB laser, the W-band DD-OFDM-RoF signal with a fixed QPSK format and 8.5-GHz bandwidth will suffer from 4.5-dB sensitivity penalty at the FEC threshold (BER of  $3.8 \times 10^{-3}$ ) following 100-km fiber transmission, and the signal will not be able to attain the attainment of the FEC threshold after 150-km fiber transmission. This study employed pilot-aided phase noise suppression (PPNS) to eliminate CD-induced PN through the insertion of a pilot tone to estimate the CD-induced PN. The implementation of PPNS can make an OFDM signal with 1.5~10.3-MHz linewidth insensitive to transmission distances of 0~150 km. We also adopted the Levin-Campello (LC) bit-loading algorithm to cope with uneven frequency responses and maximize spectral efficiency. The integration of the bit-loading algorithm with PPNS led to a 93% improvement in the data rate of the 10.3-MHz-linewidth signal from 11.53 to 22.27 Gbps over 150-km fiber and 2-m wireless transmission.

## 2. Pilot-aided phase noise suppression

The origin of CD-induced PN is illustrated in Fig. 1(a). Although the phases of the beating tone and all subcarriers are exactly the same in the DD system, CD will result in walk-off among them in the time domain. Hence, the differential PN is no longer zero. Let  $\theta(t)$  and  $\Delta t_n$  stand for the laser PN and the CD-induced walk-off between the beating tone and the  $n$ -th subcarrier, respectively, and the CD-induced PN experienced by the  $n$ -th subcarrier would be denoted as  $\phi_n = \theta(t + \Delta t_n) - \theta(t)$ . Equivalently speaking, the CD-induced PN would multiply the  $n$ -th received subcarrier by  $\exp(j\phi_n(t))$  in the time domain, resulting in random phase rotation and inter-carrier interference (ICI) [9]. In the PPNS scheme, the estimation and suppression of differential PN is achieved by inserting a pilot tone surrounded by a guard band, as shown in Fig. 1(b), and the CD-induced PN experienced by the pilot tone is denoted

as  $\phi_p(t)$ . However, unlike a wireless or CO system, in which the PNs affecting all subcarriers are identical, the differential PNs of the pilot tone and the subcarriers are not entirely the same due to differences in the CD-induced time delay [6]. Fortunately, the differences in frequency among the pilot tone and the subcarriers ( $<10$  GHz) are far smaller than the difference between the beating tone and the signal (100 GHz). Thus, we can assume that the pilot tone and subcarriers are entirely coherent even after fiber transmission, i.e.  $\phi_p(t) \approx \phi_n(t)$ . The “common” differential PN can be estimated by applying a filter to the pilot tone to reject unwanted information such as the sidelobe of an OFDM signal band, as shown in Fig. 1(b). If  $F\{\cdot\}$  and  $W(t)$  denote the filtering effect and the unwanted information normalized by the pilot tone power, respectively, the filtered pilot tone can be approximated as  $F\{\exp(j\phi_p) + W\} \approx F\{1 + j\phi_p + W\} \approx \exp(j \cdot F\{\phi_p\}) + F\{W\}$ , whereupon PPNS is carried out by multiplying the conjugated version of the filtered pilot tone to the received signal [9]. Hence, in addition to the desired PN suppression of  $\phi_n - F\{\phi_p\}$ , the PPNS scheme will result in the undesired noise enhancement due to multiplying  $F\{W^*\}$ .

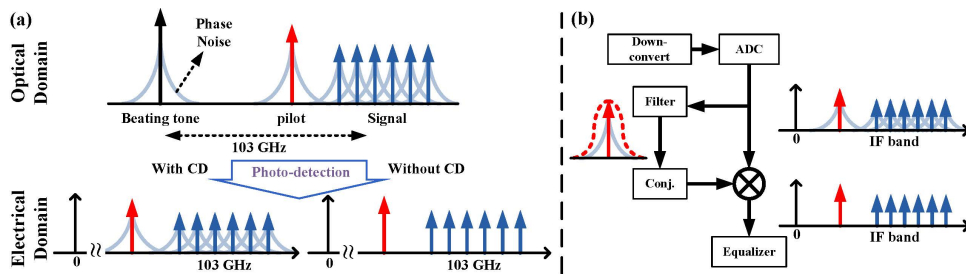


Fig. 1. Depiction of (a) the origin of the CD-induced PN and (b) PN elimination by PPNS.

### 3. Experimental setup and result

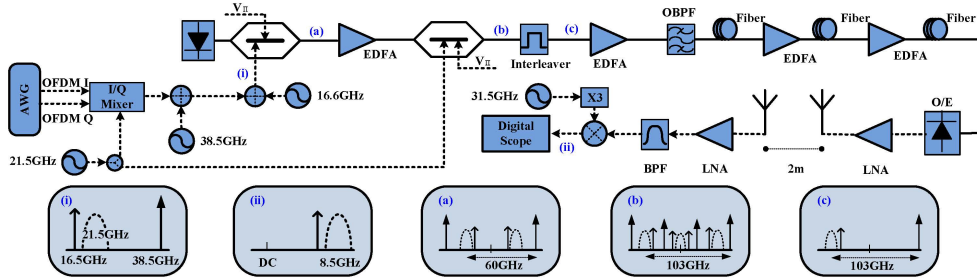


Fig. 2. Experimental setup of 100-GHz DD-OFDM-RoF system.

Figure 2 presents the experimental setup utilizing two cascaded single-drive Mach-Zehnder modulators (SD-MZMs) (Sumitomo; 40 GHz intensity modulator) biased at the null point to realize an optical double side band scheme with carrier suppression. We began by generating 4.25-GHz QPSK baseband OFDM signals, with an FFT length of 512 and 362 subcarriers using an arbitrary waveform generator (AWG) (Agilent, M8190A) at a sampling rate of 12-GSample/s. The cyclic prefix (CP) was set at 1/16. After being up-converted via an electrical I/Q mixer (Hittite Microwave, HMC-C046), an OFDM signal with bandwidth of 8.5-GHz was generated at 21.5 GHz. The OFDM signal was then combined with 16.6-GHz and 38.5-GHz sinusoidal tones corresponding to the pilot tone and the beating tone, respectively. The combined signal was used to modulate the first SD-MZM. The spectra of the driving signal and the corresponding optical signal are presented in insets (i) and (a) of Fig. 2, respectively. The second SD-MZM was modulated using the 21.5-GHz sinusoidal tone to achieve a frequency difference of 103-GHz between the beating tone and optical signal. Unnecessary

carriers and signals were filtered using an optical interleaver; insets (b) and (c) of Fig. 2 present the optical spectra before and after application of the interleaver. Note that the pilot tone is inserted at the frequency lower than that of the OFDM signal due to the limited bandwidth of the receiver, and the location of the pilot tone has been optimized by experimental testing. Following 0~150-km fiber transmission, the optical signal is detected using a PD (u2t, XPDV4120R) with 3-dB bandwidth of 100-GHz to generate the W-band signal. A pair of rectangular waveguide-based standard gain horn antennas with 24-dBi gain was used for 2-m wireless transmission. At both transmitter and receiver, a customized low-noise amplifier (LNA) is inserted, and the gain, the voltage standing wave ratio (VSWR), and the passband are 24 dB, 1.2:1, and 75-100 GHz, respectively. The received W-band signal was down-converted to 8.5 GHz and captured via a real-time scope (Tektronix, DSOX91604A) at a sampling rate of 80-GSample/s. Finally, an off-line DSP including PPNS was applied to demodulate the signal. Note that the output power of the DFB laser was intentionally adjusted to obtain different linewidth.

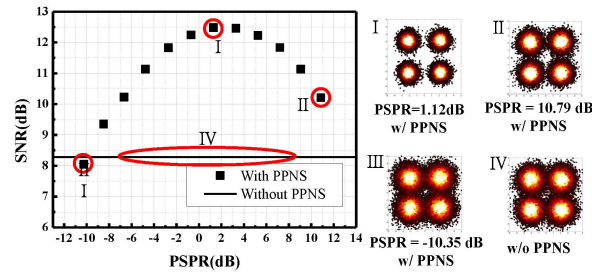


Fig. 3. PSPR optimization with 10.3-MHz linewidth over 150-km fiber transmission.

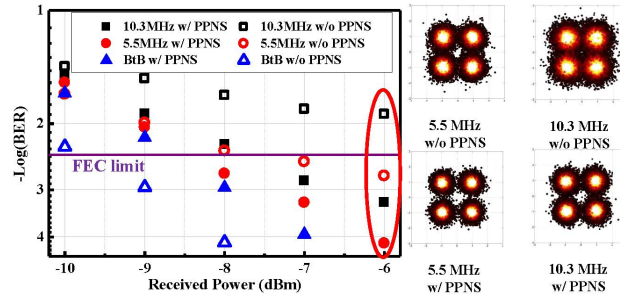


Fig. 4. BER curves over 150-km fiber with 5.5-MHz and 10.3-MHz linewidth.

The pilot-to-signal power ratio (PSPR) is an important parameter in the PPNS scheme. Figure 3 shows that a PSPR of ~2 dB was optimized for the QPSK OFDM signal with 10.3-MHz linewidth laser and optical received power of -6-dBm following fiber transmission of 150-km. Increasing the power of the added pilot tone resulted in two effects: reducing the OFDM signal power, which degraded the SNR before PPNS, and increasing the pilot-to-noise ratio resulting in improved CD-induced PN estimation. The second effect is equivalent to the reduction of  $F\{W^*\}$ . Thus, for PSPR lower than ~2 dB, SNR decreased with a decrease in PSPR, because the pilot-to-noise ratio was low enough for the CD-induced PN information from the pilot tone to be disturbed by the noise. If the PSPR were higher than ~2 dB, the poor SNR prior to application of the PPNS would dominate the SNR after PPNS. The constellations of the extreme cases are also presented in Fig. 3. Adopting an optimized PSPR of ~2 dB, we measured BER curves with laser linewidth of 5.5 MHz and 10.3 MHz over 150-km fiber transmission, as shown in Fig. 4. In the case of 5.5-MHz linewidth, the application of PPNS improved the sensitivity at the FEC limit by approximately 1 dB. In the case of 10.3-MHz linewidth, the signal was unable to attain the FEC threshold until the application of

PPNS, and PPNS improved the BER of the  $-6$ -dBm signal from  $>10^{-2}$  to  $<10^{-3}$ . However, at optical back-to-back (BtB), the signal suffered a 1-dB sensitivity penalty due to the addition of a useless pilot tone. It should be noted that although no CD-induced PN was induced at optical BtB, the elimination of CD-induced PN in Fig. 1(b) was still implemented in cases with PPNS, such that the filtered pilot tone carried only undesired random noise. Consequently, the PPNS scheme reduced OFDM power and produced additional distortion to lower the sensitivity at optical BtB.

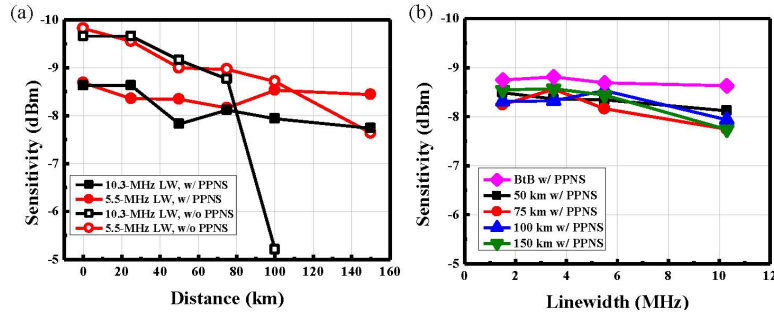


Fig. 5. The sensitivities with (a) various fiber distances and (b) sensitivities with various laser linewidth.

Figure 5(a) presents the sensitivities associated with linewidths of 5.5-MHz and 10.3-MHz following fiber transmission over various distances. Note that the sensitivity is referred to the required optical power at the FEC limit of  $3.8 \times 10^{-3}$ . At shorter distances, the CD-induced PN was only minor leaving little room for improvement by PPNS, and even the undesired noise will dominate signal performance. Therefore, the insertion of the pilot tone achieved little more than reducing the signal power and degrading the SNR. However, in the case of 10.3-MHz linewidth at transmission distances of  $> 80$ -km, CD-induced PN became a critical factor; under these conditions the PPNS scheme led to a considerable improvement in sensitivity. The relatively small CD-induced PN in the case of 5.5-MHz linewidth meant that the PPNS scheme was unable to provide a meaningful improvement until transmission distances exceeded 100 km. Figure 5(b) presents sensitivity figures at 0, 50, 75, 100, and 150 km as the functions of laser linewidth with all sensitivity values in the range of  $-8.8 \sim -7.7$  dBm. Note that the sensitivity was referred to the received optical power at the FEC limit of  $3.8 \times 10^{-3}$ . These results imply that the PPNS scheme can clamp fluctuations in sensitivity to less than  $\sim 1$  dB during transmission. Figure 6 presents the number of subcarriers in each modulation format with and without PPNS at 150-km fiber transmission following the application of the LC bit-loading algorithm. As shown in Fig. 6(a), in the case of 5.5-MHz linewidth without PPNS, only low-order modulation formats of QPSK and 8-QAM could be applied. In contrast, applying the PPNS scheme enabled the adoption of 16- and 32-QAM with higher-order modulation to increase capacity. In the case of 10.3-MHz linewidth in Fig. 6(b), most subcarriers were modulated by BPSK and QPSK prior to the application of PPNS. After applying PPNS, all of the subcarriers were modulated by QPSK or higher-order formats. This led to distinct differences in the data rates with and without PPNS over various fiber transmission distances. Figure 7(a) plots the total capacities with a linewidth of 1~10-MHz and fiber transmission of 0~150-km, and the optical received optical power is  $-6$  dBm. For cases without obvious CD-induced PN, the PPNS scheme reduced the capacity, such as a  $\sim 5$ -Gbps penalty at optical BtB and  $\sim 3$ -Gbps penalty in the cases of 1.5-MHz and 3.5-MHz linewidth at fiber transmissions of 50-km. The degree to which PPNS improved data rates increased with an increase in laser linewidth and/or distance of fiber transmission. Furthermore, PPNS shows high tolerance to fiber transmission distance with fluctuations in data rates of less than 1.5 Gbps over 0~150-km transmission, as shown in Fig. 7(a). Figure

7(b) plots the improvement in data rates compared with the data rate achieved without PPNS at optical BtB. At a fiber transmission distance of 150-km, the improvement in data rates was no less than ~14% in any of the cases and reached 93% at a linewidth of 10.3-MHz from 11.53 Gbps to 22.27 Gbps.

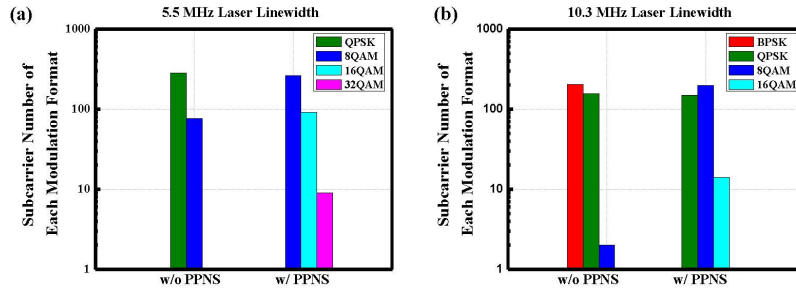


Fig. 6. Subcarrier number of each modulation format with and without PPNS over 150-km fiber transmission with (a) 5.5-MHz and (b) 10.3-MHz linewidth.

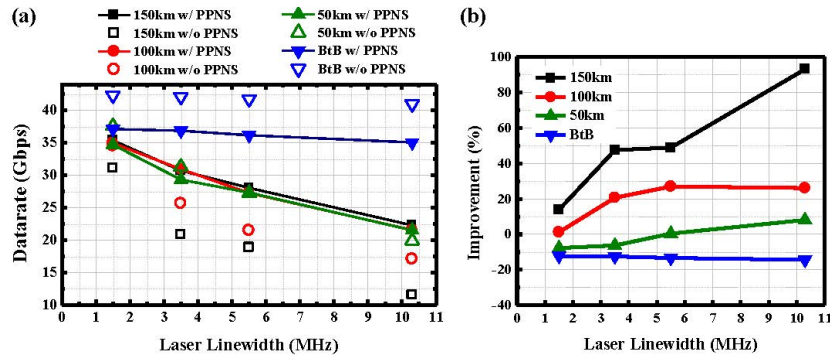


Fig. 7. (a) Data rate and (b) data rate improvement by PPNS with various laser linewidth employing bit-loading algorithm.

#### 4. Conclusion

This study proposed a 103-GHz DD-OFDM-RoF system using PPNS to suppress CD-induced PN. Using the QPSK modulation format, BER was improved by more than one order of magnitude from  $>10^{-2}$  to  $<10^{-3}$  with laser linewidth of 10.3-MHz at a transmission distance of 150-km fiber and 2-m air. PPNS also provided high tolerance to CD-induced PN within distances of 150-km. After maximizing spectrum efficiency via the LC bit-loading algorithm, PPNS increased the achievable data rate in cases that typically suffer from CD-induced PN. The application of PPNS led to a 93% improvement in data rates with a 10-MHz-linewidth signal at 150-km fiber and 2-m wireless transmission.

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