Toward Massive-MIMO mmWave ISAC: An Open Framework for Scalable RF Sensing and Communications

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Abstract

Next-generation wireless networks are expected to support sensing and communication through shared spectrum, hardware, and waveforms. However, most existing integrated sensing and communications (ISAC) demonstrations are built around a specific waveform, frequency band, or dedicated sensing platform, leaving a gap between standards compliant wireless infrastructure and practical sensing implementations across multiple frequency ranges. In this work, we present an open software-defined radio (SDR)-based experimental pathway for ISAC using existing fifth-generation New Radio (5G NR) infrastructure from sub-6 GHz to Frequency Range 2 (FR2) millimeter-wave (mmWave) operation.

We introduce PolyBase, which reuses a 3GPP-compliant 5G NR downlink waveform for long-range sensing using an OpenAirInterface (OAI) gNB and USRP X410. We also introduce an FR2 platform that extends the concept of 5G-infrastructure-enabled mmWave sensing to 27.5 GHz using USRP and Sivers mmWave frontends, with channel state information reference signal (CSI-RS)-based channel measurements and over-the-air (OTA) sensing experiments. Experimental results demonstrate simultaneous detection of multiple outdoor targets with PolyBase and detection of a static human target in a controlled indoor FR2 environment after clutter subtraction. The resulting framework provides a practical roadmap for extending open, standards-based wireless infrastructure toward real-time, wideband, and next-generation ISAC systems.

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1. Introduction

Imagine a next-generation wireless system in which a traditional communication radio frequency (RF) link not only serves as a secondary sensing layer, but also performs competitively with dedicated sensing systems without relying on a legacy or reference radar.

In such a system, there would be no practical need to separate communication links from sensing nodes. Any radio could communicate with nearby radios while also reliably sensing targets, adapting its waveform to the surrounding environment, and estimating health information, such as vital signs, when the target is a person. In defense applications, the same system could detect swarms of unmanned aerial vehicles (UAVs) while maintaining secure communication links with unmanned ground vehicles (UGVs) as showed in Fig. 1. From robotics and healthcare to defense and emergency triage, such a capability would be valuable wherever fast and accurate sensing, together with secure data links, is required.

A substantial body of work has explored ISAC systems, waveform co-design, orthogonal frequency-division multiplexing (OFDM)-based sensing, and over-the-air (OTA) validation. More recently, OpenISAC introduced an open-source platform for real-time monostatic and bistatic delay and Doppler sensing using OFDM waveforms (Zhou et al., 2026). These efforts demonstrate the value of open SDR experimentation, but they mainly focus on configurable OFDM waveforms rather than a roadmap spanning several standards-compliant wireless platforms (Mehlhose et al., 2025). In this paper, we present a straightforward path for using existing 5G NR infrastructure for sensing across multiple frequency ranges, including FR1 and FR2. We demonstrate this path using an SDR-based testbed with hardware-in-the-loop (HWIL) and OTA operation. The goal is not to invent a new waveform for ISAC, but to show how existing operational 5G NR infrastructure can support sensing at sub-6 GHz and mmWave frequencies. The key contributions of this paper are as follows:

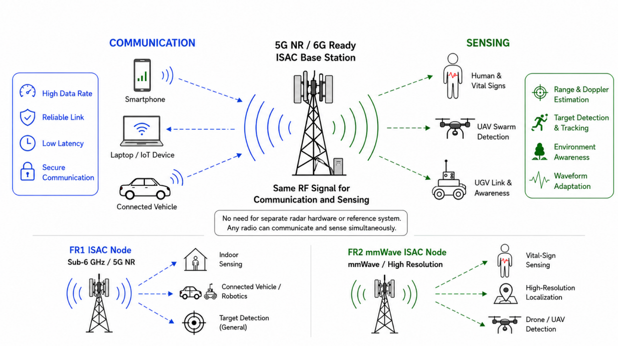

Figure 1. Conceptual illustration of a unified ISAC network in which a shared 5G NR waveform supports both communication and sensing. The FR1 node enables sub-6 GHz applications such as indoor sensing, connected vehicles, robotics, and general target detection, while the FR2 mmWave node supports vital-sign sensing, high-resolution localization, and UAV detection.

1.0.1. Key Contributions

- **PolyBase:** We present PolyBase, an open SDR-based ISAC framework that provides a practical implementation path for next-generation ISAC systems.
- **mmWave ISAC:** We demonstrate a practical experimental pathway toward massive-multiple-input multiple-output (MIMO) mmWave ISAC using existing 5G NR infrastructure.
- **OTA Validation:** We validate both systems using SDR-based HWIL and OTA testbeds. The captured in-phase and quadrature (I/Q) samples are processed using a real-time radar digital signal processing (DSP) pipeline in both indoor and outdoor environments.

2. Related Work

ISAC has emerged as a central capability for Future-G and beyond-5G NR systems, where wireless infrastructure is expected to support both data transmission and environmental perception (Liu et al., 2022; 3GPP, 2025). Prior work by Doly et al. used GNU Radio and Universal Software Radio Peripheral (USRP) B210 devices to demonstrate a hardware-in-the-loop OTA ISAC waveform codesign testbed (Doly et al., 2023a). The system demonstrated a path toward implementing the mathematically formulated ISAC waveform co-design problem presented in (Doly et al., 2022; 2023b) on the GNU Radio platform. In parallel, an open-source SDR-based platform that uses cellular signals for device-free sensing in real-world environments has also been explored (OpenAirInterface Software Alliance, 2025; Otani et al., 2025).

More recently, OpenISAC (Zhou et al., 2026) introduced an open-source platform for real-time monostatic and bistatic OFDM delay and Doppler sensing (Zhou et al., 2026). These efforts show the value of open software-defined radios (SDRs) experimentation, although they mainly focus on a configurable OFDM waveform rather than a roadmap across several standards-compliant wireless platforms (Mehlhose et al., 2025).

The openwifi (Jiao et al., 2020) project provides an open-source IEEE 802.11 implementation that allows direct access to and modification of the physical layer (PHY) and medium access control (MAC) layers (Jiao et al., 2020). Experimental studies have demonstrated sensing with sub-6 GHz 5G NR waveforms using OAI and SDRs (Carbonara et al., 2025). Full-stack downlink testbeds have also compared communication and control signals for multi-target detection (Carbonara et al., 2026). Moving from FR1 to FR2 provides access to wider communication bandwidths and enables finer sensing resolution at mmWave frequencies. Experimental work has demonstrated environmental sensing and mapping at 28 GHz using a 400 MHz 5G NR waveform (Baquero Barneto et al., 2022).

3. Open SDR-Based System Architecture

3.1. PolyBase: OAI 5G NR-Based Sensing

PolyBase is a UE-free monostatic OFDM radar platform that reuses a 3GPP-compliant 5G New Radio (NR) downlink waveform for environmental sensing without requiring active user equipment. The platform is motivated by the established joint radar–communication concept, in which known OFDM symbols can serve as sensing references for estimating propagation delay and Doppler (Sturm et al., 2009). Previous work has also demonstrated the suitability of OpenAirInterface (OAI) for experimental 5G NR positioning and physical-layer data acquisition (Mundlamuri et al., 2025). Based on these principles, the experimental PolyBase gNB is implemented using OAI and a single USRP X410, as illustrated in Fig. 2. The transmitted waveform and received echoes are processed to form a range–Doppler representation for target detection and the estimation of range and radial velocity.

3.2. 5G NR-Based FR2 ISAC System Architecture

Although our original OTA experiments are based on OpenAirInterface (OAI), we also include a GNU Radio implementation of the proposed 5G NR FR2 OFDM-based sensing testbed, shown in Fig. 2 and 3, to provide a more accessible reference implementation for new researchers.

The flowgraph generates an NR-like OFDM waveform, routes the signal through the USRP transmit chain, and captures the reflected signal through the USRP receive path for real-time visualization and sensing analysis.

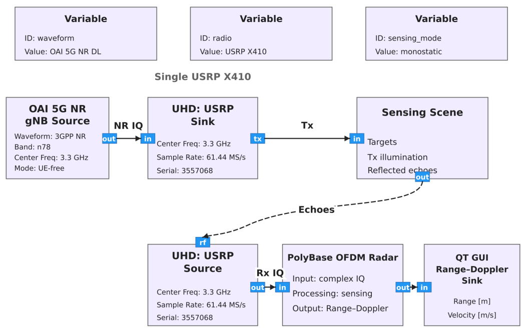

Figure 2. GNU Radio flowgraph for PolyBase, a 3GPP-compliant, UE-free 5G NR FR1 radar.

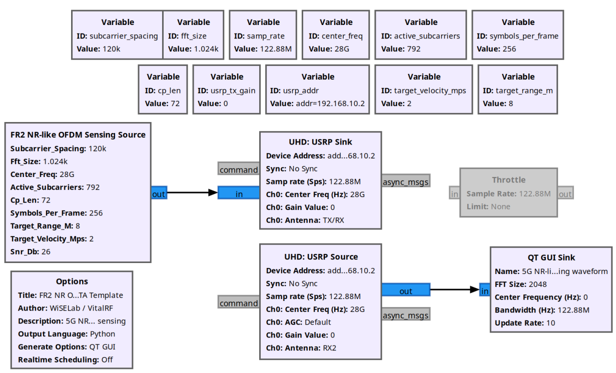

Figure 3. GNU Radio flowgraph for the 5G NR FR2 OFDM-based sensing testbed using USRP-based OTA transmit and receive paths.

4. Signal Processing and Algorithms

Before extracting CSI-RS-based channel measurements (MathWorks), the receiver must first acquire and synchronize with the 5G NR downlink. In the OAI Frequency Range 2 (FR2) testbed, this begins with detection of the synchronization signal block (SSB), which contains the primary synchronization signal (PSS), secondary synchronization signal (SSS), and physical broadcast channel (PBCH).

Fig. 4 shows the SSB acquisition result for the 27.53 GHz OTA link. The received samples are correlated with the known SSB sequence, producing a dominant matched-filter peak near the expected timing location. The detected peak is approximately 46 dB above the noise floor, confirming successful SSB detection and synchronization of the FR2 downlink. Following this acquisition step, the receiver can identify the CSI-RS resource elements and use them for channel measurements.

For subcarrier k and orthogonal frequency-division multiplexing (OFDM) symbol m, the received frequency-

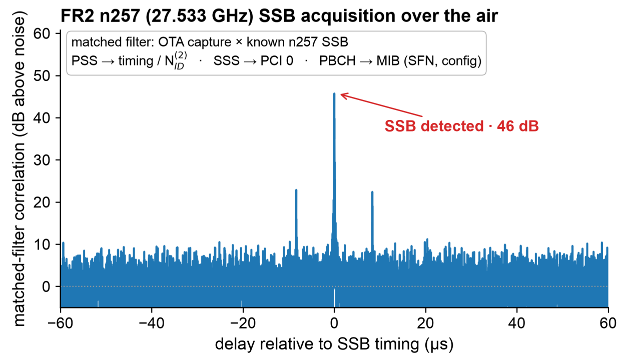

Figure 4. OAI FR2 downlink acquisition at 27.53 GHz. Matched-filter correlation with the known SSB produces a dominant detection peak approximately 46 dB above the noise floor, confirming successful synchronization and PBCH acquisition prior to CSI-RS-based channel measurements.

domain sample can be expressed as

$$Y[k,m] = H[k,m]X[k,m] + n[k,m], \qquad (1)$$

where $X[k,m]$ is the transmitted symbol, $H[k,m]$ represents the time-varying wireless channel, and $n[k,m]$ denotes noise and residual interference. The channel can be estimated as:

$$\widehat{H}[k,m] = \frac{Y[k,m]}{X[k,m]}. \qquad (2)$$

5. Experimental Results

5.1. PolyBase: OAI 5G NR Multi-Target Sensing

To evaluate PolyBase's ability to detect long-range multiple targets simultaneously, an outdoor experiment was conducted with two pedestrians and a vehicle located at different ranges and exhibiting different motion states. As shown in Fig. 5, the photograph in the left panel presents the experimental scene, including one pedestrian walking toward PolyBase, another pedestrian running away from the system, and a vehicle preparing to move. The corresponding range–Doppler map in the right panel shows distinct target signatures associated with these objects. These results demonstrate PolyBase's capability to distinguish multiple targets within the same sensing interval based on their estimated range and radial velocity.

5.2. 5G NR mmWave ISAC System

5.2.1. Indoor Test Setup

Figs. 6 and 7 show the indoor FR2 OTA test setup used for ISAC sensing. The testbed consists of one Sivers TX, one Sivers RX, a USRP X410, and an OctoClock providing 10 MHz/PPS synchronization. The Sivers TX transmits a 27.5 GHz FR2 signal toward the sensing region, while

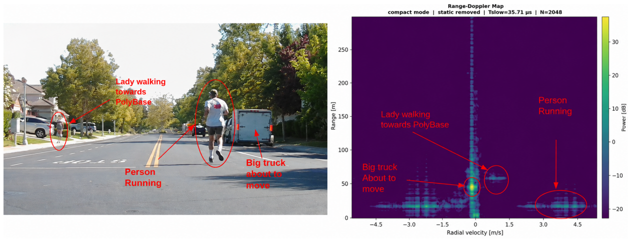

Figure 5. Multi-target detection using PolyBase with a live 3GPP-compliant 5G NR downlink waveform. The experimental scene and its corresponding range–Doppler map illustrate the simultaneous detection of multiple targets at different ranges and radial velocities.

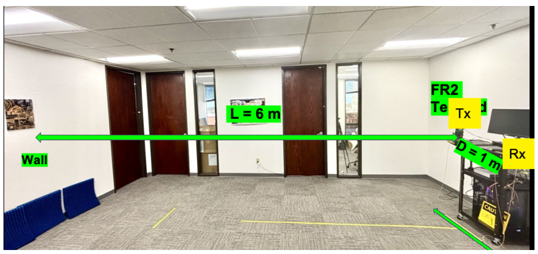

Figure 6. Indoor FR2 OTA empty-room baseline setup using one Sivers TX, one Sivers RX, the USRP X410, and OctoClock synchronization.

the Sivers RX captures the reflected signal for downstream sensing processing.

The experiment was conducted over a controlled 6 m indoor test lane. An empty-room measurement was first collected to characterize the background response from the wall, floor, furniture, and other static objects in the environment. A static human target was then introduced at approximately 3 m while keeping the RF configuration and TX/RX geometry unchanged.

5.2.2. mmWave Sensing Performance

The OTA results corresponding to the empty-room and static-target configurations in Figs. 6 and 7, respectively, are compared in Fig. 8. In the empty-room measurement, strong near-zero-Doppler responses are observed from static environmental objects, including the wall and surrounding furniture.

After introducing the static human target at approximately 3 m and applying clutter subtraction, a distinct target response appears around the expected range in Fig. 8(b). Weaker residual components are also visible and are attributed to remaining static clutter and indoor multipath. Keeping the two range-Doppler maps together provides a direct comparison between the baseline environmental response and the human-target response under the same RF configuration.

Figure 7. Indoor FR2 OTA sensing setup after introducing a static human target at approximately 3 m.

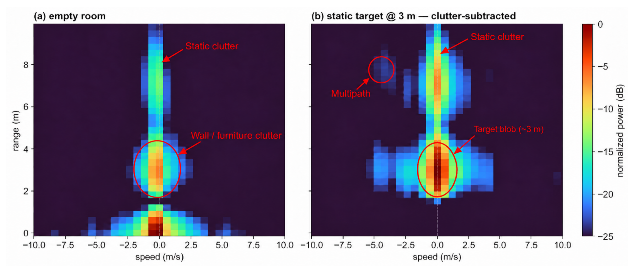

Figure 8. Range–Doppler comparison for the indoor FR2 sensing experiment. (a) Empty-room baseline showing static reflections from the wall, furniture, and surrounding indoor environment. (b) Clutter-subtracted response after introducing a static human target at approximately 3 m.

6. Conclusion

This paper presented two practical open SDR-based paths toward next-generation ISAC: PolyBase for sub-6 GHz 5G NR sensing and an FR2 mmWave platform for higher-resolution sensing. Both systems were validated using HWIL and OTA experiments with real-time radar DSP processing. The results demonstrate multi-target sensing in outdoor scenarios and static human-target detection in an indoor FR2 environment. The next-step is building a scalable, standards-based ISAC framework that enables spectrum convergence between communication and sensing across FR1, FR2, and future wireless systems.

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