PULSE: Portable Unit Life-Sign Extractor

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***Abstract*— This paper presents PULSE, a portable, low-cost radar sensing node developed to enable rapid and reliable human detection in obstructed and hazardous environments, with a primary focus on search-and-rescue operations. PULSE integrates a 24 GHz Frequency Modulated Continuous Wave (FMCW) millimeter-wave radar module with a Raspberry Pi 4, which handles signal acquisition, basic processing, and wireless communication. Collected data are transmitted via Bluetooth Low Energy (BLE) to a custom-built Android application that provides real-time visualization and user feedback. Unlike conventional visual or audio-based systems, the radar-based approach enables operation in smoke, darkness, dust, and partially obstructed environments. Experimental evaluation demonstrates consistent human detection across a range of 0.5 m to 6 m in free-space conditions, as well as reliable detection through light obstacles such as thin walls and debris. The prototype maintains stable wireless transmission and low-latency visualization suitable for field deployment scenarios. The results highlight the feasibility of low-cost radar platforms for scalable disaster-response applications, offering a compact and cost-effective alternative to other emergency life-detection systems.**

***Keywords*—disaster response technology, mmWave radar, sign of human life detection, through-obstacle sensing, embedded radar detection systems**

I. Introduction

In large-scale disaster events such as building collapses, earthquakes, and structural fires, the rapid localization of trapped victims is critical, as survival probability decreases sharply within the first 24–72 hours following entrapment [1]. Victims are often buried beneath dense debris or trapped behind reinforced structural barriers, where conventional search methods become inefficient or unreliable. Traditional approaches, including manual probing, acoustic listening devices, thermal imaging, and trained canine units, require substantial time, specialized personnel, and favorable environmental conditions to operate effectively [2]. Their performance degrades significantly in the presence of heavy rubble, high ambient noise, dust, wind, smoke, or unstable structures that obstruct direct line-of-sight or attenuate acoustic signals [3].

Radar-based through-wall and life-sign detection systems have emerged as promising alternatives due to their ability to operate independently of lighting conditions and partial visual obstruction [4]. However, many existing systems are expensive, bulky, and designed for specialized military or high-end industrial applications, limiting their scalability and accessibility for smaller emergency response agencies and humanitarian deployments [4][5]. These constraints highlight the need for compact, low-cost, and rapidly deployable radar sensing platforms capable of reliable human presence detection in obstructed environments.

While existing methodologies like acoustic listening, thermal imaging, and canine units are effective, they possess domain-specific constraints: acoustic systems are susceptible to ambient noise, thermal imaging requires clear line-of-sight, and canine units are resource-intensive. The proposed mmWave radar node addresses these limitations by leveraging the penetrating capability of radio-frequency sensing, which remains effective through non-metallic debris and obscurant-filled air. Critically, the system's novelty lies in the deliberate integration of low-cost, modular components—enabling rapid, scalable field deployment that is particularly suited for humanitarian response organizations operating under resource constraints.

II. Radar System Architecture

The PULSE radar node is designed as a compact, modular sensing platform capable of supporting multiple front-end radar sensors. The current implementation integrates a 24 GHz millimeter-wave radar module (RD-03D) with a Raspberry Pi 4 Model B, which provides embedded processing, power management, and wireless communication within a single deployable unit. All components are enclosed in a custom 3D-printed housing designed for ground-level placement in post-disaster, real-world emergency response situations.

Figure 1 illustrates the end-to-end architecture of the PULSE system. The radar module transmits detection messages over a UART serial interface to the Raspberry Pi, where measurements are parsed and formatted into compact detection packets. These packets are transmitted wirelessly via Bluetooth Low Energy (BLE) to a paired Android device for real-time visualization and user feedback. The system is powered by an external battery pack, enabling fully untethered and portable operation suitable for rapid deployment by a single responder.

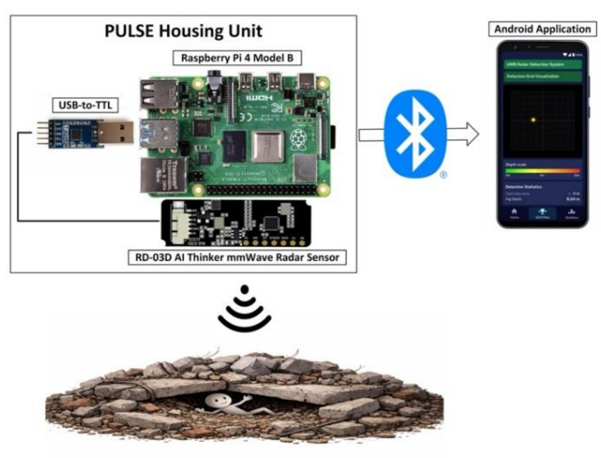

Figure 1. PULSE System Overview and Connectivity

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A. Frequency Modulated Continuous Wave

The system employs Frequency Modulated Continuous Wave (FMCW) radar for short-range human micro-motion detection [6]. In FMCW operation, a continuous waveform is transmitted with linearly increasing frequency over a defined sweep interval (chirp). A target reflection returns with a propagation delay proportional to its range. When the received signal is mixed with the transmitted chirp, a beat frequency f_b is produced that is directly related to target distance [6][7], denoted by R:

$$R = \frac{cf_b}{2S}$$

where c is the speed of light, and S is the chirp slope.
By collecting multiple chirps over time, phase variations between successive sweeps enable Doppler estimation, allowing detection of motion and micro-movements

B. MmWave Radar Front End (RD-03D)

The radar front end used in this implementation is the Ai-Thinker RD-03D 24 GHz mmWave radar module [8], which operates within the ISM band and incorporates integrated FMCW signal generation and on-board processing. The module employs a single transmit and dual-receive antenna configuration and outputs processed target detection data over a standard UART interface [8]. Unlike raw radar platforms that provide in-phase and quadrature (I/Q) samples, the RD-03D performs internal range processing and motion classification [8].

This architecture significantly reduces computational load on the host processor and simplifies embedded system design. The module operates from a 5 V supply and is compact enough to be integrated within the 3D-printed enclosure alongside the computing and communication hardware.

C. Embedded Processing and BLE Link

The Raspberry Pi 4 Model B serves as the embedded host controller for the radar node. Its responsibilities include:

- Reading detections from the RD-03D via UART
- Parsing and validating detection outputs
- Formatting data into compact transmission packets
- Managing Bluetooth Low Energy communication

Parsed detection messages are transmitted to the Android application using Bluetooth Low Energy (BLE). BLE was selected due to its low power consumption, efficient handling of small periodic data packets, and compatibility with mobile devices [9]. This makes it well-suited for battery-powered, real-time sensing applications in field environments.

In our testing, the BLE link sustained high update rates with low latency. The Android application displayed the detections without any noticeable delay, supporting the concept of the project being used in real time.

III. Software Architecture

The PULSE software stack is structured into three functional layers: embedded data acquisition and parsing on the Raspberry Pi, Bluetooth Low Energy (BLE) communication using a custom GATT server, and a mobile Android application for real-time visualization.

A. Embedded Data Acquisition and Parsing

The Raspberry Pi 4 Model B functions as the embedded host controller, interfacing with the Ai-Thinker RD-03D mmWave radar module via a UART serial connection. Its responsibilities include frame acquisition, validation, filtering, and packet formatting for wireless transmission via Bluetooth Low Energy.

The RD-03D sensor communicates via UART at a baud rate of 256000 bps and with 8N1 configuration (8 data bits, no parity, 1 stop bit). A finite state machine is implemented on the Raspberry Pi to reliably parse the incoming byte stream, as shown below in Figure 2. The parsing process consists of the following stages:

1. **Header Detection:** Continuous scanning of the byte stream for valid frame header sequences.
2. **Length Extraction:** Determination of payload size based on header metadata.
3. **Frame Validation:** Verification of frame integrity using predefined footer bytes.
4. **Payload Parsing:** Extraction of target attributes, including range, motion state, and signal strength.

The parsing module maintains a circular buffer of the most recent 10 frames and applies simple temporal filtering (e.g., majority vote/persistence check) to reduce false positives caused by measurement noise and intermittent detection flicker.

Bytes	0-3	4-7	8-11	12-15	16-17	18	19
Data	X Position Float32, m	YPosition Float32, m	Depth Float32, m	Signal to Noise Ratio Float32, dB	Time uint16, ms	Object Type	Confidence

Figure 2. BLE detection packet format used for sensor data parsing

B. BLE Transmission

Wireless communication between the Raspberry Pi and the Android application is implemented using Bluetooth Low Energy (BLE). The system implements a custom GATT (Generic Attribute Profile) server using the Bleak Library for cross-platform functionality. A custom BLE Service was designed with the UUID Scheme shown in Table 1.

Table I. GATT Service Configuration

Element	UUID	Properties
Service	00001101-0000-1000-8000-00805F9B34FB	Primary
Radar Data	00002A01-0000-1000-8000-00805F9B34FB	Notify
Command	00002A02-0000-1000-8000-00805F9B34FB	Write

The Radar Data characteristic transmits 20-byte detection packets using the binary format specified in Figure 2. Data is encoded in little-endian byte order for compatibility with ARM processors on both the Pi and the Android devices.

The GATT server performs automatic advertising upon booting the Pi. The Android client filters scan results to devices that are advertising the PULSE service UUID, allowing the devices to establish a connection. The scan period is configured for 10 seconds, after which scanning stops if no connection is established.

C. *Android Application*

The Android application provides the user with an interface to visualize radar detections in an intuitive display. The application was developed in Kotlin using Android Studio, as follows:

1) Application Architecture: The application follows a Model-View-ViewModel (MVVM) architecture. The Model layer (BleService class) manages BLE scanning, connection, and disconnection while parsing the incoming 20-byte data packets. The view later renders the coordinate radar visualization, displaying connection status and detections in real time.
2) Data Parsing Implementation: The ParseRadarData function extracts detection information from the 20-byte BLE data packets. A ByteBuffer collects X, Y positions, depth, and SNR at their respective offsets and timestamps.
3) Visualization Model: The radar display shows detected targets on a coordinate system centered on the sensor position. The visualizations include color-coded target indicators indicating position and depth at a quick glance.
4) User Interface and Design: The application prioritizes understanding at a glance, which is needed in emergency response situations. Design considerations include a high contrast color scheme for outdoor visibility and large buttons to use with gloves.

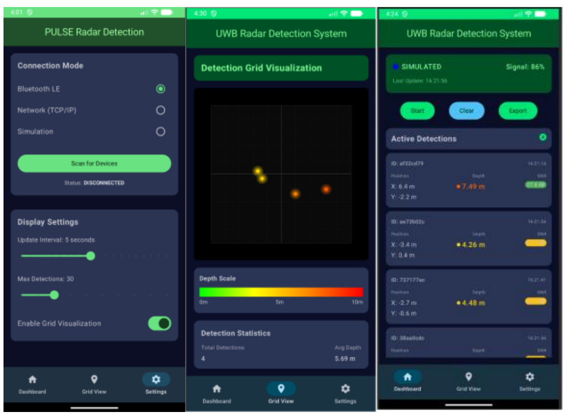

Figure 4. Settings, Visualization, and Dashboard screens on the app

IV. Experimental Setup

A. Hardware Configurations

The experimental prototype consisted of a compact, battery-powered radar sensing node integrating a 24 GHz mmWave radar front-end, embedded processing, and a mobile visualization interface.

The radar front-end was the Ai-Thinker RD-03D FMCW mmWave module operating in the 24 GHz ISM band. The module was connected to a Raspberry Pi 4 Model B via UART (256000 bps, 8N1 configuration). The Raspberry Pi executed Python-based frame parsing and implemented a Bluetooth Low Energy (BLE) GATT server for wireless transmission to the Android application. The key radar specifications are:

- Operating frequency: 24 GHz
- Maximum detection range: 6 m
- Range resolution: 0.75 m
- Ranging accuracy: ±0.15 m
- Field of view: ±60° (azimuth)
- Power consumption: 92 mA @ 5 V

All components were housed in a custom 3D-printed enclosure designed for ground-level deployment. The enclosure provided approximately 20 cm of elevation to reduce ground clutter reflections and included access for charging and power control.

B. Test Environment

Experiments were conducted in a controlled indoor laboratory environment consisting of concrete flooring, drywall partitions, and a long hallway used for range validation. The radar node was placed at ground level and oriented toward the test region. Two primary test categories were evaluated: free-space detection and through-obstacle detection.

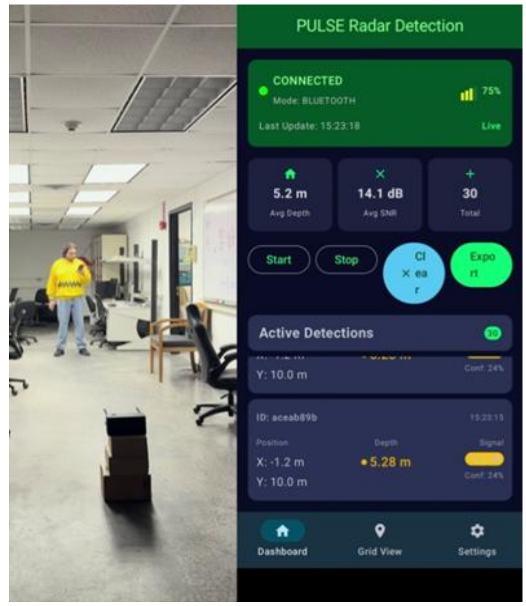

Figure 5. Free-space detection result with the target positioned at 5m from the radar node

C. Obstacle test configurations

Obstacles were positioned between the radar and the target with a gap of roughly 2 m. The control test was on a wooden table, testing detections with and without a human target. The objects used are presented in Table II.

Table II. Object type and thickness

Material	Thickness
Cardboard	3mm
Foam Board	7.5 mm
Wooden Table	50 mm
Styrofoam	25 mm
Plastic Sheet	2 mm
Folding Chair	variable
Wall Reinforcements	1 m
Stainless Steel	0.5 mm

Low-density dielectric materials were selected to represent light debris and indoor obstruction scenarios. The system maintained stable detections through cardboard, foam, plastic, and wood. Performance degraded significantly when a stainless steel sheet was introduced, consistent with conductive shielding effects at mmWave frequencies.

Figure 6 shows the test conducted to evaluate the system's ability to detect a human subject through common indoor materials, specifically a wooden table surface and a layer of Styrofoam. The dashboard interface demonstrates that the radar module successfully identified the subject positioned directly beneath the table, reporting a depth of approximately 0.31 m and maintaining a consistent signal-to-noise ratio across repeated measurements. These results indicate that the sensing pipeline can penetrate low-density dielectric materials, such as wood and Styrofoam.

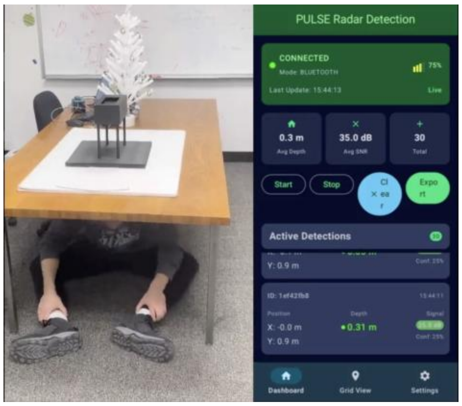

Figure 6. Testing with a human target through obstacles

Battery endurance testing demonstrated approximately 3.5–4 hours of continuous operation under active radar sensing and BLE transmission using a single 10 Ah battery pack. BLE connectivity testing also evaluated the device discovery time, connection latency, packet reliability, and reconnection performance. The Android device discovered the PULSE node within 30 seconds of Raspberry Pi startup. Detection packets (20 bytes at 10 Hz) were transmitted without observable packet loss. When the mobile device moved outside the BLE range, reconnection occurred automatically within 5–8 seconds upon return.

V. Results

A. Free-Space Detection

We tested PULSE in a controlled indoor environment. With the RD-03D module active, we could detect a standing or walking human from 0.5 m out to about 6 m range. In free space, the module consistently tracked a person walking back and forth, displaying their range and angle on the app grid. When the person sat still, we still saw a stable detection (chest micro-motions from breathing). Introducing non-metallic obstacles (cardboard or plastic) between the radar and the person had little effect: the system still reported the target, indicating it can sense through light obstructions. The 2.4 GHz BLE link and Android UI performed as intended: once paired, the phone display updated automatically with each new detection frame.

Overall range accuracy was ±0.2 m, limited by the module's 0.16 m resolution. Angular resolution was coarser (discrete bins from −9 to +9 corresponding to left/right). We observed no false detections in empty scans. Battery tests showed ~3.5 hours of continuous operation on a single 10 Ah pack (running the Pi, radar, and peripherals). The Android app's user interface was clear: users could scan an area in front of the sensor and immediately see any detected humans marked on the map. This completes a full demonstration of the system's intended functionality: a portable radar node with live smartphone telemetry.

B. Through-Obstacle Detection

Light obstacles such as thin cardboard or thin plastic showed minimal attenuation, and detections remained stable. This demonstrates the feasibility for short-range, small rubble scenarios. The system's performance suffered heavily when attempting to penetrate through thicker obstacles or through large metallic objects.

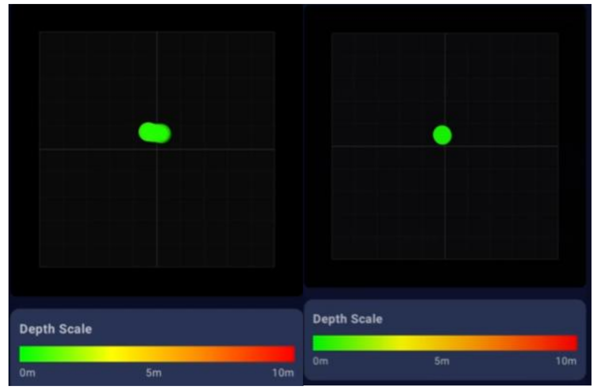

Figure 7. Through obstacles (left) and a metal sheet (right). Result with Target at 0.3m away (left) and No Target (right)

C. Environmental Effects

Environmental conditions significantly influenced detection reliability. Metallic objects near the radar introduced multipath reflections and occasional spurious detections. In one test, a moving fan produced intermittent false returns due to periodic motion within the radar's field of view. Despite these environmental sensitivities, stable operation was maintained in typical indoor environments with drywall partitions and furniture. The elevated enclosure design (~20 cm above ground) reduced ground-clutter reflections and improved detection consistency.

While the prototype demonstrated reliable detection of human subjects, environmental factors such as rotating fans produced intermittent false returns due to periodic motion within the radar's field of view. Additionally, metallic surfaces can introduce multipath reflections that manifest as spurious detections. To mitigate these effects in future iterations, the embedded parsing logic could incorporate signal-strength thresholding and more robust temporal filtering—such as requiring detection persistence across multiple consecutive frames—to better distinguish transient environmental noise from the sustained micro-motion signatures characteristic of living subjects.

D. Real-Time BLE Visualization

BLE communication remained stable across all test scenarios. Device discovery occurred within 30 seconds of Raspberry Pi startup. Once connected, the Android application maintained a consistent 10 Hz update rate without observable packet loss. Connection resilience was tested by moving the mobile device outside the BLE range. Automatic reconnection occurred within 5–8 seconds upon return, and connection state changes were accurately reflected in the user interface. The visualization interface provided immediate situational awareness, allowing users to identify the target position without additional calibration or setup.

VI. Discussion

The experimental results demonstrate that a low-cost mmWave radar module can support short-range human presence detection in obstructed environments [6]. The RD-03D sensor reliably detected subjects within 1–6 m and maintained stable performance through common non-metallic materials such as drywall, wood, foam, and plastic. This through-obstruction capability is critical for search-and-rescue scenarios where visual access is limited.

However, performance was sensitive to environmental conditions. Metallic surfaces introduced multipath reflections and degraded detection reliability, and the module's limited range and coarse angular resolution restrict precision compared to higher-end radar systems. Additionally, the sensor reports presence and approximate position only, without access to raw I/Q data for detailed vital-sign extraction. This limitation is central to the current hardware configuration; because the module's firmware exposes only processed detection outputs via UART, the implementation of advanced vital-sign extraction algorithms—such as those resolving precise respiration or heartbeat—is precluded. Furthermore, while the system excels through dielectric materials, mmWave propagation is strongly attenuated by metallic shielding, which may reduce signal return in metal-dense collapse scenarios. Finally, the angular resolution of this single-module configuration is coarser than high-end industrial phased-array systems, limiting the ability to precisely localize multiple simultaneous targets.

Despite these limitations, the prototype demonstrated reliable field operation, stable wireless connectivity, and practical battery endurance (~4 hours). The results confirm the feasibility of a compact, cost-effective radar node for rapid human localization in short-range emergency response applications.

VII. Conclusion

PULSE demonstrated a portable, embedded radar node capable of detecting human presence through obstructions [11][12]. The integration of the RD-03D module enabled full end-to-end operation, including sensor data acquisition, BLE transmission, and visualization on a mobile device. The results confirm the viability of a low-cost system for short-range human localization and serve as a foundation for future research [11][12].

The platform developed in this project is scalable and can be extended in several key directions to improve overall system performance, robustness, and usability in real-world rescue scenarios. One important next step is incorporating the ADALM-Pluto SDR [13] as the primary transmitter and receiver, enabling full FMCW chirp generation, signal mixing, filtering, and Doppler FFT processing. With these advanced signal processing capabilities, the SDR-based system is expected to significantly outperform the current mmWave sensor in terms of flexibility, resolution, and configurability [10][13]. Operating both systems in parallel would also allow for direct performance comparisons and a clearer evaluation of design tradeoffs.

Beyond improvements to the radar front-end, the current single-sensor architecture could be enhanced through multi-sensor fusion [10][12]. Integrating multiple radar sensors operating at different frequency bands and combining their output using rule-based or data-driven logic could improve detection reliability, reduce false positives, and increase robustness in cluttered environments. This approach would be especially beneficial in complex disaster scenes with varied materials and obstructions.

System packaging improvements are also recommended, particularly the development of a more robust and waterproof enclosure suitable for harsh rescue environments. Adding electromagnetic interference shielding could further improve signal integrity. Finally, the Android application could be expanded beyond simple visualization by incorporating data smoothing, multi-sample processing, cloud-based storage, and data export features for long-term analysis and post-mission review.

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