Multi-Functional Automotive Antenna System for Accident Prevention and Detection

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I. Introduction

Modern intelligent transportation systems are increasingly limited by conventional line-of-sight sensors, such as radar and LIDAR, which struggle in complex environments and fail to consider the driver's physiological state.

To address these gaps, this proposal presents a low-power, multi-modular architecture integrating high-precision GNSS, V2V communication, and real-time biometric monitoring for a holistic approach to hazard prediction. The architecture combines human factors with environmental sensing via custom RF components, including a superdirective wideband RHCP GNSS antenna and a planar monopole antenna to enable physiological and kinematic data exchange. Using low-cost components within compliant ISM bands, the research demonstrates critical applications in accident prevention, congestion mapping, and automated emergency response.

II. Proposed System Architecture

The system centers on a Raspberry Pi 5 microcomputer managing all subsystem data. The architecture (Fig. 1) illustrates interconnections between the GNSS module, cellular module, V2V communication module, and wearable biosensor. Environmental sensors (accelerometer, thermometer, smoke detector) provide supplementary safety data, while speakers and screen alerts inform the driver before or during emergencies.

A. Cellular and GNSS Module

The cellular subsystem uses a SIM7600G-H HAT and a commercial LTE antenna (WaveShare 4G High Gain supporting 4G/3G/2G/LPWA) as a communication gateway between accident-prediction logic and emergency authorities. Connected via USB to a Raspberry Pi 5, the module's integrated

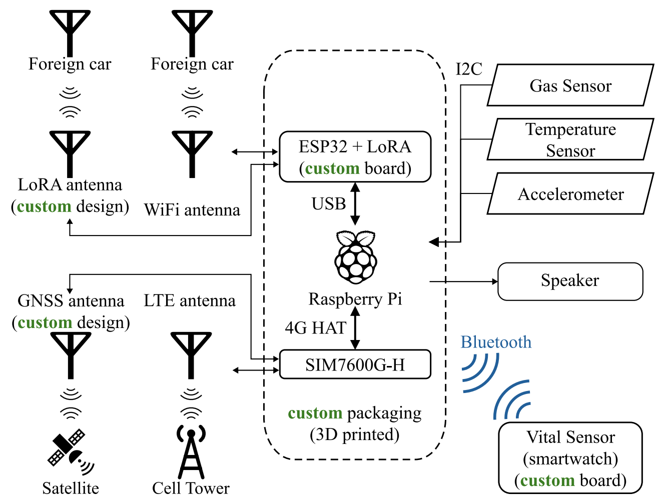

Fig. 1. The proposed system architecture illustrating module interconnections.

GNSS subsystem continuously tracks vehicle coordinates using a custom antenna. This setup enables instant automated emergency calls or SMS alerts with precise location data when an accident is detected.

B. GNSS custom-designed antenna

The antenna was designed using MATLAB *Antenna Toolbox*. Its geometry and dimensions are shown in Fig. 2a. The array consists of two elements spaced 0.15λ apart. Element "1" (bottom) is driven, while element "2" (top) is parasitic with a reactive load. This technique achieves low-complexity superdirectivity [1] while minimizing ohmic losses.

The geometry of each element consists of two L-shaped arms, with one arm defined by the dimensions l_j^i, w_j^i where $i, j = 1, 2$, where i denotes the antenna array element, and the other arm being a $180°$ rotation of the first. The distance between the arms is $\lambda/200$. Ports are vertically placed between these two arms. To model the ports, we use the *Delta-gap Probe Feed Model* provided by the MATLAB Antenna Toolbox. As mentioned, one element is fed with a voltage of 1 V (RMS) at 1.575 GHz,

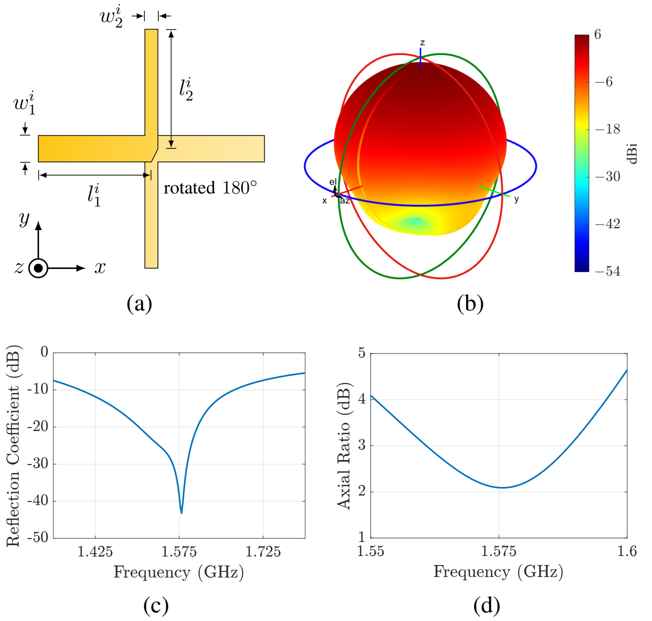

Fig. 2. Custom GNSS antenna geometry (a), RHCP realized gain (b), return loss (c), and AR (d) of the proposed antenna.

while the other is not excited but loaded with a reactive load of X_l Ω. The degrees of freedom are the dimensions l_j^i, w_j^i for both elements and the load X_l, resulting in 9 degrees of freedom. Because of the relatively large number of degrees of freedom, a genetic algorithm is used via the *Global Optimization Toolbox*. The fitness function is the RHCP realized gain (RG_{RHCP}) at 1.575 GHz in the z-direction (Fig. 2a). Mathematically, the optimization problem is defined as:

$$\max_{l_j^i, w_j^i, X} RG_{\text{RHCP}} \quad \text{s.t.} \begin{cases} l_j^i \in [0.3, 0.6]\lambda \\ w_j^i \in [0.005, 0.05]\lambda \\ |X| \leq 5000 \end{cases} \qquad (1)$$

The optimum dimensions are tabulated in Table I and the resulting maximum RHCP realized gain is 6 dBi (Fig. 2b). The return loss at 50 Ω is depicted in Fig. 2c: the antenna operates from $1.39 - 1.67$ GHz, resulting in a fractional bandwidth (FBW) of 18.3%. The axial ratio (AR) bandwidth, however, spans $1.56 - 1.59$ GHz (Fig. 2d), resulting in a 3-dB AR FBW of 1.9%.

C. Custom PCB designs for V2V, biosensor and power management

The V2V subsystem uses a custom PCB integrating an ESP32-S3 microcontroller and a LoRa module (Wio-E5-LE). The ESP32-S3 offers a 240 MHz clock with DSP accelerator and low power consumption, enabling the ESP-NOW protocol for real-time V2V data exchange. The LoRa module provides long-range, high-latency packet transceivers while communicating with the MPU. The ESP32 features a 5dBi gain off-the-shelf antenna, while the LoRa module uses a custom one; both are omnidirectional for maximum coverage.

TABLE I
OPTIMAL PARAMETERS FOR THE GNSS ANTENNA

El.	l_1^i	l_2^i	w_1^i	w_2^i	X_l
1	0.5069	0.4738	0.0428	0.0053	n.a.
2	0.4516	0.4278	0.0247	0.0499	-13.2

Note: Dimensions normalized to λ; reactance in Ω.

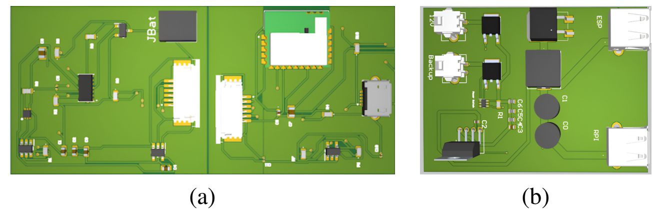

Fig. 3. Custom designs for (a) Biosensor-Smartwatch and (b) PMS.

The proposed system includes a custom wrist-wearable BT device/board featuring an STMicroelectronics BlueNRG-M0L microcontroller for Bluetooth Low Energy (BLE) for continuous, low-power data transmission. Heart rate is measured via an I^2C-connected MAX30102 Photoplethysmography (PPG) sensor, integrating red and infrared photodetectors for accurate, low-noise monitoring. The modular two-section PCB is linked by a 6-pin flexible flat cable and powered by a 3.8 V single-cell Li-Po battery with on-board charging, overcharge, and overdraw protection. Processed data is wirelessly transmitted via BLE to a Raspberry Pi receiver. Both the V2V system and Raspberry Pi feature a custom power management system (PMS) supporting a constant 12 V source and a backup battery with minimal voltage drop.

D. V2V Communication mechanism

1) ESP-NOW Protocol for Short-Range V2V: The V2V communication system utilizes ESP-NOW to transmit data within the IEEE 802.11 Action Frame's Vendor Specific Content field. GNSS measurements, including Latitude, Longitude, Speed

Over Ground, Heading, and Timestamps, are first converted into the Cartesian UTM system to provide a linear framework for relative positioning. To eliminate GPS jitter, an Unscented Kalman Filter processes these coordinates into a calibrated state estimate vector $\mathbf{x} = [X, V_x, Y, V_y]^T$. The UKF is preferred over the standard EKF because it avoids the linearization of non-linear vehicle dynamics.This core data is encoded into the VSC Body field of the protocol. Finally the packet includes additional fields such as a unique Vehicle ID, health status, crash indicator, and a CRC checksum to ensure data validation. The prediction is quantified by calculating the ratio of relative distance to relative velocity, termed the Time-to-Collision (TTC):

$$\mathrm{TTC} = -\frac{\vec{D} \cdot \vec{V}}{\left|\vec{V}\right|^2}, \tag{2}$$

where $\vec{D} = [\Delta X, \Delta Y]^T$ i and $\vec{V} = [\Delta V_x, \Delta V_y]^T$. This formula utilizes the relative distance vector $\vec{D}$ and the relative velocity vector $\vec{V}$. Because the vectors are collinear in this specific projection, the calculation correctly accounts for complex closing movements while maintaining computational efficiency. This is a crucial vector approach that correctly accounts for complex scenarios like diagonal or parallel closing movements [2].

2) Accident Detection: To minimize false positives, both location and acceleration data must be used for crash detection following an established method [3]. Additionally, temperature, atmospheric composition, and biometric data improve assessment of the emergency's urgency. If readings pass specific checks, the device notifies authorities and triggers a local alarm.

3) Congestion Mapping: Leveraging the ESP-NOW protocol's close-range efficiency, the proposed system performs decentralized congestion analysis through vehicular ad hoc networks (VANETs) using standard techniques [4]. Specifically, the device records its position A_{id} and congestion parameter (based on driving speed) and broadcasts a signal to nearby listeners, spreading the information peer-to-peer using a gossip protocol. Additionally, we propose a privacy improvement by broadcasting selective congestion incidents to achieve an equal spread around the user, thus obfuscating the path followed. This requires an allowed privacy radius parameter R such that $\overline{A_{id}} \leq R$.

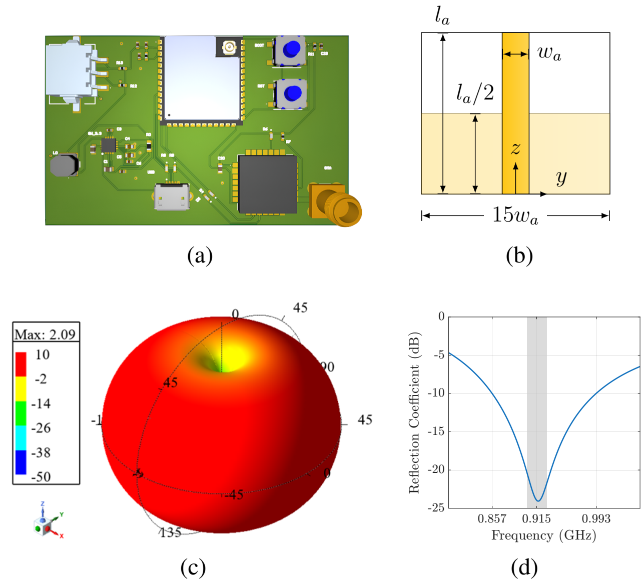

Fig. 4. Custom ESP-LoRa board design (a), proposed LoRa antenna design (b), simulated gain (c), and antenna reflection coefficient (d).

4) LoRa Long-Range Communication: To extend operational range in remote areas, the system integrates a LoRa (Long Range) module, a low-power wireless protocol capable of communication over several kilometers. When an emergency is triggered, the vehicle broadcasts a LoRa packet containing GPS coordinates, vehicle ID, biometric data, and a timestamp. If the impacted vehicle loses LTE signal, LoRa receivers can place the call on its behalf.

A planar monopole antenna for the LoRa band at 915 MHz was designed on Rogers 6010 substrate ($\epsilon_r = 10.2$, $\tan\delta = 0.0023$, thickness 1.9 mm). Simulations used *Ansys Electromagnetic Desktop*. It features length $l_a = 11.75$ cm and strip width $w_a = 1.96$ mm for 50 Ω impedance (Fig. 4b). At 915 MHz, it exhibits an omnidirectional radiation pattern, desirable for LoRa, with a maximum gain of 2.09 dBi (Fig. 4c) and 97.4% efficiency. It operates from $857-993$ MHz (Fig. 4d), yielding 14.7% FBW and covering the $902-928$ MHz LoRa range.

III. Demonstration

To maximize the system's educational value and reproducibility, all custom PCB schematics, Gerber files, and antenna simulation models (MATLAB and ANSYS HFSS) will be made publicly available via GitHub. This source-available design supports modular scalability and plug-and-play expandability, enabling seamless integration of additional modules and network-based extensions through internet connectivity. Consequently, the architecture can be adapted from dynamic kinematic testing using RC vehicles, to a simplified stationary classroom setup, utilizing two ESP32 modules to demonstrate V2V handshakes and sensor data exchange. The output is further augmented by a custom Python-based real-time GUI, which translates kinematic and biometric data,including vehicle positions, a live TTC countdown, and the driver's heart rate, into an interactive dashboard.

1. GNSS Antenna Characterization

Following the dynamic demonstrations, we will measure and showcase the key parameters of the GNSS antenna using a calibrated VNA.

2. Congestion Mapping Demonstration

The congestion mapping function will be demonstrated by stopping a vehicle at specific points along its path. The system will interpret this as a traffic jam and broadcast the congestion data to a second vehicle. This exchange can be shown to the public via a live interactive map.

3. Collision Prediction System Demonstration

This segment presents a series of driving scenarios, with predictive alerts displayed on laptop screens acting as the in-car interface. First, in a Freeway Lane-Change scenario, two vehicles drive in parallel to demonstrate: (i) a vehicle approaching from behind and cutting in front, and (ii) a vehicle approaching from the rear, posing a side-collision risk. Second, an Intersection Scenario: two vehicles follow converging paths leading to a predicted collision. Finally, a Non-Collision Scenario: a demo shows no alerts triggered when vehicle trajectories safely diverge.

4. Emergency Response System Demonstration

Our goals are to simulate a controlled crash with the test car against a stationary object and a health crisis (heart rate spike) to test the biosensor system. Upon detecting the hazard, the system initiates a help call: In the primary method, for practical and ethical reasons, the code is modified to call a team member's phone instead of emergency services (911/112). In the fallback method (LoRa), the backup LoRa function can also be demonstrated using the second vehicle.

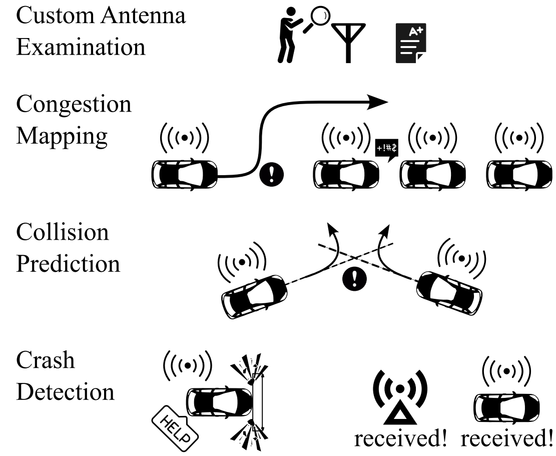

Fig. 5. The proposed demonstration

TABLE II
BILL OF MATERIALS

Category / Component	**Part/Model**	**Cost ($)**
Processing Unit	Raspberry Pi 5 (8GB)	69×2
Cellular/LTE Hub	SIM7600G-H HAT + Ant.	78×2
V2V/WiFi Comms	ESP-NOW (GW.29.A153)	15×2
Sensor Suite	SHT45, BMI323, MQ-2	13×2
Batteries	Li-Po, (YB1206000-USB)	150×2
Custom Hardware	3 PCBs, stencils, Antennas Fabrication + Assembly	200
Coaxial Cable/Adapters	RG405, SMA adapters	100×2
FR4	Rogers 6010.2	30×2
VNA	LiteVNA 64	185
RC vehicles	-	60×2
Total Est.		**1415**

Note: Sources include Digi-Key, Mouser Electronics, Amazon, Online PCB manufacturer; custom antennas fabricated in-house.

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