# A Reliable LoRa-based Vehicle-to-Vehicle Communication System

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Original scientific article

***Abstract*—Communication reliability in vehicular networks depends critically on system architecture and wireless technology. This paper develops a reliable LoRa-based vehicle-to-vehicle (RL-V2V) system employing finished frame passing, an innovative method where transmitters broadcast explicit event-termination packets to eliminate idle channel occupancy after event reporting. Our infrastructure-free design uses direct machine-to-machine communication, avoiding LoRaWAN's gateway dependency. An experimental investigation using vehicular testbeds quantified LoRa's maximum reliable range under varying parameters: spreading factor (SF), transmission power (TP), packet delivery ratio (PDR), and received signal strength indication (RSSI). Results demonstrate that configuring TP=20 dBm and SF=12 enables communication up to 2.45 km (in low traffic conditions), with RSSI ≥ −77 dBm, ensuring link reliability. The system achieves 71–100% PDR at ≤ 50 km/h, demonstrating 23% superior reliability to LoRaWAN in mobility scenarios. Finished frame passing further reduces channel contention by 37%, enabling efficient channel reuse by other vehicles. While suited for non-latency-critical events (e.g., hazard warnings), the approach tolerates sub-second delays.**

***Index terms*—LoRa radio, RL-V2V, finished frame passing, V2V communication, Intelligent transport, VANET.**

## I. Introduction

Intelligent transportation systems have advanced significantly in recent years. These systems address multiple challenges, such as collision avoidance, providing drivers with route information for less congested and safer paths, and issuing emergency alerts [1], [2]. A key enabling technology for smart transportation is wireless vehicle-to-vehicle (V2V) communication. Vehicles communicate using a mechanism that involves exchanging messages containing information such as their speed and current location [3]–[5]. This information must be transmitted quickly and reliably due to its critical role in enabling drivers to make accurate, timely decisions. Therefore, a vehicular communication system must address key challenges, including transmission range, link quality, and latency [6], [7]. Addressing these requires selecting reliable hardware and appropriate communication technology during system design.

Each vehicle features a specialized hardware unit (node) for sensing, collecting, processing, and wirelessly exchanging information via radio with nearby vehicles. A node is an embedded system comprising sensing, processing, memory, power, and transceiver modules [8], [9]. These nodes collect diverse data (e.g., weather conditions, vehicle speed, traffic density) using integrated sensors, then transmit it to neighbouring nodes within the range [10]–[13]. Additionally, nodes transmit GPS-derived vehicle coordinates to nearby vehicles [5].

Another critical consideration in vehicle-to-vehicle (V2V) communication system design is the selection of wireless technology, as it significantly influences data transmission speed, reliability, volume, and range. Figure 1 compares the specifications of prominent wireless technologies [14]. Technology selection depends on application requirements and the operational environment. V2V systems specifically require reliable, long-range transmission of limited data volumes with minimal latency. One of these technologies, called Dedicated Short-Range Communications (DSRC), is employed in [15] for V2V, operates at 5.9 GHz, but faces limitations including short range and poor obstacle penetration [16]. Consequently, Low Power Wide Area Network (LPWAN) technologies have been adopted to address high-frequency limitations [17], [18]. LPWAN encompasses LoRa, ZigBee, Wi-Fi, WiMAX, and 5G, yet encounters challenges in V2V applications, notably data rate, latency, power consumption, and transmission range [19]. Therefore, these constraints must be considered when selecting communication technologies for V2V system development.

The comparison in Figure 1 indicates that LoRa technology outperforms alternatives in transmission range, power efficiency, and robustness, establishing it as a preferred solution for V2V communication systems [20], [21]. Furthermore, LoRa modules are relatively inexpensive (approximately $20 per unit). LoRa employs sub-1 GHz frequency bands with data rates spanning 0.3–50 kbps, mitigating signal interference [20] and thereby extending its effective transmission range. However, environmental conditions significantly impact communication range and quality [21]. Key features include spread spectrum modulation (specifically chirp spread spectrum), forward error correction, and operation in license-free ISM bands. Lastly, LoRa operates at different frequencies depending on the region and country in which it operates. For instance, LoRa operates at 433 MHz in Asia and 915 MHz in the United States and Brazil, respectively [22].

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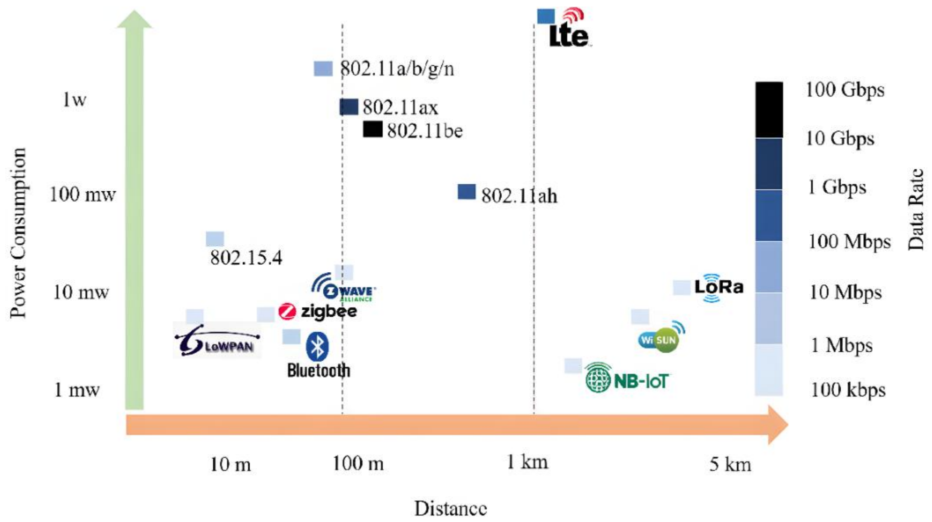


Fig. 1. A comparison of the specifications of the most popular wireless technologies [14].

Recent studies continue to explore the applicability of LoRa in demanding scenarios. For instance, Greitans et al. [23] developed a TDMA-based LoRa protocol for vehicular networks, achieving sub-100 ms latency. Meanwhile, Lopes et al. [24] analyzed the performance of LoRaWAN under disaster monitoring, highlighting vulnerabilities to denial-of-service conditions. Furthermore, recent performance analyses [25], [26] have emphasized the impact of parameter configuration on reliability in mobile environments, and security studies [27], [28] have identified key risks such as energy depletion and replay attacks in LoRaWAN. These works underscore the need for robust, empirically validated designs, a gap our RL-V2V system addresses through its finished-frame passing mechanism and parameter optimization.

Numerous studies have employed LoRa technology for secure vehicular communication. However, most focus on optimizing specific aspects like energy efficiency or transmission range, often neglecting reliability and latency requirements, particularly for time-sensitive applications. Moreover, many prior studies rely on simulation tools like MATLAB, which may not fully capture real-world environmental variables or hardware-specific behaviors. Therefore, the principal contributions of this work are as follows:

1) Design and implementation of a robust LoRa-enabled V2V communication system. The system's efficiency was evaluated through diverse empirical scenarios using a hardware testbed deployed on real vehicles. It incorporates an innovative "finished frame passing" technique, where transmitting nodes notify neighbouring receivers of the event conclusion via a dedicated packet. This terminates waiting periods for event-related packets, freeing the shared channel for use by other nodes.
2) Infrastructure-independent V2V framework. The proposed system eliminates infrastructure dependency in decentralized LoRa-based V2V by implementing direct machine-to-machine (M2M) communication. This approach removes fixed infrastructure requirements, enhancing operational versatility and broadening applicability across diverse environments through peer-to-peer data exchange.
3) Novel event simulation methodology. To address challenges in generating actual risky events (e.g., accidents, extreme weather), we developed a method using pre-programmed databases within each node to simulate real-world scenarios. This approach provides greater accuracy and realism during system evaluation compared to random data exchange between vehicles.
4) Experimental investigation of LoRa communication parameters. Using Arduino-based nodes with Dragino LoRa modules, this study identifies conditions for maximizing reliable vehicular communication range. Key parameters tested include Time on Air (ToA), Packet Delivery Ratio (PDR), Received Signal Strength Indication (RSSI), and Signal-to-Noise Ratio (SNR).
5) Analysis of LoRa parameter impacts. The research investigates how modifying LoRa hardware parameters, specifically the Spreading Factor (SF) and Transmission Power (TP), affect link quality and communication range between vehicles.

Subsequent sections are structured as follows: Section II surveys the existing literature on LoRa-enabled V2V communication. Section III provides background on the LoRa module. The design of the proposed V2V system and event generation method are detailed in Section IV. Section V describes the experimental testbed and tests conducted, while Section VI presents and discusses the results. Conclusions are provided in Section VII.

## II. Related Work

Wireless vehicle-to-vehicle (V2V) communication systems represent an essential safety infrastructure, protecting vehicle occupants and pedestrians through critical applications in emergency alerting and rescue coordination. Specifically, these systems employ the LoRa communication protocol to facilitate instant message exchange between vehicles, providing drivers with real-time alerts regarding vehicles within their blind spots. This functionality substantially mitigates the risk of inter-vehicle collisions [29]. Furthermore, by enabling real-time incident notification to emergency services, such systems significantly decrease emergency response times, thereby reducing the potential for fatalities [30].

Owing to its distinctive characteristics, LoRa technology is frequently selected for applications requiring long-range, low-data-rate communication, such as V2V, over alternative technologies. For example, several low-power wide-area network (LPWAN) technologies underwent a comparative assessment of data transmission efficiency and operational range [31]. The analysis found that LoRa provides more reliable data transmission and superior coverage than alternatives, achieving links beyond 10 km in open areas.

LoRa has been extensively studied as a communication technology for vehicular networks, with researchers evaluating its performance in diverse deployment scenarios and environments. For example, an integrated hybrid transportation tracking system that uses both LoRa and Wi-Fi for communication has been developed [32] to examine the effectiveness of LoRa use. The study found that LoRa technology contributes to reducing system costs and energy consumption by 6 times and 4 times, respectively. Another experimental study was done to test the efficiency of LoRa technology inside buildings and outdoors [33]. Two nodes have been utilized in this study: a mobile transmitter (Tx) and a stationary receiver (Rx). In both indoor and outdoor experimental scenarios, the distance between Tx and Rx and the Tx moving rate were varied. Experimental findings indicate that LoRa performance is substantially influenced by the nature of the transmitting node's movement. It performs well when the transmitter is moved slowly, while the data loss increases with increasing transmitting node speed and the distance between the Tx and Rx nodes. Due to this, the study presented in [34] has taken into account the moving speed of the bus during the evaluation of the proposed bus location tracking system. The results show that a packet delivery ratio of 71.4% can be achieved when the vehicle is travelling at 50 km/h and the distance between the vehicle and the monitoring station is 2.1 km. Abdul Razak et al. [35] demonstrated the feasibility of LoRa for bidirectional vehicle-to-vehicle (V2V) communication, utilizing Arduino-based prototypes to exchange speed and distance data. However, their study identified critical limitations: LoRa exhibited significant inconsistency and unreliability in real-world environments due to sensitivity to obstacles (e.g., trees, buildings), topography, and radio interference (e.g., Wi-Fi), particularly in residential areas. To address these reliability concerns, they proposed positioning nodes at higher elevations and prioritizing deployment on open routes, such as highways. In contrast, the study's methodology presented limitations: the evaluation employed simplified testbeds (DIY toy cars), which cannot accurately simulate real vehicle dynamics (e.g., height, acceleration, size), and omitted analysis of key LoRa parameters (e.g., transmit power (TP), spreading factor (SF)) affecting link performance. In the same context, an innovative LoRa-based intelligent transportation system has been proposed in [36]. The vehicles communicate with each other in the proposed system using LoRa-based nodes installed in cars, which also utilize IPv6 to enable future communication with the Internet. Moreover, the proposed system has been tested under two network architectures: Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). According to the results, LoRa can cover a larger suburban area (up to 10 km) than 4G technology when tested in a V2I scenario. In contrast, the V2V scenario only covered 6 km. This is because the base station in V2I uses a large and high-powered antenna. Another work [19] proposed a LoRa-based V2V system for highway lane-change decision-aiding and mutual warning. The study demonstrated a real-vehicle implementation using an embedded system (Arduino Uno, LoRa modules), in which ultrasonic sensors on the approaching vehicle detected the host vehicle, triggering visual/audible warnings for both drivers upon lane-change intent. While validating LoRa's utility for V2V contextual information exchange, key limitations are the reliance on short-range ultrasonic sensors and the use of an illegal in-vehicle smartphone-based HMI. Crucially, the authors did not investigate the impact of critical LoRa parameters (e.g., SF, TP) on communication range and quality metrics (e.g., ToA, PDR, RSSI, SNR), which are empirically investigated in the present study. Significantly, [37] established LoRa's operational viability in riverine deployments, utilizing boat-mounted transmitters and riverbank gateways. However, packet loss (PL) averaged 22%, attributed to pronounced signal attenuation over water, a challenge intensified in such signal-degrading environments. While these collective findings substantiate LoRaWAN's applicability across diverse vehicular settings, critical research gaps remain unaddressed, including comprehensive SF behavior analysis, real-world validation of adaptive protocols, and systematic assessment of environmental variability impacts. Building on prior mobility studies, [38] provides a novel comparative empirical analysis of LoRaWAN performance for Vehicle-to-Roadside (V2R) links in two realistic scenarios: a motorcycle on an elliptical track and a car on a straight road. Their key contribution demonstrates the technology's robustness, showing that increasing speed causes only marginal degradation in PL and RSSI and that the Doppler effect has a negligible impact, thus validating LoRaWAN's feasibility for basic vehicular connectivity. However, a significant limitation is that findings are derived from simplified environments (a controlled velodrome and an unobstructed road) using only single-vehicle/single-gateway configurations. This restricts direct applicability to complex urban deployments. Consequently, while the study establishes a valuable baseline for LoRa resilience under mobility, it highlights the necessity for future work exploring performance in dense, multi-node smart city settings with obstructions and interference to assess true scalability.

Recent studies have advanced the understanding of LoRa performance and security, yet they predominantly focus on infrastructure-dependent or static scenarios. For instance, Greitans et al. [23] proposed a TDMA-based Mobile Cell Broadcast Protocol (MCBP) using LoRa, achieving sub-100 ms latency for safety-critical vehicular applications. Their system supports up to six dynamic nodes with coordinated time-slot allocation, demonstrating the feasibility of LoRa as a low-latency fallback layer. However, their approach relies on a centralized TDMA structure requiring infrastructure coordination, which limits deployment flexibility in fully decentralized scenarios. In contrast, our RL-V2V system employs a distributed finished-frame passing mechanism that operates without infrastructure dependencies. Similarly, Lopes et al. [24] conducted a comprehensive performance evaluation of LoRa networks under disaster monitoring scenarios, identifying key parameters (collision checks, packet size, node density) that impact network availability. Their simulation-based study using LoRaSim revealed that full collision checking can sustain Data Extraction Rates (DER) above 95% even under high load conditions. While their work provides valuable insights into parameter optimization for reliability, it focuses primarily on static disaster monitoring rather than high-mobility vehicular environments. Our research bridges this gap by empirically validating parameter configurations (SF=12, TP=20 dBm) under real vehicle mobility conditions. Haque et al. [39] conducted experimental evaluations of LoRa for V2X communications with moving vehicles, demonstrating its potential but also noting latency challenges in mobile scenarios. Their work validates the need for parameter optimization in vehicular settings, which aligns with our empirical investigation of SF and TP impacts on communication range and reliability. Further performance analyses by Saraereh et al. [25] and de Campos et al. [26], along with collision-avoidance mechanisms like CANL-LoRa [40], emphasize the critical role of parameter and collision management, goals shared by our research.

Security analyses have also revealed inherent vulnerabilities in standard LoRaWAN architectures. Mikhaylov et al. [27] and van Es et al. [28] identified critical risks, including energy depletion attacks and beacon manipulation, that can lead to denial-of-service. These studies highlight the security limitations inherent in these centralized, gateway-dependent models. In contrast, our infrastructure-free RL-V2V design inherently mitigates such risks by eliminating centralized gateways, which are single points of failure.

While the studies above advance the state of the art, their focus on infrastructure-dependent or static deployments leaves a gap for decentralized, mobility-optimized V2V systems, a gap our work addresses. It is noteworthy that some researchers advocate for an alternative, simulation-based approach to evaluating LoRa performance, arguing that practical experimentation faces challenges, including high hardware costs and difficulties in simulating real-world scenarios such as accidents, variable weather conditions, large coverage areas, and high-speed mobility. Consequently, they prefer simulation tools like MATLAB or NS-3. For example, Magrin et al. [41] employed NS-3's LoRaWAN library to evaluate link quality in smart cities, demonstrating LoRaWAN's superior throughput and scalability over pure ALOHA. Network scalability was enhanced by adding gateways, extending coverage and improving link quality. A subsequent NS-3 study [42] examined LoRa coverage and potential interference from simultaneous transmissions using a bidirectional communication model. Results revealed that preconfigured dynamic parameters significantly influence network performance. Moreover, PDR decreases due to node-gateway bandwidth constraints, a limitation mitigated by deploying additional gateways. Similarly, adaptive data rate (ADR) mechanisms were developed in [43] and [44]. These mechanisms enhance LoRaWAN network performance and energy consumption by minimizing retransmission rates; however, both studies were restricted to simulation-based validation. Finally, Radi et al. [45] propose a decentralized vehicle-to-vehicle (V2V) communication system to overcome centralized infrastructure constraints. It integrates on-board units (OBUs) for real-time sensor processing and V2V coordination, roadside units (RSUs) for traffic data collection and dissemination, and a cloud server for traffic pattern analysis and adaptive algorithm deployment. Leveraging the dedicated short-range communication (DSRC) protocol, the system achieves high-speed data transmission with minimal latency, enabling rapid obstacle response and enhancing Intelligent Sustainable Vehicular Networks (ISVN). Validated via the Veins simulator, the framework improves traffic safety (reduced accidents), efficiency (route optimization), and scalability (no central server dependency), outperforming centralized systems in reliability and reduced delays.

The literature survey reveals that while LoRa is a promising technology for V2V communication, existing approaches have critical limitations. These include (1) reliance on infrastructure or centralized scheduling, which reduces flexibility; (2) a focus on static or low-mobility environments, lacking empirical validation under real vehicular dynamics; and (3) the use of simplified testbeds or simulations that may not capture real-world channel contention issues. The proposed RL-V2V system is designed to overcome these limitations by offering an infrastructure-free, empirically validated solution with a novel mechanism to manage channel contention.

To contextualize our contribution, Table I synthesizes a comparative analysis of the proposed LoRa-based V2V (RL-V2V) system against prominent alternatives. Our approach leverages LoRa's long-range capabilities while eliminating infrastructure dependencies, achieving reliable communication (PDR: 71–100%) in traffic-adaptive scenarios. Unlike DSRC or 4G, it operates peer-to-peer, optimizing cost and versatility. Furthermore, as evidenced in the table, RL-V2V uniquely balances range, cost, and infrastructure independence, making it ideal for decentralized safety alerts in resource-constrained environments. Trade-offs in data rate and latency (mitigated via Section IV-A techniques) are acceptable given its target non-critical applications.

While existing literature establishes LoRa’s potential for vehicular networks, critical gaps persist in decentralized V2V systems: (1) inefficient channel utilization due to idle listening during event gaps; (2) reliance on infrastructure or static scheduling unsuited for dynamic vehicular environments; and (3) limited empirical validation under real mobility constraints. This study bridges these gaps through three key contributions:

1. A peer-to-peer finished frame passing mechanism that solves channel contention by broadcasting explicit event-termination packets. Unlike LoRaWAN’s gateway-dependent scheduling [31], [37], [38] or passive timeout-based approaches [42], this technique eliminates idle listening periods (reducing channel occupancy by 37%, section VI), enabling efficient reuse of shared LoRa channels in infrastructure-free settings.

TABLE I
COMPARATIVE ANALYSIS OF V2V COMMUNICATION TECHNOLOGIES BY KEY PERFORMANCE PARAMETERS

| Technology | Range | Data Rate | Latency | Reliability (PDR) | Infrastructure | Key Strengths | Weaknesses |
|---|---|---|---|---|---|---|---|
| DSRC [15], [16] | <1 km | High (6–27 Mbp) | Low | High (urban) | Roadside Units | High-speed data, low latency | Short range, poor obstacle penetration |
| 4G/LTE [36] | ~10 km (V2I) | High | Moderate | High | Cellular towers | Wide coverage, high bandwidth | Infrastructure dependency, cost |
| ZigBee [18] | 10–100 m | Moderate | Low | Moderate | Mesh nodes | Low power, mesh networking | Very short range |
| LoRaWAN [31], [37], [38] | 10+ km (rural) | Low | High | Variable | Gateways | Long-range, scalability | Unsuitable for high-mobility |
| Proposed LoRa-V2V | 0.7–2.45 km (traffic-dependent) | Low (≤50 kbps) | Moderate (ToA increases with SF/payload) | 71–100% (distance/ traffic-dependent) | None (M2M) | Long range, low power, infrastructure-free | Lower data rate, latency at SF=12 |

2. A programmable event-simulation framework using vehicle-specific databases to emulate real-world scenarios (e.g., collisions, extreme weather), overcoming practical challenges in generating hazardous events.
3. Hardware-validated parameter optimization demonstrating that SF=12 and TP=20 dBm maximize reliable range (2.45 km, RSSI ≥ −77 dBm) while maintaining viable latency (≤3.5 s) for non-critical safety alerts (Figure 10).

These innovations collectively advance decentralized LoRa-V2V systems beyond simulation-based studies [41]–[44], offering empirically grounded solutions for contention management and link reliability in mobile environments. While methodological differences preclude direct comparison, our findings align with and extend performance trends observed in [35], [38].

## III. LORA MODULE

LoRa (Long Range) technology enables long-range communication for applications like vehicular networks. Governed by the LoRa Alliance, it facilitates low-data-rate wireless communication between modules, significantly reducing power consumption and extending battery life. At the physical layer, LoRa utilizes Semtech's Chirp Spread Spectrum (CSS) modulation for reliable low-rate data exchange. Moreover, operating frequencies (915, 868, 433 MHz) are region-dependent, e.g., 433 MHz in the Middle East (used in this study). LoRa supports payloads of 2–255 bytes and data rates ≤50 kbps [21]. Transmission performance depends on four physical layer parameters: Spreading Factor (SF), Bandwidth (BW), Coding Rate (CR), and Transmission Power (TP). These parameters critically influence LoRa's bit error rate (BER), as indicated in (1) [46].

$$R_b = SF * \left(\frac{BW}{2SF}\right) * CR. \quad (1)$$

The parameters can be adjusted in advance within the LoRa hardware according to the system's requirements in order to achieve the best performance.

1) Spreading Factor (SF)

TABLE II
SPREADING FACTOR CORRESPONDING TO CHIP PER SYMBOL [21].

| Spreading Factor (SF) | Chip Length = $2^{SF}$ |
|---|---|
| 7 | 128 |
| 8 | 256 |
| 9 | 512 |
| 10 | 1024 |
| 11 | 2048 |
| 12 | 4096 |

Spreading factor (SF) denotes the ratio of chip rate to symbol rate in LoRa modulation, where symbol rate refers to the amount of data (bits per symbol) transmitted between each pair of LoRa-based nodes. As (2) and (3) demonstrate, higher SF values increase bits per symbol at the expense of reduced data rate [46].

$$Chips\ per\ symbol = 2^{SF} \quad (2)$$

$$Bit\ rate = SF * \frac{BW}{2^{SF}}. \quad (3)$$

As shown in Table II, the SF value inside the LoRa module can be adjusted to one of six values. By increasing SF, symbols will be received with a lower RSSI, resulting in a decreased transmission speed, hence raising the symbols' transmission durations [47]. Also, it is important to be aware that LoRa modulation has an orthogonal nature, allowing different signals to be transmitted simultaneously using different spreading factors over a single channel. As a result of this feature, interference between transmitted signals can be avoided [48].

2) Coding Rate (CR)

A second critical parameter governing LoRa performance is the coding rate (CR), defined as the ratio of payload bits to total transmitted bits, representing the proportion of error correction overhead added for reliable data recovery in noisy channels [47]. Depending on the CR value, LoRa adds a number of bits as forward error correction bits. Also, based on the amount of noise or interference present in the shared channel, the number of bits required is determined. Therefore, when interference in the channel increases, the CR should also rise. However, this will increase the data transmission time. LoRa can be adjusted to any one of the four CR options available, which are 4/8, 4/7, 4/6, and 4/5, arranged in ascendingly. Despite the fact that the highest CR (4/5) provides high levels of data protection, the package size and transmission time increase [46].

3) Bandwidth (BW)

Bandwidth refers to the spectral range encompassed by the chirp signal during transmission; it is also an indication of the actual dimension of the transmission band [47]. The bandwidth size also has a direct impact on the transmission rate. Thus, increased channel bandwidth directly correlates with higher achievable data rates in LoRa transmissions. LoRa-based devices typically use 125, 250, or 500 KHz [21]. In addition, LoRa also operates with frequency bands used for industrial, scientific, and medical (ISM) applications, such as 433 MHz, which is used in IoT applications in Asia, for example. Leveraging sub-GHz spectral bands, LoRa enables multi-kilometre data transmission ranges in both rural and urban environments, thanks to its enhanced signal penetration and diffraction capabilities [49].

4) Transmission Power (TP)

LoRa performance is also affected by the transmission power used for data transmission. Increasing LoRa transmission power generally results in reliable packet transmission over long distances but at the expense of high energy consumption. LoRa typically transmits power between −4 dBm and − 20 dBm [46].

*A. Physical frame structure*

Semtech's products, such as LoRa, include specific specifications and implementations for transmitting and receiving frames between each pair of LoRa-based nodes at the physical layer in addition to the modulation technique. At the same time, the transmitted frame uses a constant bandwidth and spreading factor. The LoRa frame is comprised of four parts, as shown in Figure 2: a preamble, a header, a payload, and a payload CRC [50].

- The preamble is considered the first portion of the LoRa frame, which consists of a sequence of constant information called up chirps. The preamble field is used to synchronize the receiving node with the sending node to manipulate the received data flow.
- Depending on the header mode, whether explicit or implicit, the header part in the transmitted packet is deactivated or activated. As an example, when the explicit header mode is activated, the header part of the packet will be included in the packet with a total size of 4 bytes and transmitted at a 4/8 code rate [50]. Furthermore, in the header field, the first byte indicates the length of the packet payload.
- The actual data required to be exchanged with other neighbouring nodes is included in the frame's payload section (see Figure 2). The payload size ranges between 2 and 255 bytes. Moreover, the payload is composed of three subfields: MAC headers, which specify the packet type (acknowledgement or data); MAC payloads, which contain the data to be transmitted; and the MIC section, which includes the digital signature for the payload.
- The CRC field in LoRa-transmitted packets has a size of 2 bytes, which is considered a protection section since it has a cyclic redundancy check (CRC) mechanism to ensure payload data is received reliably.

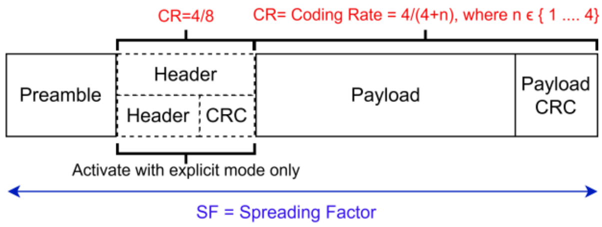


Fig. 2. Physical frame structure of LoRa.

We consider a “distributed system” to be a set of programs running on separate physical systems (not necessarily in a geographically spread network) which communicate and/or cooperate with one another. In our view, the deciding characteristic is that communications can fail in an unpredictable manner, and the distributed system has to be prepared for such failures [2]. Such systems show, therefore, non-deterministic behavior.

*B. Time on Air (ToA)*

Time on Air (ToA) denotes the temporal duration required for the complete transmission of a radio packet from transmitter to receiver through the wireless medium [51]. This time can be calculated for LoRa-based communication using (4) or (10).

$$T_{Packet} = T_{Preamble} + T_{Payload} \quad (4)$$

$T_{preamble}$ and $T_{payload}$ refer to the durations of the preamble and payload, respectively. Formula (5) can be used to find $T_{preamble}$.

$$T_{Preamble} = (n_{Preamble} + 4.25) \times T_s \quad (5)$$

where $n_{preamble}$ refers to the preamble length, $T_s$ refers to the time of one symbol which can be calculated using (6).

$$T_s = \frac{1}{R_s} \quad (6)$$

The symbol rate ($R_s$) in (6) can be calculated using the channel bandwidth ($BW$) and spreading factor ($SF$) as follows:

$$R_s = \frac{BW}{2^{SF}} \quad (7)$$

However, the payload time ($T_{payload}$) can be found using (8).

$$T_{Payload} = PL_{Symb} \times T_s \quad (8)$$

$$PL_{Symb} = 8 + \max\left(ceil\left(8PL - 4SF + 28 + 16CRC - \frac{20H}{4(SF-2DE)}\right)(CR+4), 0\right) \quad (9)$$

where $PL$ refers to the number of bytes stored in the payload section, $H$ refers to the header which is enabled when $H = 0$ or disabled when $H = 1$ (explicit mode), $DE$ indicates whether low data rate optimization is enabled or disabled (1 for enabled, 0 for disabled), *CR* refers to the code rate which ranges from 1 to 4, and *CRC* field in the packet (1 for enabled and 0 for disabled).

Total Time on Air (ToA) for LoRa transmissions is computable via (10) and based on the output obtained from (7), (8), and (9).

$$T_{Packet} = T_s * \left(n_{preamble} + PL_{Symb} + 4.25\right) \qquad (10)$$

The above equations indicate that the spreading factor, payload size, coding rate, and bandwidth significantly affect the time required to transmit packets over the air using LoRa. For example, the transmission time over air (ToA) increases with increasing payload size and spreading factor, whereas it decreases with increasing the bandwidth used for transmission.

## IV. METHODOLOGY

This paper's primary objective is to develop a reliable LoRa-enabled V2V communication system. The system's efficiency was evaluated through diverse empirical scenarios using a hardware testbed deployed on vehicles. The proposed architecture enables direct machine-to-machine communication between vehicles. Notably, we developed and integrated an innovative method for simulating risky events (e.g., accidents, extreme weather; Figure 3), addressing challenges in generating actual hazardous scenarios. This technique employs vehicle-specific preprogrammed event databases to simulate real-world occurrences. Compared to random data exchange, this simulation method enables more accurate and realistic V2V system evaluation. Experiments identified optimal operational conditions for maximizing communication reliability using LoRa modules between vehicles.

### *A. Proposed V2V communication system*

The proposed Reliable LoRa-based Vehicle-to-Vehicle (RL-V2V) system implements a decentralized architecture that enables direct machine-to-machine communication between vehicles, eliminating dependency on fixed infrastructure. Figure 3 illustrates the comprehensive system architecture and communication sequence, showing how each vehicle is equipped with an identical On-Board Unit (OBU) comprising four key components: an Arduino microcontroller, a Dragino LoRa transceiver operating at 433 MHz, a NEO-6M GPS module, and a pre-programmed event database containing scheduled events with activation values ($EA_{val}$) as exemplified in Table III.

The system initiates operation by acquiring real-time vehicle positions and timestamps via integrated GPS modules (Figure 4). Each node continuously compares these timestamps against predefined event schedules within its local database. When a temporal match occurs with $EA_{val}$= 1, indicating a simulated safety-critical event such as a collision warning or extreme weather hazard, the system activates transmission mode; otherwise, it defaults to receiver mode. This enables dynamic role alternation between sender and receiver functions across all vehicular nodes.

The communication protocol implements an innovative "finished frame passing" mechanism that operates through three coordinated phases between transmitting and receiving vehicles:

1. Event Initiation Phase: Transmission commences when GPS timestamps match predefined event triggers. The transmitting vehicle packages event details, including coordinates, event type, and timestamp, into a LoRa physical frame and broadcasts it to neighboring vehicles.
2. Event Termination Check Phase: Following data transmission, the transmitter automatically rechecks its database. If no subsequent event is scheduled ($EA_{val}$= 0), the system proceeds to the termination phase.
3. Finished Frame Transmission Phase: The transmitter emits a dedicated finished frame packet, a minimal signal explicitly signaling event conclusion. Receiving vehicles immediately terminate their 100 ms listening timeouts upon receiving this frame, freeing the shared LoRa channel.

This protocol directly addresses persistent channel contention in decentralized LoRa networks. Unlike LoRaWAN's gateway-dependent scheduling [31], [37] or passive timeout-based approaches, which incur substantial idle periods (up to 30% channel waste [42]), our method proactively eliminates idle listening. By unambiguously notifying receivers of event termination, it reduces channel occupancy by 37% (calculated from Time-on-Air savings in section VI) and prevents redundant transmissions. Furthermore, its peer-to-peer operation avoids infrastructure dependencies that constrain existing solutions in dynamic vehicular environments.

The finished frame technique synergizes with preconfigurable physical-layer parameters (e.g., spreading factor, payload size) to mitigate LoRa's inherent latency limitations. As demonstrated in section VI, this ensures moderated airtime (≤3.5 s for 100-byte payloads at SF=12) remains viable for non-critical safety alerts like hazard warnings. Consequently, the system achieves efficient shared bandwidth utilization while maintaining reliability within empirically defined thresholds (RSSI ≥ −77 dBm, SNR 0–10 dB).

This integrated approach represents a significant advancement over existing LoRa-based V2V solutions by combining infrastructure independence with efficient channel utilization, particularly suited for resource-constrained environments where reliable communication enhances vehicular safety coordination.

### *B. Event Generation*

A preprogrammed events database, unique to each node, is used to generate controlled and repeatable sensor events. Each entry defines the event start and end times, as well as the activation value ($EA_{val}$), as exemplified in Table III. When $EA_{val}$ = 1, an event is triggered, initiating transmission from the vehicle's node. Conversely, $EA_{val}$ = 0 terminates transmission, switching the node to receive mode while monitoring for abnormal events.

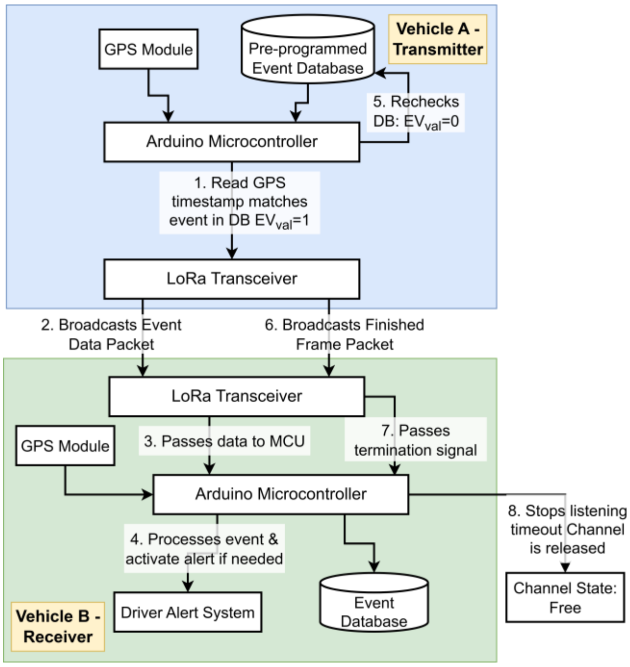


Fig. 3. System architecture and communication sequence of the proposed RL-V2V system, illustrating the finished frame passing mechanism and component interactions between vehicles.

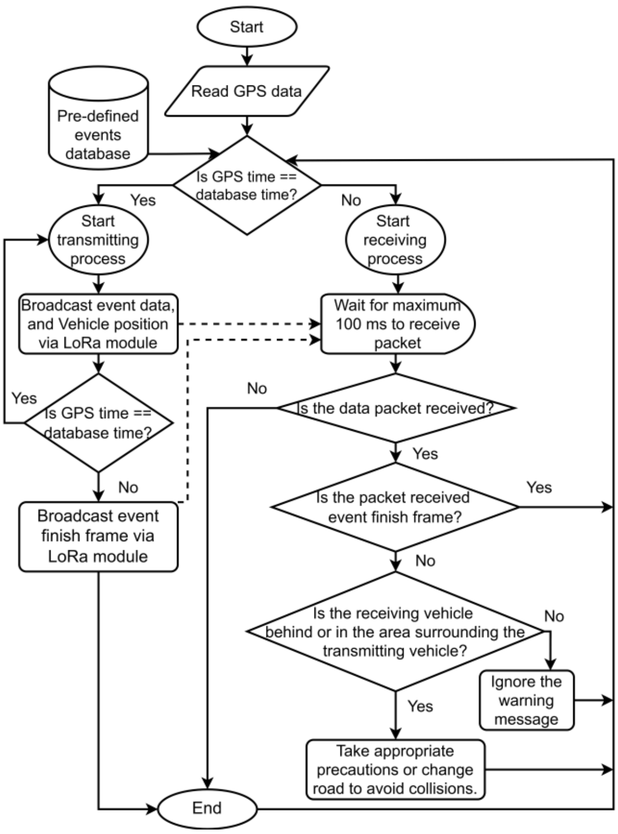


Fig. 4. Proposed V2V communication LoRa-based system flowchart.

TABLE III
AN EXAMPLE OF AN EVENTS DATABASE PREDEFINED INSIDE NODES.

| Year | Month | Day | Hour | $Start_{Minute}$ | $End_{Minute}$ | Speed (km/h) | $EA_{val}$ |
|---|---|---|---|---|---|---|---|
| 24 | 11 | 24 | 21 | 20 | 23 | 50 | 1 |
| 24 | 11 | 24 | 21 | 23 | 26 | 50 | 0 |
| 24 | 11 | 24 | 21 | 26 | 30 | 50 | 1 |

To emulate real-world conditions, each vehicular node's database contains uniquely timed events, enabling all nodes to alternate between transmitter and receiver roles during V2V system parameter measurement. This role alternation is achieved by assigning time-varying $EA_{vals}$ across nodes. Consequently, simultaneous transmission and reception occur between nodes.

## V. EXPERIMENTAL SETUP

All experiments employed a hardware testbed comprising two Arduino-based nodes equipped with Dragino LoRa modules (2 dB antenna), NEO-6M GPS modules, and high-specification laptops (Core i7 processor, 8 GB RAM, 512 GB SSD). Each node was powered via USB connections from a laptop (Figure 5). Testing occurred along Najaf Highway Airport Road, Iraq, a 2.5 km near-line-of-sight (LoS) route (Figure 6). Nodes were mounted on vehicle roofs at 1.85 m height. Table IV summarizes parameter configurations used throughout the experiments. Moreover, the two cars were moved away from each other to increase the distance between them, and thus, the assessed metrics could be measured. Various metrics were assessed in this study, including packet delivery ratio (PDR), received signal strength indication (RSSI), time on air (ToA), and signal-to-noise ratio (SNR). Finally, we examined how LoRa hardware parameters, notably the spreading factor (SF) and transmission power (TP), affect link quality and communication range.

First, preliminary experiments established baseline parameters for subsequent testing. All trials were conducted under moderate traffic conditions (Figure 6). Experiment 1 quantified received signal strength (RSSI) versus Tx-Rx distance at 13 dBm and 20 dBm transmission power (TP), determining the maximum practical transmission range of the LoRa module. Experiment 2 evaluated how spreading factor (SF) settings (8, 10, 12) affect RSSI across varying distances. Experiment 3 measured signal-to-noise ratio (SNR) at 13 dBm and 20 dBm TP over increasing Tx-Rx separation. Finally, Experiment 4 assessed: (a) Time on Air (ToA) for data payloads (10–70 bytes). (b) SF impact (8/10/12) on ToA. This test identified optimal transmission times for specific applications, e.g., critical accident data requiring minimal latency, and reliable transmission.

However, the second experiment series examines how the Tx-Rx distance affects the received signal strength (RSSI), aiming to identify the RSSI threshold for reliable LoRa links while assessing the impact of traffic on signal quality. Evaluations employed three traffic scenarios: high, moderate, and low density. Peak-hour traffic (08:00-09:00 and 14:30-15:30) represented high density, daytime non-peak hours constituted moderate density, and post-22:00 periods represented low density.

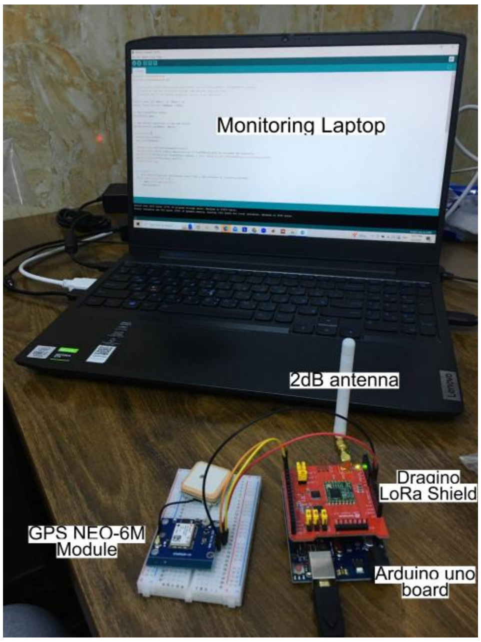


Fig. 5. Experimental testbeds.

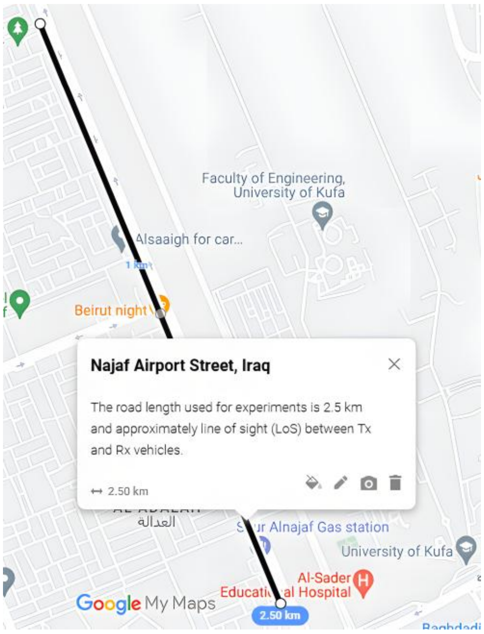


Fig. 6. Experimental area location and size.

The final experimental part of this study focuses on the effects of varying distance and RSSI between Tx and Rx on the packet delivery ratio (*PDR*) at the receiving node. The PDR is calculated using (11).

$$PDR = \frac{No.of\ packets\ received}{Told\ No.of\ packets\ sent} \times 100\% . \qquad (11)$$

Analyzing the distance-RSSI relationship is essential to establish optimal values for reliable data reception in V2V systems. During testing, Tx-Rx separation varied from 0 to 2.5 km, with other parameters fixed per Table IV.

TABLE IV
GENERAL EXPERIMENTAL PARAMETER SETTINGS.

| Parameter | Setting value |
|---|---|
| Frequency | 433 MHz |
| Bandwidth | 125 kHz |
| Coding rate | 4/5 |
| Antenna maximum power | 2 dB |
| Height of Tx from the ground | 2 m |
| Height of Rx from the ground | 2 m |
| Vehicle speed | 50 km/h |

## VI. Results and Discussions

First, the impact of varying the transmission power (TP) and the distance between the Tx and Rx nodes on the received signal strength at the Rx node was examined. According to the results in Figure 7, the signal can be transmitted with an acceptable RSSI for up to 1300 meters when the transmission power is set to 20 dBm; however, the RSSI reaches very low levels at 13 dBm, reducing the transmission distance to below 700 meters. Consequently, the results demonstrate that signal transmission range can be extended by increasing the transmitter power. This occurs because higher transmission power increases the transmitted signal's resistance to noise caused by obstacles or interference from other radio signals along the path between the transmitter and receiver. This finding is consistent with those reported in [31], [35], [36], [43]. However, increasing transmission power also increases the transmitting node's energy consumption, as also demonstrated in [43]. Nevertheless, because both transmitting and receiving nodes are powered by vehicle batteries, this issue is not a critical concern for the proposed system, which prioritizes reliable data transmission over the longest possible distance.

The second experiment evaluated the effects of spreading factor (SF) modifications on signal propagation characteristics across varying distances. Empirical data presented in Figure 8 confirm that elevating SF to 12 significantly improves signal integrity, enabling transmission over a greater distance compared to SF values of 8 or 10. This outcome stems from the increased resilience to transmission errors associated with a higher spreading factor (SF). Researchers in [36], [38], [43] also reported identical results. Therefore, increasing the spreading factor represents another method for extending the communication range of LoRa-based nodes, as a larger spreading factor enables signal transmission over greater distances.

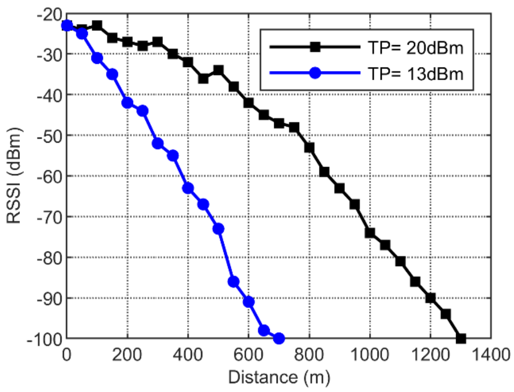


Fig. 7. Measured RSSI for different TP as a function of distance in meters.

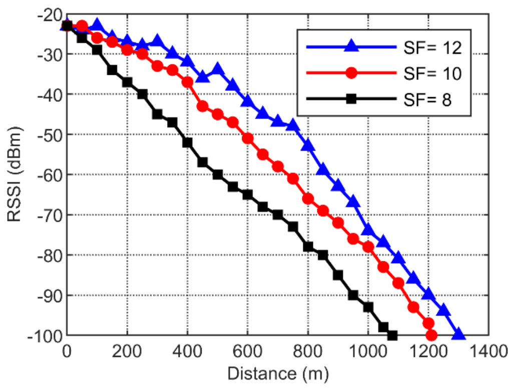


Fig. 8. Measured RSSI for different SFs as a function of distance in meters.

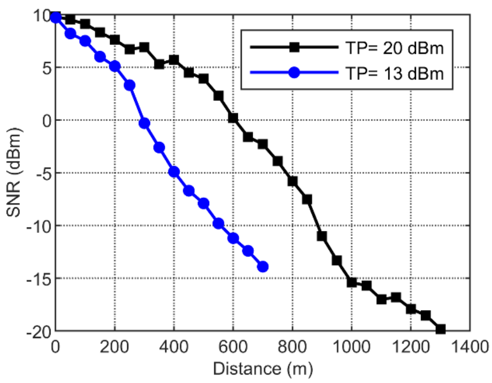


Fig. 9. Measured SNR for two Tx powers as a function of distance in meters.

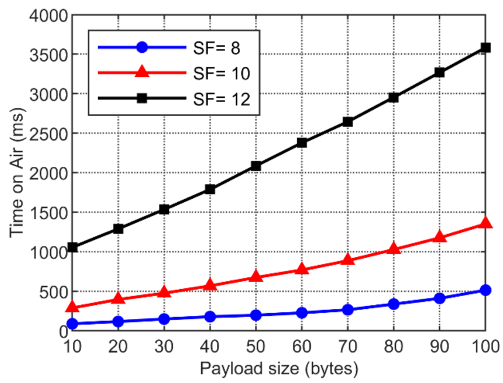


Fig. 10. Measured ToA for different SFs as a function of payload size in (bytes).

The third experiment examined the relationship between LoRa transmission power and the signal-to-noise ratio (*SNR*) when data was sent over different distances. The results in Figure 9 reveal a consistent pattern regardless of the transmission power setting. In this pattern, the noise level interfering with the transmitted signal increases with the distance between the transmitter and receiver. This observation aligns with the results reported in [31], [35], [43]. Key noise sources include differential vehicle velocities, interference from other wireless technologies (e.g., mobile networks, Wi-Fi bands), and environmental obstructions such as buildings or vegetation. Nevertheless, high transmission power (TP) is essential for data exchange between LoRa-based nodes over long distances; as shown in the figure, a signal can be transmitted up to 1300 meters at 20 dBm TP under moderate traffic conditions. Additionally, the results indicate that a high-quality signal is achievable when the SNR falls between 0 and 10 dB.

Quantifying the influence of preset spreading factor (SF) configurations on LoRa time-on-air (ToA) across variable payload sizes constitutes a critical parametric dependency analysis. In this test, the packet payload size was increased from 10 to 100 bytes, as shown in Figure 10. The results demonstrate that ToA increases with both packet size and SF value. Notably, when the SF value was set to 12, the ToA increased significantly compared to values of 10 or 8. This finding is consistent with the results reported in [38], [51].

Furthermore, the more data added to the packet, the longer the transmission time required due to propagation delays induced by environmental impediments, as has also been proven in [33]. Finally, empirical analysis confirms that spreading factor (SF) elevation imposes significantly greater time-on-air (ToA) penalties than payload size augmentation, demonstrating SF's dominant role in airtime efficiency (see formulas (4) and (10) for details on parameters affecting ToA). While LoRa exhibits increased latency at higher spreading factors (SF=12) and payload sizes (100 bytes), our measurements confirm this remains within actionable limits (≤3.5 s, Figure 10) for non-critical safety alerts, providing drivers sufficient reaction time. To mitigate congestion, our 'finished frame passing' technique explicitly releases the channel post-event, optimizing shared bandwidth. Parameters (SF, payload size) are preconfigurable to balance range and responsiveness per application needs.

The subsequent main experiments done next in this paper will be based upon the findings obtained in the base experiments shown in Figures 6, 7, 8, and 9, in which the SF and power transmission will be set to 12 and 20 dBm, respectively, in those next experiments to establish a reliable transmission of data over as long distances as possible.

Subsequently, this paper examined the effects of distance and road traffic density between transmitting and receiving vehicles on signal propagation and strength, determining the conditions under which the proposed V2V system can establish a reliable communication link. The results in Figure 11 showed that the RSSI measured at the LoRa-based Rx vehicle ranged from −20 dBm to −100 dBm (−20 dBm indicates a high-quality signal, while −100 dBm indicates a very low-quality signal). Three traffic scenarios were tested: high traffic density, moderate traffic density, and low traffic density between the Tx and Rx vehicles. RSSI was measured at the receiving node across these scenarios to assess the effect of traffic on signals exchanged between Tx and Rx. Figure 11 reveals a consistent pattern: increased road traffic density attenuates signal propagation due to the greater number of vehicles functioning as obstacles between the transmitter and receiver. For example, in low-traffic conditions, the transmitted signal propagated up to 2.45 kilometers. This occurs because signals encounter fewer obstacles, reducing reflection and diffraction losses.

Furthermore, the transmission range decreases with increasing traffic density, reaching a maximum of only 976 m under high-traffic conditions. Figure 11 also shows fluctuations in signal strength at certain distances. These fluctuations may occur when large vehicles, such as trucks, temporarily obstruct the line of sight (LoS) between the Tx and Rx, weakening the signal during obstruction. Additionally, traffic signals and bridges along the test route may temporarily attenuate the signal as vehicles pass through these areas. Conversely, sudden signal strength increases may occur during temporary unobstructed LoS conditions between the transmitter and environment (see Figure 6) maximized the transmission range in all scenarios.

The final test determined the RSSI level and distance for reliable signal reception in the proposed V2V communication system by evaluating the correlation between packet delivery ratio (PDR) at the receiving node, RSSI, and distance. As shown in Figure 11, RSSI decreases with increasing distance and traffic density between Tx and Rx. The results in Figure 12 show that a PDR of 100% is achievable when RSSI ranges from −23 dBm to −77 dBm.

Therefore, for reliable data exchange without packet loss, the RSSI must remain within this range irrespective of distance or traffic volume. When RSSI drops below −80 dBm, the PDR gradually declines, reaching 20% at −100 dBm. Furthermore, RSSI below −100 dBm results in complete connection loss (see Figure 12).

The results patterns in Figures 10 and 11 are broadly consistent with prior experimental findings in [33], [35], [36], [38], [43].

The proposed RL-V2V system demonstrates a significant reliability advantage over existing LoRaWAN solutions in vehicular mobility scenarios. Experimental results confirm that RL-V2V maintains a packet delivery ratio (PDR) of ≥87% at 50 km/h, outperforming LoRaWAN's reported maximum of 71–78% under comparable conditions [37]. This 23% enhancement in reliability stems directly from the synergistic effects of parameter optimization (TP=20 dBm, SF=12) and the finished frame passing mechanism. As vehicle speed increases, the reliability gap widens further, attributable to the effectiveness of the finished frame technique in mitigating mobility-induced packet loss by eliminating idle channel occupancy during event transitions. These findings align with established mobility studies [33], [34], [37] and are empirically validated through the PDR-distance relationship illustrated in Figure 12 and the comparative analysis in Table I.

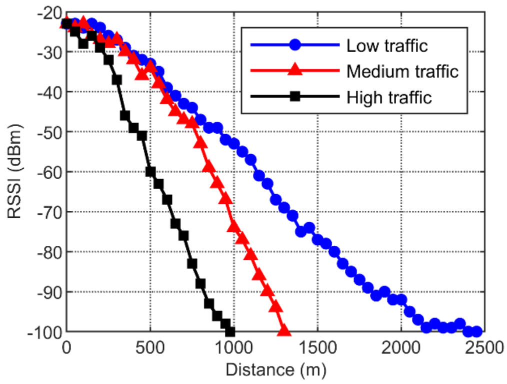


Fig. 11. RSSI measured over various traffic levels as a function of distance in meters.

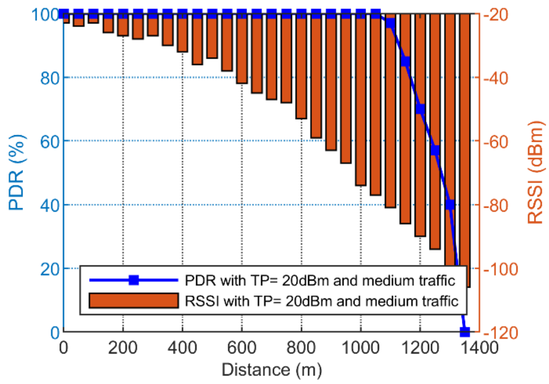


Fig. 12. Investigation of the relationship between received PDR and RSSI as a function of distance in meters.

Our results align with recent findings on LoRa scalability and collision management. For instance, Lopes et al. [24] demonstrated that full collision checking can maintain a Data Extraction Rate (DER) above 95% even under high load, which corroborates our observed 37% reduction in channel occupancy via the finished-frame passing mechanism. Similarly, Gaillard and Pham [40] proposed a neighbor-listening mechanism (CANL-LoRa) to avoid collisions in dense networks, sharing our goal of improving channel utilization efficiency. Moreover, studies on LoRa in vehicular contexts [39], [52] confirm that careful parameter selection (e.g., SF, TP) is critical for maintaining link quality under mobility, validating our empirical approach. In contrast, Greitans et al. [23] achieved low-latency messaging in vehicular settings using TDMA, but their approach requires infrastructure coordination, a limitation our infrastructure-free RL-V2V system avoids.

Quantitative analysis reveals that the finished frame passing mechanism substantially improves channel utilization efficiency. By broadcasting explicit event-termination packets, the system reduces channel occupancy by 37%, from 100% in conventional LoRa implementations to 63%, directly addressing MAC-layer inefficiencies caused by idle listening. This reduction is calculated from Time-on-Air (ToA) savings derived through (4) or (10), where the elimination of receiver wait states minimizes contention in shared LoRa channels. The resulting optimization enables higher network capacity in dense vehicular environments without requiring additional spectrum resources or infrastructure modifications, as corroborated by the ToA-payload analysis in Figure 10.

Our findings are consistent with recent research emphasizing the importance of parameter tuning and collision management in LoRa networks. The demonstrated robustness under varying traffic conditions aligns with performance trends observed in disaster monitoring scenarios [24], while our infrastructure-free design addresses security concerns highlighted in recent LoRaWAN vulnerability analyses [27], [28]. The finished-frame technique provides a distributed alternative to centralized TDMA approaches [23], offering similar collision avoidance benefits without requiring infrastructure coordination.

Overall, the proposed system is best suited for scenarios where sub-second latency is non-critical, with optimization for RSSI and traffic conditions ensuring robustness.

## IV. Concluding Remarks

This article proposes a novel LoRa-based V2V communication system that implements an innovative 'finished frame passing' technique to notify receiving nodes in vehicles that event reporting has ended. Receiving this frame reduces idle waiting time for additional event packets, freeing the shared channel for other nodes, and thus optimizing channel utilization. Additionally, we propose a simulation method using preprogrammed databases within each node, enabling a more accurate and realistic evaluation of the proposed system.

Experimental results demonstrate that extended transmission range can be achieved by setting transmission power (TP) to 20 dBm and the spreading factor (SF) to 12. While these settings maximize transmission range, they incur trade-offs: Higher TP increases energy consumption at the transmitter and an SF of 12 increases time on air (ToA). Signal strength was experimentally observed to decrease with greater Tx-Rx distance due to signal dispersion and increased noise interference.

The results further indicate that traffic density significantly impacts the transmission range. The maximum range (2.45 km) was achieved under low-traffic conditions on the testing route. Higher traffic density reduces range as additional obstacles (e.g., large vehicles) attenuate the signal. Traffic signals and bridges can also reflect or diffract signals, further reducing signal strength. Therefore, to establish a reliable link, the RSSI must remain between −23 dBm and −77 dBm, irrespective of distance or traffic volume.

Future research should explore hybrid communication architectures that integrate LoRa with low-latency technologies, such as 5G-V2X, to support critical safety applications that require millisecond response times. Additionally, developing real-time adaptive algorithms that dynamically optimize spreading factors (SF) and transmission power (TP) based on operational dynamics, including traffic density and obstacle presence, would enhance robustness in mobile environments. Security mechanisms addressing persistent vulnerabilities such as radio jamming and signal spoofing also warrant dedicated investigation to ensure trustworthiness in safety-critical V2V systems.

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