Retro-Reflective Optical ISAC with Hybrid Modulated–Unmodulated Retro-Reflectors

Xin Xiong(1), Sihua Shao*(1), Tiantian Chu(2), and Chen Chen(2)

(1) Colorado School of Mines, Golden, CO 80401, USA, xin_xiong@mines.edu, sihua.shao@mines.edu

(2) Chongqing University, Chongqing 400044, China, 20241101050@stu.cqu.edu.cn, c.chen@cqu.edu.cn

***Abstract*—This paper presents a visible-light integrated sensing and communication (ISAC) system based on an illuminative, spatially dispersive LED area light source and retro-reflective devices. The proposed system employs two co-located corner-cube retro-reflectors (CCRs), one of which is coupled with a liquid-crystal (LC) shutter, to enable simultaneous ranging and tag-to-reader communication. The unmodulated CCR provides a stable, high-intensity reference signal to support robust distance estimation and reliable signal extraction in the presence of background noise, while the LC-integrated CCR enables data modulation without degrading ranging performance. Experimental results demonstrate a ranging accuracy of 6.28 cm and reliable signal recovery at distances of up to 5 m.**

I. Introduction

Retro-reflective optical integrated sensing and communication (RO-ISAC) has emerged as a promising paradigm for indoor, UAV, underwater, and satellite applications [1]. Compared with passive radio-frequency (RF) backscattering, retro-reflective optical links are inherently line-of-sight (LoS) dominated, which effectively suppresses multipath-induced fading [1]. The geometric property of corner-cube reflectors ensures that incident light is returned directly to its source [2], enabling alignment-free connectivity without the need for complex antenna arrays, as commonly required in passive RF backscattering systems. By modulating the reflected optical signal, RO-ISAC systems can simultaneously support high-precision ranging and uplink data transmission [3].

In our earlier work [4], we proposed a system architecture based on a customized LED array and a hybrid retro-reflector configuration. However, that design lacked an effective integration of a high-bandwidth photosensitive receiver with the high-temperature LED light disk, rendering it incapable of receiving real-time uplink-modulated signals. This work addresses that limitation by integrating a commercial off-the-shelf photodetector (PD) behind the heat sink and embedding a convex lens at the center of the LED source to concentrate the retro-reflected light. Despite the extremely limited LED bandwidth (-10 dB bandwidth of only 4 MHz), the proposed system achieves centimeter-level ranging accuracy with a mean absolute error of 6.28 cm and enables reliable On–Off Keying (OOK) signal recovery at distances of up to 5 m.

II. System Architecture

The proposed online RO-ISAC experimental platform is implemented in an indoor environment, as illustrated in Fig. 1. The transmitter employs a customized high-power LED array (top right), with a convex lens integrated at its center to concentrate the retro-reflected light. A PD is separately positioned behind the central aperture of the source heat sink (middle right) to mitigate thermal noise and receive the retro-reflected signals. On the tag side, a hybrid retro-reflector configuration is used (bottom right), comprising an unmodulated retro-reflector (URR) for robust ranging and a modulated retro-reflector (MRR) for uplink data transmission.

A. Reader and Tag Hardware Configuration

The transmitter comprises an LED array arranged in a 4×34 topology, in which 34 LEDs are connected in series within each group and the four groups are connected in parallel. The array is driven by a 102 V DC bias combined with an AC modulation signal from an arbitrary waveform generator (AWG) through a bias tee. The input modulation is a 4 MHz single-tone sinusoid with a peak-to-peak voltage (V_{pp}) of 5 V. For the hybrid retro-reflective tag, two types of CCRs are employed. The URR is a total-internal-reflection (TIR)-based corner cube, while the MRR consists of an aluminum-coated hollow corner cube integrated with a Pi-cell LC shutter. The LC shutter is operated at a modulation frequency of 150 Hz. At the receiver, a convex lens with a focal length of 12 cm is mounted at the center of the light source to focus the retro-reflected light onto a PD placed at the focal plane. The PD output is captured by an oscilloscope for subsequent signal processing. A visual overview of the testbed is also provided in the accompanying YouTube demo[1] .

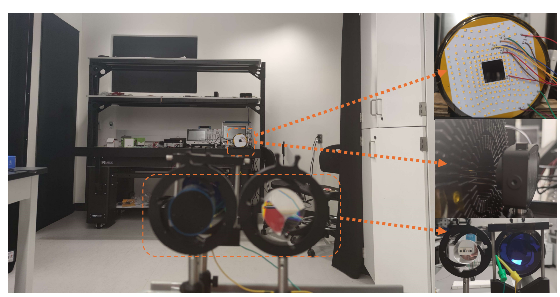

Fig. 1. Experimental setup of the online RO-ISAC platform.

B. Signal Processing Workflow

The signal-processing pipeline is designed to enable simultaneous ranging and data recovery through real-time waveform acquisition. At the transmitter, the 4 MHz sinusoidal signal

[1] YouTube demo: https://youtu.be/5gCNkkePWPY

978-1-7334677-3-5 © 2026 ACES

generated by the AWG is split into two identical paths using a 1-to-2 BNC connector. One path drives the LED array as the illumination source, while the other is routed directly to Channel 2 of the oscilloscope and serves as the reference signal. The retro-reflected light is detected by the PD and recorded on Channel 1. Both channels are digitized at a sampling rate of 1.25 GSa/s, corresponding to a spatial resolution of 12 cm between adjacent samples.

For each measurement, 10 million samples are acquired per channel and segmented into 1,000 frames (10^4 samples/frame). The signal-processing steps are summarized as follows:

- **Correlation:** For each frame, a digital cross-correlation is performed between Channel 1 and Channel 2, producing a sequence of 1,000 correlation peaks indexed by the *correlation frame index*.
- **Ranging:** To overcome the 12 cm spatial resolution limit imposed by discrete sampling, the system first identifies the mode (most frequent value) of the integer sample delays across all frames. Polynomial regression is then applied to interpolate the correlation curve and refine the peak location to a continuous value, which is used to estimate the time of flight (ToF).
- **Data Recovery:** The amplitude sequence of the 1,000 correlation peaks captures the 150 Hz modulation imposed by the MRR. A sliding integration window of length 200 is applied to this sequence, followed by thresholding, to reconstruct the OOK on–off symbol periods.

III. Experimental Results

A distance sweep experiment was conducted from 3.0 m to 5.64 m with a spatial interval of 12 cm.

A. High-Precision Ranging Performance

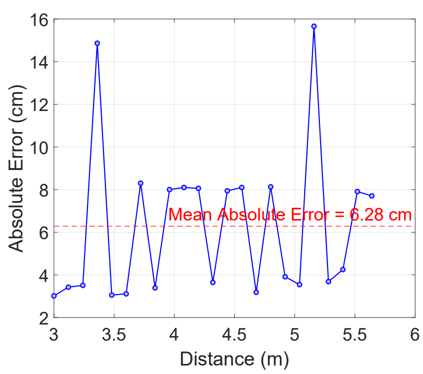

Fig. 2. Ranging accuracy analysis of the hybrid RO-ISAC system.

As shown in Fig. 2, the mean absolute error (MAE) over the tested range is 6.28 cm, corresponding to approximately half of a sampling interval (12 cm) at a 1.25 GSa/s sampling rate. The maximum absolute error is 15.66 cm, which is roughly equivalent to a single-sample shift. Notably, the ranging error does not exhibit a significant increasing trend with distance. These results demonstrate that the correlation-based ranging method maintains high precision and robustness even under lower signal-to-interference-plus-noise ratio (SINR) conditions at the 5.64 m boundary. In other words, despite background reflections from surrounding indoor fixtures, the retro-reflected signal remains highly distinguishable at longer distances.

B. Signal Recovery and Communication Performance

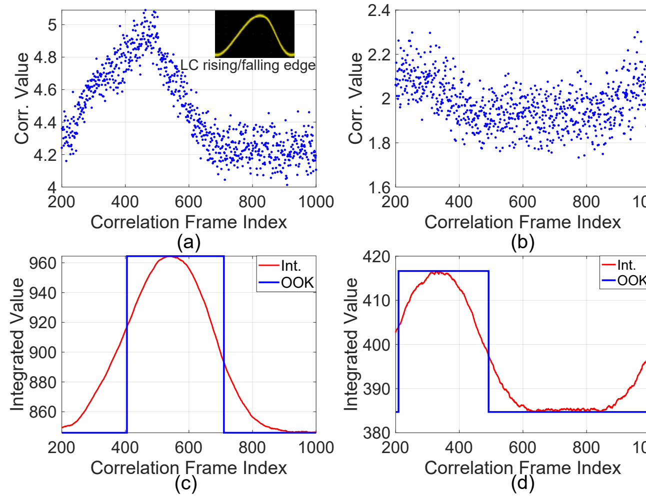

Fig. 3. OOK signal recovery at 3 m and 5 m: (a) raw correlation peak sequence at 3 m; (b) raw correlation peak sequence at 5 m; (c) recovered on–off periods at 3 m; and (d) recovered on–off periods at 5.04 m.

To enable detailed observation of the OOK recovery process, the results in Fig. 3 are truncated to two symbol periods. As shown in Fig. 3 (a), at a distance of 3 m, the retro-reflected signal exhibits a high SINR, and the OOK envelope is clearly discernible even in the raw correlation peak sequence. In contrast, Fig. 3 (b) shows that at 5.04 m the signal amplitude is significantly attenuated. Nevertheless, as illustrated in Figs. 3 (c) and (d), the red curves—corresponding to the sliding-integral output—indicate that the data remain recoverable using the proposed signal-processing pipeline.

The recovered signals do not exhibit an ideal 50% duty cycle; instead, the duty cycle varies between 30% and 40%. This behavior is primarily attributed to the limited switching bandwidth of the Pi-cell LC shutter, which results in asymmetric rise and fall times in the optical modulation, as shown in the upper-right inset of Fig. 3(a). Despite these hardware-induced distortions and the reduced SINR at longer distances, the proposed processing workflow demonstrates sufficient robustness to maintain reliable communication over the 5 m indoor experimental range. Future work will investigate more robust decoding algorithms for reliable OOK bit-stream recovery.

References

[1] T. Chu, C. Chen, J. Ye, X. Xiong, S. Shao, Z. Zeng, D. Wang, F. Yang, G. Xu, and H. Haas, "Retroreflective Optical ISAC for 6G: Technologies, Applications and Future Directions," *arXiv preprint:2512.01275*, 2025.

[2] D. A. Arnold, "Method of calculating retroreflector-array transfer functions," *SAO Special Report*, vol. 382, 1979.

[3] H. Wang, C. Chen, Z. Zeng, S. Shao, and H. Haas, "Bidirectional retroreflective optical ISAC using time division duplexing and clipped OFDM," *IEEE Photonics Technology Letters*, vol. 37, no. 10, 2025.

[4] X. Xiong, H. Wang, S. Shao, and C. Chen, "Hybrid MRR-Assisted Long-Range SDMA for RO-ISAC Systems in Industry IoT Applications," *IEEE/OPTICA Journal of Lightwave Technology*, 2025.