W-Band Photonics-aided ISAC Wireless System Sharing OFDM Signal as Communication and Sensing

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Abstract: We experimentally demonstrate the dual functionality of OFDM signals for both communication and sensing. Photonics-aided ISAC system in W-band achieves range-Doppler imaging with 0.0102m resolution and data rate of 48.04 Gbit/s over wireless link. © 2024 The Author(s)

1. Introduction

The emerging sixth-generation (6G) mobile communications system is designed to seamlessly integrate the digital and physical worlds, enabling ubiquitous connectivity. Unlike the existing 5G air interface standard, 6G utilize higher frequency bands and wider bandwidths in the millimeter wave (MMW) and terahertz ranges, to enable high-resolution and high-speed communications while integrating communications and sensing functions within a single system [1,2]. ISAC (Integrated Sensing and Communication) systems have received much attention in research. Previous studies have typically used time-division or frequency-division techniques to combine Linear Frequency Modulation (LFM) and Orthogonal Frequency Division Multiplexing (OFDM) signals, which require filtering at the receiver to separate communication and radar signals [3-6]. However, this approach usually fails to fully utilize the signal bandwidth, resulting in spectral inefficiency and overall system performance degradation. OFDM waveforms are considered to be a strong contender for ISAC waveforms due to its spectral efficiency and adaptability to multipath effects in wireless channels. However, most of the existing OFDM radar studies are limited to frequencies below 24 GHz [7,8], which cannot fulfill the 6G standard. The 802.11ad standard has extended the communication frequency to 60 GHz, making the low atmospheric attenuation and broadband W-band a suitable candidate for 6G. Unlike the conventional method of generating millimeter waves by multiplying electrical signals, photonics-aided technology utilizes two carriers at different frequencies, providing the flexibility to generate MMW signals that theoretically cover all available atmospheric transmission windows. In addition, well-established electro-optical modulators provide a wide bandwidth, eliminating the bandwidth bottlenecks associated with electronic systems and reducing signal generation costs. Thus, photonics-aided MMW system is an excellent match for W-band broadband signals.

In this paper, a photonics-aided W-band OFDM ISAC system is proposed and experimentally verified. The system uses OFDM signals as both communication signals and sensing signals, making efficient use of the system's spectrum resources. With the help of offline digital signal processing (DSP) algorithm, the system achieves a high-speed communication of 47.06 Gbit/s over a 10-meter wireless link and provides a distance resolution of 1.02 cm in the sensing part. Range-Doppler two-dimensional imaging is achieved by successfully detecting two corner reflectors two meters in front of the transmitter. The system is expected to enable various potential applications in future 6G networks.

2. Principle and experimental setup

Fig. 1(a) illustrates the experimental setup of the proposed method. An external cavity laser (ECL1) with a linewidth of 100 kHz generates a 1550 nm optical carrier, which is fed into an IQ Mach-Zehnder modulator (IQMZM) with a bandwidth of 30 GHz. An OFDM signal with a baud rate of 16 GBaud, generated by an arbitrary waveform generator (AWG) with a sampling rate of 120 GSa/s, a 3-dB bandwidth of 45 GHz, and 8 bits of vertical resolution, drives the IQMZM. The OFDM signal consists of 4096 points, a cyclic prefix (CP) length of 256, resulting in an OFDM frame duration of 2.72 microseconds. The modulated signal is then amplified to 10 dBm using a polarization maintaining erbium-doped fiber amplifier (PM-EDFA) with a linewidth of 100 kHz. ECL2 with a linewidth of 100-kHz generates a continuous wave at 1550.7 nm, serving as the optical local oscillator (OLO). Both optical signals

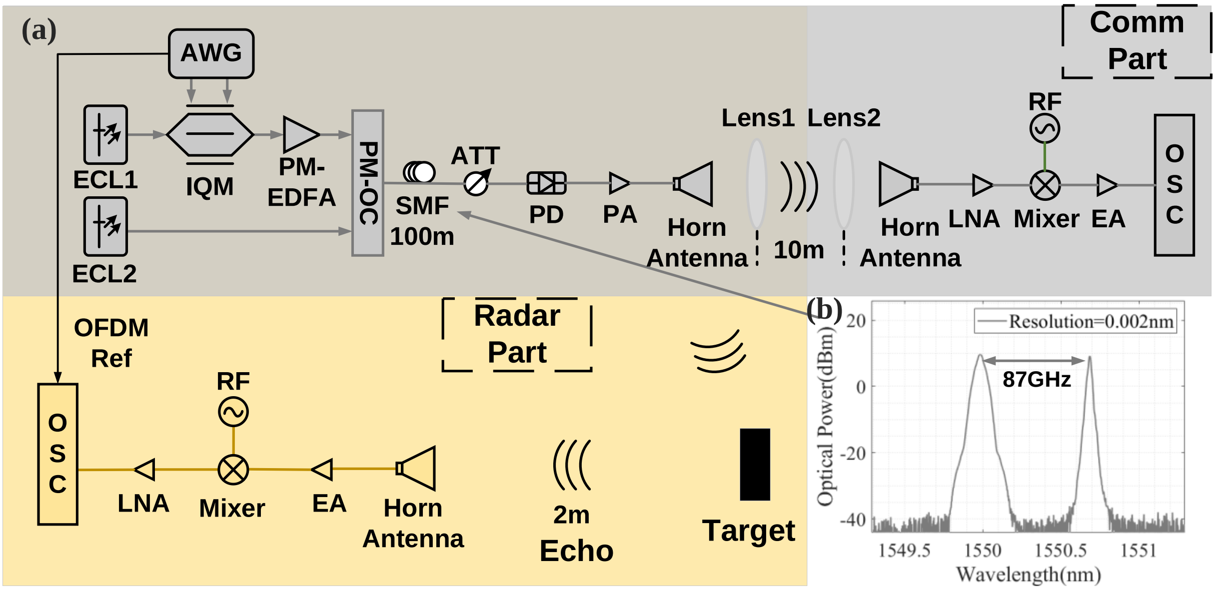

Fig. 1. (a) Experimental setup of photonisc-aided OFDM ISAC system. (b) Spectrum of coupled signals

are coupled using a polarization maintaining optical coupler (PM-OC). The frequency interval between ECL1 and ECL2 is 87 GHz. The measured optical spectrum after PM-OC coupling is shown in Fig. 1(b). The coupled signals are transmitted through a 100 m single-mode fiber (SMF) and enter a variable optical attenuator (ATT) to control the optical power before reaching the photodetector (PD). After photonic-to-electric conversion, the W-band signal is amplified by a 20 dB gain electrical amplifier (EA) and radiated into free space by a 25 dBi gain horn antenna. At the communication receiver, to mitigate signal power loss, Lens1 and Lens2, each with a diameter of 10 cm and a focal length of 20 cm, are placed in the signal path, providing a total gain of 30 dBi. After a 10 m wireless transmission, the signal is amplified by a 25 dBi gain horn antenna and a 25 dB gain low noise amplifier (LNA).

The MMW signal is then down-converted to an intermediate-frequency (IF) signal by a mixer driven by an electrically local oscillator (ELO) operating at 75 GHz. The center frequency of the IF signal is 12 GHz. After amplified by a 25 dB gain EA, it is sampled by a real-time oscilloscope (OSC) with a bandwidth of 16 GHz and a sampling rate of 50 GSa/s. In the communication part, the offline algorithms include digital down-conversion, resampling, CP removal, training sequence extraction, Fast Fourier Transform (FFT), channel estimation, intra-symbol frequency-domain averaging (ISFA), pilot equalization and calculation of bit error rate (BER) after blind phase search (BPS). In the sensing section, the MMW signal is sampled by the same receiver setup as in the communication, but with the addition of a corner reflector for reflection at a distance of two meters from the transmitter. For the sensing function, the oscilloscope also samples the OFDM signal generated by the AWG as a reference signal. In the offline processing algorithm, the initial steps are similar to the communication processing. After FFT, the data is divided element-by-element by QAM modulated data and then FFT is performed in the OFDM symbol dimension and inverse FFT (IFFT) is performed in the subcarrier dimension. The resulting matrix is Taylor window filtered to suppress signal clutter to obtain a range-velocity 2D image.

3. Results and discussion

In the sensing part, experiments are conducted to verify the sensing performance of the system through single-target and dual-target test. Corner reflectors were placed approximately 2 m from the sensing transceiver. The OFDM signal reflected by the corner reflector is electrically down-converted and sampled by OSC. After digital domain offline algorithm processing, the system’s perception results are shown in Fig. 2. Fig. 2(a) shows the OFDM signal spectrum after down-conversion. Fig. 2(b) shows the experimental setup using corner reflectors. Fig. 2(c) shows the experimental result of one reflector without Taylor window filtering. It is observed that due to phase noise interference, the system exhibits multiple high-power side lobes, significantly affecting the sensing performance. Fig. 2(d) shows the result obtained after Taylor window filtering. At the expense of widening the main lobe, effective suppression of side lobes is achieved, thereby enabling accurate inversion of target distance and velocity information. Fig. 2(e) and (f) depict images of two reflectors without and with Taylor window filtering, respectively. Obviously, this algorithm is still effective in dual-target sensing scenarios. According to equation $R_{res} = C/2N_{sc}\Delta f = C/2B_{used}$, the distance resolution can be calculated as c / (16 * 4000 / (4096 + 256)) = 1.02 cm.

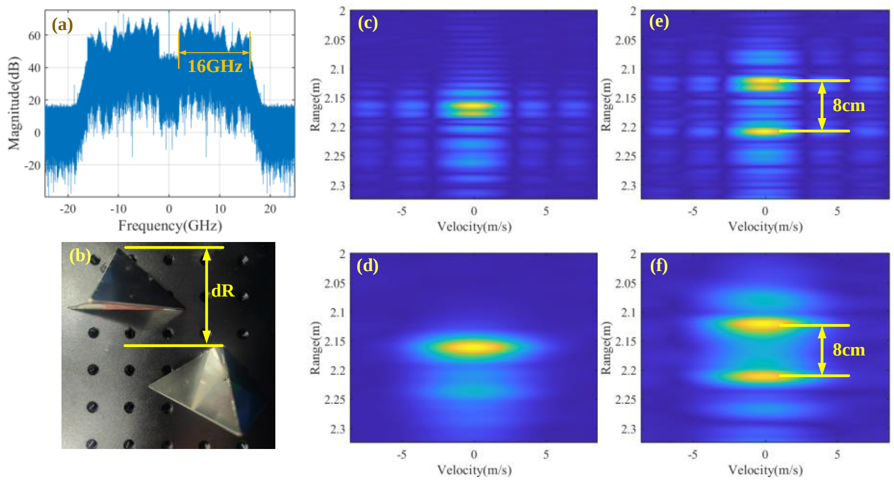

Fig. 2. (a) OFDM signal spectrum after down-conversion (b) Experimental setup of the corner reflectors. (c) and (d) Single-target 2D imaging with/without Taylor window filtering. (e) and (f) Dual-target 2D imaging with/without Taylor window filtering.

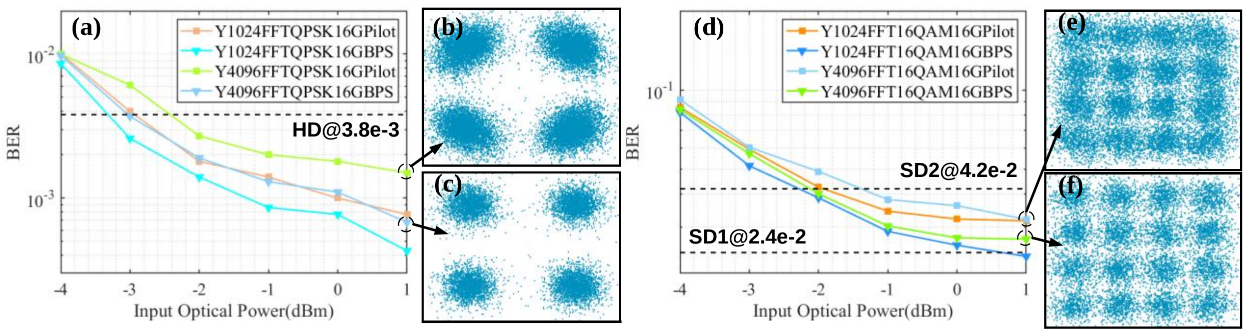

Fig. 3. (a) BER of QPSK signal with different baud versus input optical power. (b) and (c) Constellation diagrams with baud rates of 16 G and 8 G. (d) BER of 16QAM signal with different baud versus input optical power. (e) and (f) Constellation diagrams with baud rates of 16 G and 8 G

In the communication part, experiments compared the BER performance of signal transmission under different conditions. Fig. 3(a) shows the relative optical power versus BER for the system transmitting QPSK signals with different FFT sizes. It is observed that BPS significantly reduces BER of data. Due to the impact of phase noise, the signal with an FFT size of 1024 exhibits a considerably lower BER compared to the signal with an FFT size of 4096. For input optical powers greater than -3 dBm, the BER remains below the hard decision threshold (HD@3.8e-3). With a 7% overhead, the system achieves error-free transmission. Fig. 3(b) and (c) depict the QPSK signal constellations obtained with different processing approaches for an input optical power of 1 dBm. Fig. 3(d) shows the optical power versus BER for the system transmitting 16QAM signals. It is observed that, with an FFT size of 1024 and the use of BPS for phase noise mitigation, the signal quality is optimized. At the input optical power of 1 dBm, the BER can be maintained below the soft decision threshold 1 (SD1@2.4e-2). Fig. 3(e) and (f) show the 16QAM signal constellations obtained with different processing approaches at an input optical power of 1 dBm. Finally, the system's maximum transmission rate is calculated as $16\times4000/(4096+256)\times 4/(1+0.25) = 47.06$ Gbit/s(SD2@4.2e-2).

4. Conclusion

In this paper, we propose and experimentally demonstrate a photonics-aided W-band OFDM ISAC system. The system uses OFDM signals as communication signals and sensing signals to achieve efficient multiplexing of spectrum resources for ISAC signals. By using offline DSP algorithms, the proposed system achieves high-speed communication with a data rate of 47.06 Gbit/s over a 10m wireless link. In the sensing domain, it attains a remarkable distance resolution of 1.02 cm. Notably, we successfully detect and perform Range-Doppler 2D imaging of two corner reflectors positioned two meters in front of the transmitter.

5. References

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