• Supplementary File•

Real-time Integrated 2.04 centimeters Range Resolution and 16.14-Gbps Bidirectional Wireless Communication in Photonic-assisted Millimeter Wave Band System over 100 meters

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Appendix A Photonic-assisted millimeter-wave real-time ISAC signal generation

The photonic-assisted millimeter-wave (MMW) ISAC signal generation scheme is illustrated in Figure A1(a). At the transmitter, two independent external cavity lasers (ECL1 and ECL2) with a fixed frequency offset are coupled via a polarization-maintaining optical coupler (PM-OC) and injected into a Mach–Zehnder modulator (MZM) to serve as optical carriers. A real-time DMT-ISAC signal generated by an FPGA is amplified by an electrical amplifier (EA) and used to drive the MZM. The modulated optical signal is transmitted over standard single-mode fiber (SMF) and then converted into a millimeter-wave ISAC signal through heterodyne beating in a photodetector (PD).

The designed ISAC signal adopts a discrete multitone (DMT) waveform to effectively combat frequency-selective fading in the experimental environment. The corresponding frame structure is shown in Figure A1(b). Each ISAC frame generated by the FPGA consists of 32,000 samples, beginning with a 640-sample Zadoff–Chu (ZC) sequence for synchronization. This is followed by 4 pilot DMT symbols and 45 data-bearing DMT symbols, each constructed with a 512-point IFFT. Among these, subcarriers 1–64 are loaded with training or sensing/communication data, preceded by a 128-sample cyclic prefix (CP) to mitigate multipath effects. For the 4 pilot symbols, all 64 subcarriers are modulated with known QPSK symbols for channel estimation. For the 45 payload symbols, the 64 subcarriers are partitioned between sensing and communication: the first 4 subcarriers carry QPSK-modulated sensing data to ensure robust sensing under low-SNR conditions, while the remaining 60 subcarriers carry 16-/64QAM-modulated communication data, thereby verifying that the proposed ISAC waveform can enhance peak data rates through higher-order modulation.

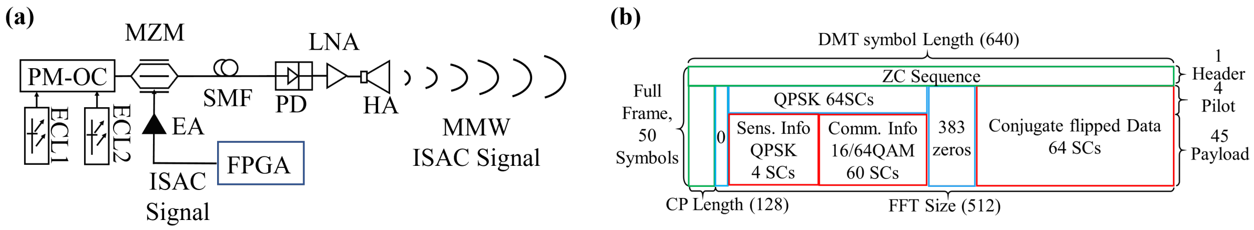

Figure A1. The principle of the photonic-assisted MMW ISAC waveform generation (a) Signal generation scheme based on photonic heterodyne beating (b) DMT-ISAC frame structure design

Appendix B Performance limitation analysis

We analyzed the performance limitations of the proposed system, including its maximum achievable range and the impact of adverse weather conditions (e.g., rain and haze).

The maximum range can be estimated using the link budget. With a UE transmitting power of 25 dBm (LNA saturated output), a BS receiver sensitivity of –40 dBm, and a 6 dB noise figure, error-free QPSK transmission requires a minimum SNR of 10 dB. This implies the received power must be at least –24 dBm. Accounting for the total gain of all components and antennas in the link (80 dB), the estimated maximum achievable range of the system d_{Max} is 0.65 km:

$$\begin{aligned} &25+80-(20\times\log10(d_{Max})+132.44+0.39\times d_{Max})=\text{-}24 \\ &\Rightarrow d_{Max}=0.65\ \text{(km)} \end{aligned} \tag{A1}$$

Next comes the influence of weather conditions on system performance. The experiments in this study were conducted under clear daytime conditions, achieving a received signal-to-noise ratio (SNR) of approximately 20 dB. Given that the sensing information uses QPSK modulation, which requires a minimum SNR of 10 dB for error-free transmission, we conclude that rainfall-induced SNR degradation exceeding 10 dB will deteriorate the ranging root-mean-square error (RMSE) performance. Figure B1 summarizes the relationship between rainfall intensity and attenuation factors for 103 GHz millimeter waves, as reported in various literature [1].

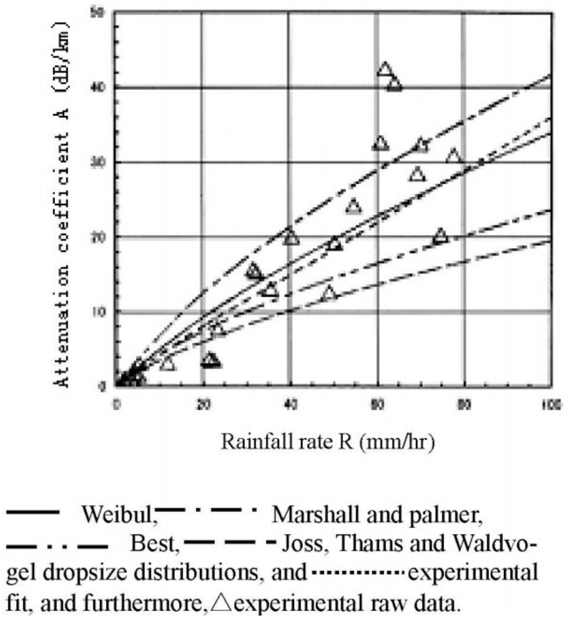

Figure B1 Comparison between calculations and measurements at 103 GHz, for a l minute integration time [1]

Taking an extreme case of 100 mm/hr rainfall (attenuation factor: ~40 dB/km), the system's SNR would decrease to 16 dB, still meeting the QPSK error-free transmission threshold but increasing the bit error rate (BER) for 16-/64-QAM communication. Notably, rainfall intensity ≥20 mm/hr is classified as "heavy rain," while intense convective weather (≥50 mm/hr) is extremely rare. Theoretically, the system can operate normally under common rainy conditions, and even extreme rainfall will not compromise ranging accuracy, but excessive humidity in such conditions poses a significant risk of damaging system components.

Compared to rainfall, haze has a relatively minor impact on millimeter-wave propagation [2]. As shown in Figure X, the attenuation of 100 GHz electromagnetic waves by haze is approximately 5 dB/km, corresponding to a 0.5 dB SNR degradation in our system. This slight degradation has negligible effects on both sensing and communication functionalities.

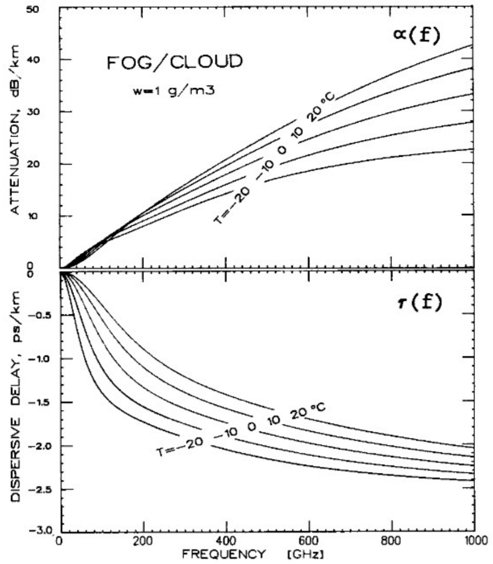

Figure B2 SWD model predictions of attenuation α(f) and delay γ(f) for frequencies up to 1000 GHz assuming a water content, w= l g/m³, and temperatures from -20 to + 20°C [2]

Appendix C The influence of digital clipping on DMT signals

Due to the 26-bit output precision of our FFT module and the 6-bit quantization resolution of the DAC, digital clipping must be applied to the FFT output to truncate excessively large or small values, ensuring proper 6-bit quantization. Specifically, the FFT output *x* is processed as follows:

$$x=\begin{cases} 8191 & x>8191 \\ -8191 & x<-8191 \\ 257 & 127<x<257 \\ -257 & -257<x<-127 \\ x & else \end{cases} \tag{C1}$$

This process inevitably introduces noise, with the noise magnitude being data-dependent and stochastic. Through analysis of multiple generated 16-/64-QAM DMT-ISAC signals, we found that the distortion caused by digital clipping scheme adds noise power equivalent to 0.05-0.1% of the original signal power. Consequently, clipping may slightly increase the bit error rate (BER) of the received signal, but the impact remains limited.

Regarding PAPR reduction, analysis of the same signal sets revealed that clipped signals exhibit a PAPR range of 9-10 dB, compared to 11-13 dB for the original signals. Thus, digital clipping effectively reduces PAPR by 2-4 dB.

Reference

[1] Qingling, Zhao, and Jin Li. "Rain attenuation in millimeter wave ranges." 2006 7th international symposium on antennas, propagation & EM theory. IEEE, 2006.

[2] Liebe, Hans J., Takeshi Manabe, and George A. Hufford. "Millimeter-wave attenuation and delay rates due to fog/cloud conditions." IEEE transactions on antennas and propagation 37.12 (1989): 1617-1612.