# Carrier Phase Noise Impact on OFDM Performance at D-band: Concepts and Experimental Assessment

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***Abstract*— In millimeter-wave (mmWave) wideband transmission, carrier phase noise is the primary limiting factor, especially for links employing Orthogonal Frequency Division Multiplexing (OFDM) signal, as orthogonality is sensitive to phase noise. This study employs two local oscillators with different phase noise (integrated rms jitter of 178 and 54 fs, respectively) to investigate the impact of carrier phase noise on wideband OFDM signal transmission at D-band. Experimental results indicate that phase noise has a significant impact on the capacity of OFDM transmission. In addition, the study shows that the number of OFDM subcarriers affects system performance, which is also linked to phase noise. Experimental results show that knowledge of phase noise can facilitate judicious choice of subcarrier number leading to optimized transmission capacity. For a bandwidth of 10 GHz OFDM signal, bit rates ranging from 44-56 Gbit/s are achieved, depending on the carrier phase noise and number of subcarriers.**

***Keywords*— Data transmission, OFDM, mmWave, D-Band, Phase noise.**

## I. Introduction

Emerging technologies such as virtual reality (VR), holography and autonomous driving set unprecedented demands on traditional wireless communication systems with high-speed, high-capacity and good signal quality performance metrics [1]. Millimeter-wave (mmWave) (30 GHz to 300 GHz) technology, with its vast bandwidth, is essential to meet these demands, making it a key technique for future communication links and networks. In mmWave transmission, especially at above 100 GHz, carrier phase noise has become a limiting factor [2]. This is because every time the carrier frequency is multiplied by 2, the phase noise degrades by 6 dB. Additionally, for wideband mmWave signals, the signal phase noise depends on the carrier phase white noise floor which manifests across the entire spectrum [3]. This imposes a significant impact on the transmission of mmWave data with high-order modulation format .

To investigate the impact of carrier phase noise on wideband mmWave transmission, several circuit designs for transceiver and corresponding phase noise measurement have been demonstrated in [4], [5], achieving transmission rates of 56.3 Gb/s and 56.7 Gb/s at D-band (110–170 GHz) using single-carrier 16QAM. To further reduce carrier phase noise, researchers [6], [7] utilized optical-assisted techniques to generate carriers, which help achieve significant carrier phase noise reduction, thus enabling ultra-high transmission rates when compared to the higher phase noise system using frequency-multiplied electronics local oscillator. In particular, by beating two pairs of frequency and phase-locked low linewidth lasers, researchers demonstrated ultra-low carrier phase noise at 92.5 and 130 GHz, and recently demonstrated a record-breaking transmission rate of 938 Gb/s, using OFDM in the mmWave band in [8]. These studies show that minimizing phase noise can greatly enhance transmission performance. However, such approaches require wideband optical modulators and optical amplifiers, which results in higher costs and increased power consumption. Notwithstanding, electronically generated local oscillators remain the method of choice as they are cost-effective and well-suited to widespread deployment in 5G communications, automotive radar and mmWave imaging. As in future systems, such as 6G, there is substantial work on the move to higher frequency mmWave, where electronically generated local oscillators become limiting and unsuitable. Therefore, investigating phase noise effects on transmission becomes highly essential. On the other hand, compared to single-carrier transmission, OFDM has become a promising candidate for next-generation mmWave system, since OFDM allows subcarrier spectra to overlap to improve spectral resource utilization and ameliorates multi-path effects [9]–[11]. However, the spectral overlap makes OFDM highly sensitive to maintaining orthogonality, which means it is more susceptible to carrier phase noise. The main effect of phase noise on OFDM systems is the inter-carrier interference (ICI) in [12], [13], which increases with the number of subcarriers. This analysis exhibits two key limitations. Firstly, the carrier numbers used in [12] are excessively large, with more than 8e4 FFT sizes, which is unrealistic in practical applications. Second, these previous works are mainly based on modelling instead of real mmWave transmission.

This paper provides an investigation into how carrier phase noise affects wideband OFDM transmission performance at D-band, focusing two different commercial local oscillator sources with phase noise of integrated root-mean-squared (rms) jitter 54 fs and 178 fs. Experimental results indicate that carrier phase noise has a significant impact on wideband OFDM transmission performance. Additionally, the number of OFDM subcarriers also affects the transmission performance and there exists an optimal carrier number for achieving the best system performance. With large numbers of OFDM subcarriers, the system is limited by inter-carrier interference (ICI), while with a low number of OFDM subcarriers, the system performance is dominated by white noise. This study

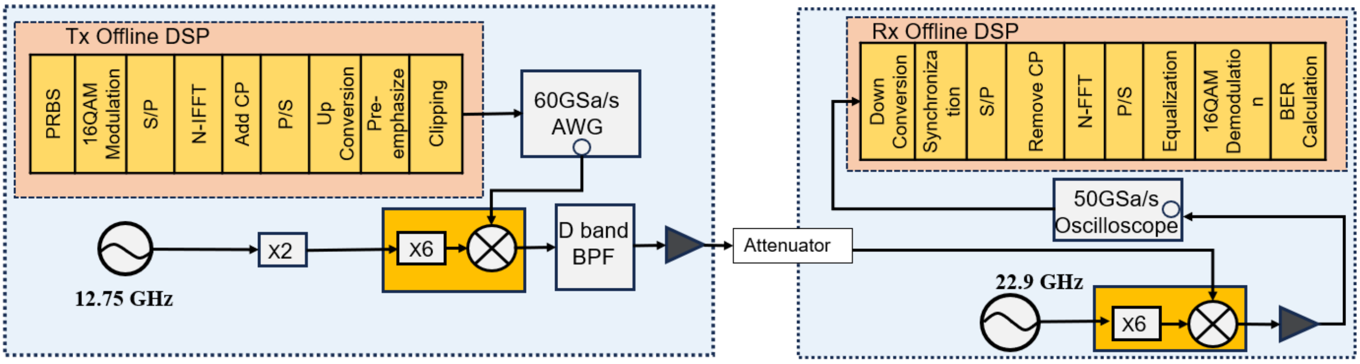


Fig. 1. System diagram and DSP process.

addresses the existing gap in practical evaluations of the impact of subcarrier numbers and provides a more realistic reference for designing multi-carrier mmWave systems.

## II. Experimental Setup

Fig. 1 shows the diagram of the setup of the experiment and the process of offline digital signal processing (DSP) for the transmission of OFDM signal at the D-band. Digital samples representing 10GHz bandwidth signals are generated from a $2^{19}-1$ pseudo-random binary sequence (PRBS) and 16QAM mapping. Following the mapping, a standard IFFT OFDM is used and 10% of IFFT size length cyclic prefix is added. The OFDM signal is then upsampled and digitally up-converted to a double sideband signal centered at 10 GHz with a 10 GHz bandwidth. Digital pre-emphasis is applied to compensate the frequency roll-off of the arbitrary waveform generator (AWG) and analog-to-digital converter (ADC). The clipping ratio of signal is optimized to ensure an optimal peak-to-average-power-ratio (PAPR) of 10.19 dB. More detail on the DSP could be found in [8]. The packet duration is set to 0.02 ms. The number of OFDM subcarriers is varied from 64 to 4096 to study its impact on transmission performance.

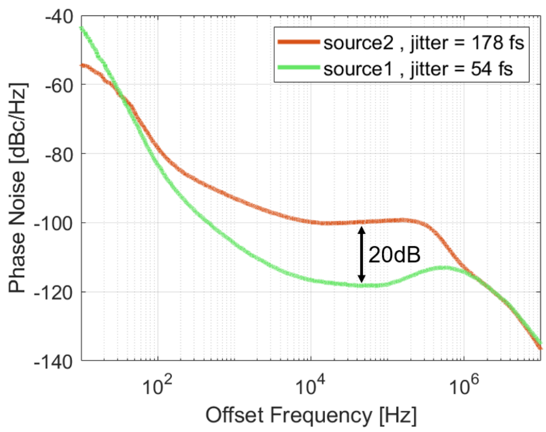


Fig. 2. Measured phase noise of the two different signal sources.

At the transmitter side, a 60 GSa/s AWG (Keysight M8195A) with 25GHz and 8-bit digital resolution was used for generating the IF signal. The 12.75-GHz carrier is generated using two different signal generators with different phase noise characteristics (phase noise measurements presented in subsequent sections). The 12.75-GHz carrier is first doubled to 25.5 GHz using a frequency doubler. The 25.5 GHz carrier is then fed into a D-band $6^{th}$ order harmonic up-conversion module (VDI WR6.5CCU), which converts the IF signal to 153 GHz. A D-band bandpass filter (135–150 GHz) is used to retain the lower sideband signal, thereby producing the D-band OFDM signal in a bandwidth of 138–148 GHz with a suppressed 153-GHz carrier. A D-band amplifier (13dB gain) is added to compensate for conversion loss. A variable D-band attenuator is added after D-band amplifier to emulate link loss.

At the receiver side, a frequency synchronized 22.9-GHz local oscillator is fed into D-band $6^{th}$ order harmonic down-conversion module (VDI WR6.5CCD) to down-convert the D-band signal to baseband. The baseband signal is amplified by a 14dB gain amplifier, which is then detected by a 50 GSa/s ADC with 23 GHz analog bandwidth and subsequently processed offline using DSP. The equalization is achieved by one-tap equalization [14], [15]. The bit loading [16] is calculated based on the signal-to-noise ratio (SNR) of each subcarrier, providing the channel capacity under soft-decision (SD) forward error correction (FEC) with an overhead that results in a bit error rate (BER) of 2e-2.

## III. Experimental Result

### A. *Phase Noise of Local Oscillator*

The phase noise of 12.75-GHz signal generated using two different signal sources (i.e. source 1 and 2) is measured using a cross-correlation-based phase noise analyzer (Rohde & Schwartz FSWP). The measurement range is configured to 10Hz-10MHz. Fig. 2 compares the phase noise of the two different 12.75 GHz carriers generated using source 1 and source 2. In this case, source 1 outperforms source 2 by around 20 dB from 5 to 500 kHz frequency offset. From 1MHz to 10MHz, the phase of these two signal sources remains similar. Over the measured frequency region (10Hz-10MHz), the integrated rms jitter of source 1 and source 2 are 54 and 178 fs, respectively.

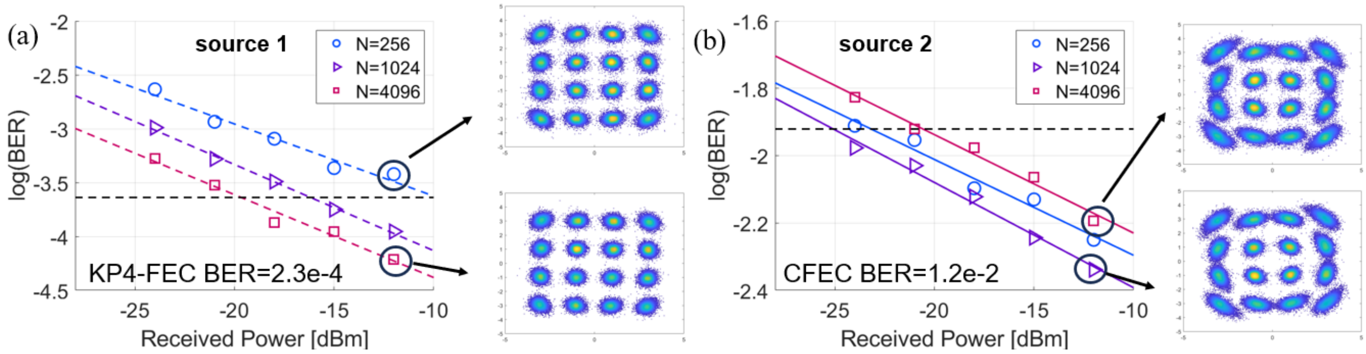


Fig. 3. (a) BER versus received power under different subcarrier numbers and constellation diagrams of the received signal at a received power of -12 dBm for $N$ =256 and $N$ =4096 utilizing source1. (b) BER versus received power under different subcarrier numbers and constellation diagrams of the received signal at a received power of -12 dBm for $N$ =1024 and $N$ = 4096 utilizing source2.

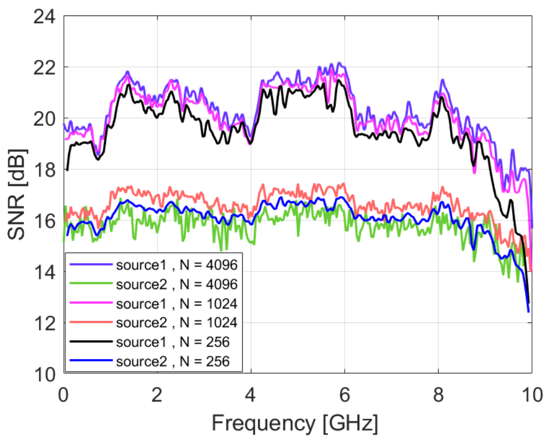


Fig. 4. SNR of each subcarrier of the transmitted 10GHz-bandwidth OFDM signal.

### *B. Point-to-Point OFDM Transmission with Different Subcarrier Numbers at D-band*

Fig. 3a and b show the BER of the received signal using two different local oscillators: source 1 and 2 with different numbers of subcarriers. When using source 1 as the local oscillator (as shown by Fig. 3a), the receiver sensitivity, considering KP4-FEC threshold (BER = 2.3e-4) [17], for 256 and 4096 number of subcarriers are -10 dBm and -21 dBm, respectively. The sensitivity was improved by 11 dB when changing the number of ubcarriers from 256 to 4096. This is because when using low-phase noise source 1 as local oscillator, the system is limited by white noise with low number of subcarriers (high frequency spacing between subcarriers). On the other hand, when using source 2 as local oscillator (as shown by Fig. 3b), the receiver sensitivity, considering CFEC (BER =1.2e-2) [18], 256 and 1024 subcarriers are -21 dBm and -25 dBm, respectively. Unlike results shown in Fig. 3a, the optimal BER performance is achieved with 1024 OFDM subcarrier instead of 4096, this is because poor carrier phase noise introduces higher ICI, thus degrading performance of OFDM with a large number of subcarriers. These results indicate that the subcarrier number of the OFDM signal could affect the sensitivity of the receiver, which a crucial parameter in system design.

Fig. 4 shows the SNR comparison of each subcarrier using source 1 and 2 with different numbers of subcarrier configurations. The purple, pink and black curves represent source 1. Red, blue and green curves represent source 2. It can be found that SNRs at different subcarriers using source 1 outperform source 2 by around 3.5dB across the entire bandwidth, which matches with previous BER measurement. When using source 2, the average SNR reaches a maximum of 15.5dB with 1024 OFDM subcarriers, which are also cross-verified with results shown in Fig. 3b.

Fig. 5a and b show the estimated capacity using bit loading technique with source 1 and 2, with different numbers of subcarriers and different received power. When using source 1 as a local oscillator, with -12dBm received power, the estimated capacity increases from 49 to 56 Gbps when the number of subcarriers increases from 64 to 4096. This is because low carrier phase noise ensures low ICI, thus providing high capacity with the increased number of subcarriers. It is worth noting that the estimated capacity saturates when the number of subcarriers reaches 2048. One possible reason is that ICI starts to limit transmission performance despite using low phase noise local oscillator. It is expected that estimated capacity would decrease when further increasing the number of subcarriers, however, in practical implementation, a further increase in a number of subcarriers (i.e. FFT size) is impractical. On the other hand, when using source 2 as the local oscillator (as shown in Fig. 5b, at -12dBm received power, the capacity increased from 39 to 44 Gbps when increasing the number of subcarriers from 64 to 1024. However, the capacity drops to 41 Gbps when further increasing the number of subcarrier to 4096. This is because when using a poor phase noise local oscillator, the system becomes more sensitive to ICI. Finally, Fig. 5c compares the estimated capacity with different numbers of subcarriers using source 1 and source 2 at the same received power of -12dBm. With 1024 OFDM subcarriers, a capacity increase of 12 Gbps (from 44 to 56 Gbps) can be achieved with low phase noise local oscillator (i.e. source 1).

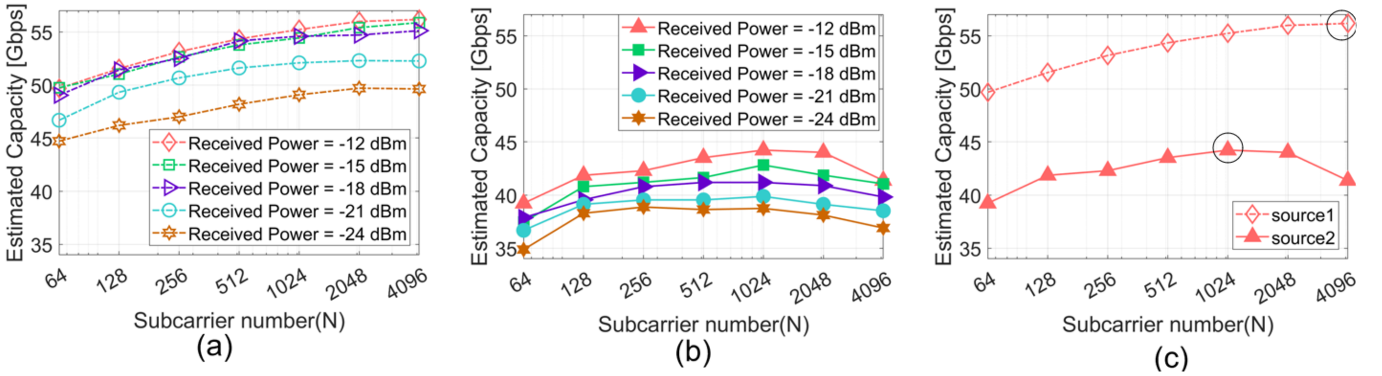


Fig. 5. Capacity comparison. (a) Capacity variation local oscillator versus subcarrier number under different received power utilizing source1. (b) Capacity variation with subercarrier number versus different received power utilizing source2. (c) Maximum capacity achieved by different subcarrier numbers.

## IV. Conclusion

We investigated the impact of carrier phase noise on mmWave wideband data transmission using two commercial local oscillators: source 1 and 2, with integrated rms jitter 54 fs and 178 fs. Experimental results show that wideband D-band OFDM transmission is greatly affected by carrier phase noise. In this proof-of-concept experiment, we have demonstrated a maximum of 56 Gbps capacity transmission with a 10GHz bandwidth OFDM signal at D-band. An achievable capacity difference of 12 Gbps is verified by comparing source 1 and source 2 as local oscillators. Furthermore, the impact of OFDM subcarrier number on system performance is experimentally verified. We have demonstrated 11dB receiver sensitivity improvement when increasing the number of OFDM subcarriers from 256 to 4096, indicating low phase noise carrier guarantees low ICI and thus improved transmission performance.

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