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# Performance Characterization of LoRa-Enabled Vehicle-to-Vehicle Safety Communication in Dynamic Road Environments

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**Abstract**

This research presents the design and experimental evaluation of LoRa-based vehicle-to-vehicle (V2V) communication system that can be used to transmit real-time hazard notifications without any dependence on cellular networks or roadside infrastructures. The design uses the ESP32 microcontroller with LoRa modules built using the SX1278 transceiver for the implementation of a peer-to-peer communication system in automobiles. The communication procedure includes hazard detection, packet creation, wireless transmission, and alerting components. The experimental analysis of the system was conducted by manipulating the environmental parameters like LOS (line-of-sight) and NLOS (non-line-of-sight). Evaluation performance measures include packet delivery ratio (PDR), received signal strength indicator (RSSI), latency, and communication distance. The experiment results demonstrate successful communication at a distance of 600 meters in LOS conditions, with a PDR of greater than 95% and latency lower than 250 ms.


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## 1. Introduction

The problem of road safety remains pertinent across the globe with more than 1.3 million deaths resulting from vehicular accidents annually, according to the WHO [1]. While considerable improvements have been made in the design and development of passive safety systems in cars, there still exists an inherent inability to deliver real-time warnings about any impending dangers such as sudden breaking, road obstructions, or poor weather conditions. This gap could be filled with reliable vehicle-to-vehicle (V2V) communication systems capable of transmitting vital information immediately. This would provide sufficient time for drivers to react.

Various V2V systems have already been tested in laboratory environments [2], [3] using approaches like DSRC and C-V2X technologies. The downside of such technologies is their heavy dependency on roadside infrastructure or the presence of a cellular network, which not only results in high setup costs but also poses some functional limitations. For instance, in nations like India where the state of the road infrastructure is poor, and there is no reliable network connectivity in rural areas, it becomes difficult to deploy such technologies.

LPWAN technologies such as LoRa prove to be promising technologies due to their low-power and decentralization nature along with being able to provide long-range communications [4]. LoRa is based on operating in sub-GHz unlicensed frequency bands that can be used for peer-to-peer communication without relying on infrastructure. Using cost-effective embedded solutions together with the ESP32 solution enables more efficient implementation of V2V communication systems in the road environment.

This research aims to examine the performance aspects of V2V communication system based on LoRa technology used for real-time transmission of hazard information. It is different from previous works that only focused on simulation and theoretical evaluation by looking into the efficiency of LoRa technology in terms of its performance in real-world road environment through analyzing packet delivery ratio, signal strength, and latency. The ultimate goal of this research is to confirm the effectiveness of LoRa as a telecommunications system without relying on infrastructure.

## 2. Literature Review

Vehicular-to-vehicular (V2V) communications are highly valuable for increasing road safety through information exchange about potential hazards in real-time among vehicles. In light of road safety data, early warning systems are likely to prove beneficial in significantly lowering the incidence of accidents on roads [1].

Various methods to perform V2V communications, like DSRC and C-V2X communications, have already been extensively researched. Low latency and operation at frequencies ranging from 5.9GHz make DSRC ideal for use in vehicular safety applications [2]. However, DSRC does not yield satisfactory results in line-of-sight conditions because of attenuation and multipath effects [5]. Moreover, implementing DSRC is expensive because of its infrastructure requirements. C-V2X is one of those communication methods that makes use of cellular networks for both vehicle-to-vehicle and vehicle-to-network communications [3].

Communications of LTE-V and 5G-based V2X technologies provide enhanced connectivity as well as reliable services compared to the previous protocols [6]. However, these technologies depend upon network connectivity, as well as periodic expenses are incurred in the process. The improvements in the IoT devices have paved the way to use of embedded systems together with wireless communication devices that can be used for the vehicles [7], [8]. From all the technologies available, the LoRa technology can be used as a choice owing to the features like long-range communication, power savings, and independent working without any infrastructure dependency [4].

Several research papers have discussed the possibility of using LoRa technology for vehicular communication applications [9], [10]. However, most of the research work on LoRa is focused on static or low mobility scenarios. Even though the LoRa communication technology is promising for the purposes of vehicular communication, there are very few works that have addressed the issues related to latency and power consumption in LoRa technology under vehicular communication scenarios. Thus, this paper proposes a decentralised V2V communication model using LoRa technology to send real-time alerts about the possible danger.

## 3. Methodology

This system utilizes a decentralized LoRa-based Vehicle to Vehicle (V2V) communication model that is meant to enable real-time transmission of hazard alerts independent of any roadside infrastructures or mobile networks. This model leverages the use of embedded system and LPWAN communication to ensure seamless and secure wireless peer-to-peer communication between vehicles. Every node in the network acts as both transmitter and receiver to facilitate two-way communication and cooperative hazard detection within the immediate vicinity of neighboring vehicles.

The architecture (Figure 1) of each vehicular node involves a combination of an ESP32 dual core processor connected to a SX1278 LoRa transceiver that works in the sub-GHz ISM band. Other peripheral devices employed here include an OLED display unit, buttons for triggering hazards, a buzzer and LED indicators for alerting the driver of danger, and a power regulating module. The main processing unit, the ESP32, handles sensor detection, data packet formation, encoding process, wireless transmission control, and managing driver alerts. The SX1278 LoRa module helps provide long-distance wireless connectivity with low energy consumption characteristics.

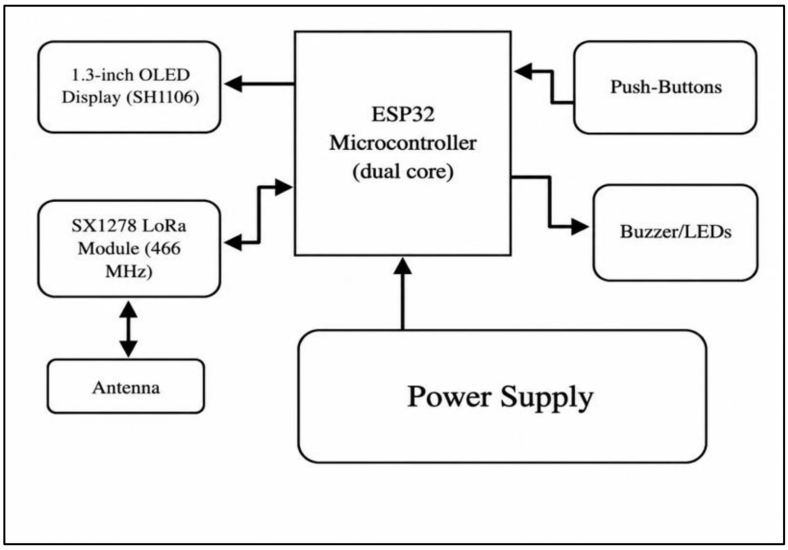


**Figure 1.** ESP32-Based LoRa V2V Node Architecture

Figure 2 shows the communication network architecture of the proposed LoRa-based V2V hazardous warning system. As illustrated, the architecture involves two vehicle nodes; Vehicle Node A serving as the transmitter while Vehicle Node B serves as the receiver. The various sensors located inside the transmitting vehicle (e.g., camera, radar sensor, and GPS) are responsible for constantly monitoring the surrounding environment and collecting information related to hazards. The detected data is analyzed by the ESP32 microcontroller and an appropriate warning message is developed.

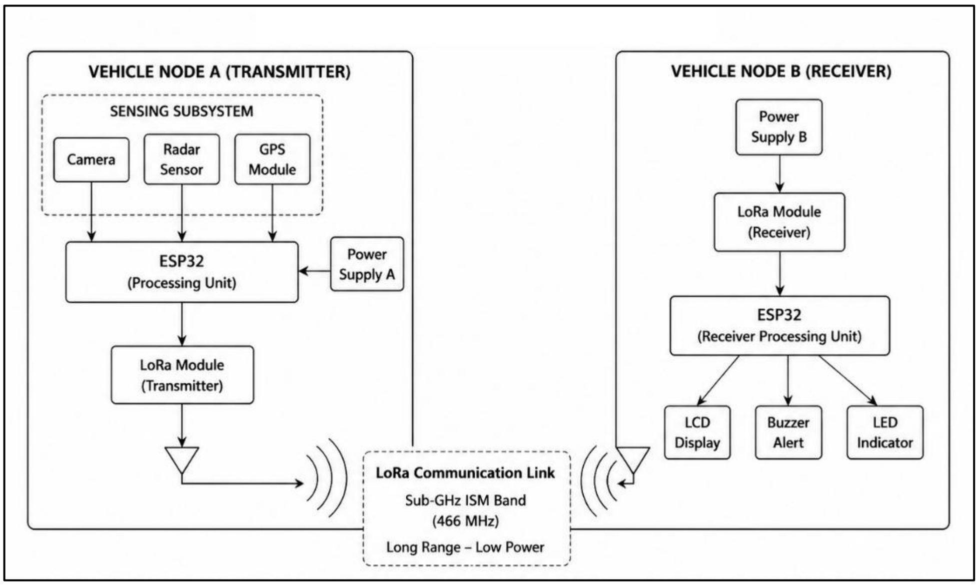


**Figure 2.** Communication Network Architecture of the Proposed LoRa-Based V2V Hazard Alert System

Finally, the generated message is transmitted using the LoRa transceiver within the sub-GHz ISM frequency range (466 MHz). The wireless link provides direct point-to-point communication between the vehicles and does not require any cellular network or roadside infrastructure. The LoRa receiver in Vehicle Node B receives the warning message from the LoRa transmitter and delivers the same to the ESP32 receiver module. Subsequently, the ESP32 decoder decodes the transmitted message and triggers multiple alert measures, namely LCD screen, buzzer warning, and LEDs.

The proposed communication system (illustrated in figure 3) works via four phases, namely hazard detection, packet formation and encoding, wireless data transmission, and packet reception. First, the ESP32 microcontroller is tasked with monitoring the input pin signals linked to hazard triggers, such as physical inputs like push buttons and onboard sensors, including accelerometers and proximity detectors. After detecting the hazardous event, the controller begins encoding packets to be transmitted wirelessly.

The hazard packet is developed using a minimal size that ensures efficient data transmission with minimum latency and channel usage. The data packet includes various fields, such as synchronization, vehicle number, hazard event code, time-stamp, and CRC bits for detecting errors. The small size of the payload enhances wireless data transmission efficiency. Table 1 highlights the structure of the data packet utilized in the proposed communication protocol.

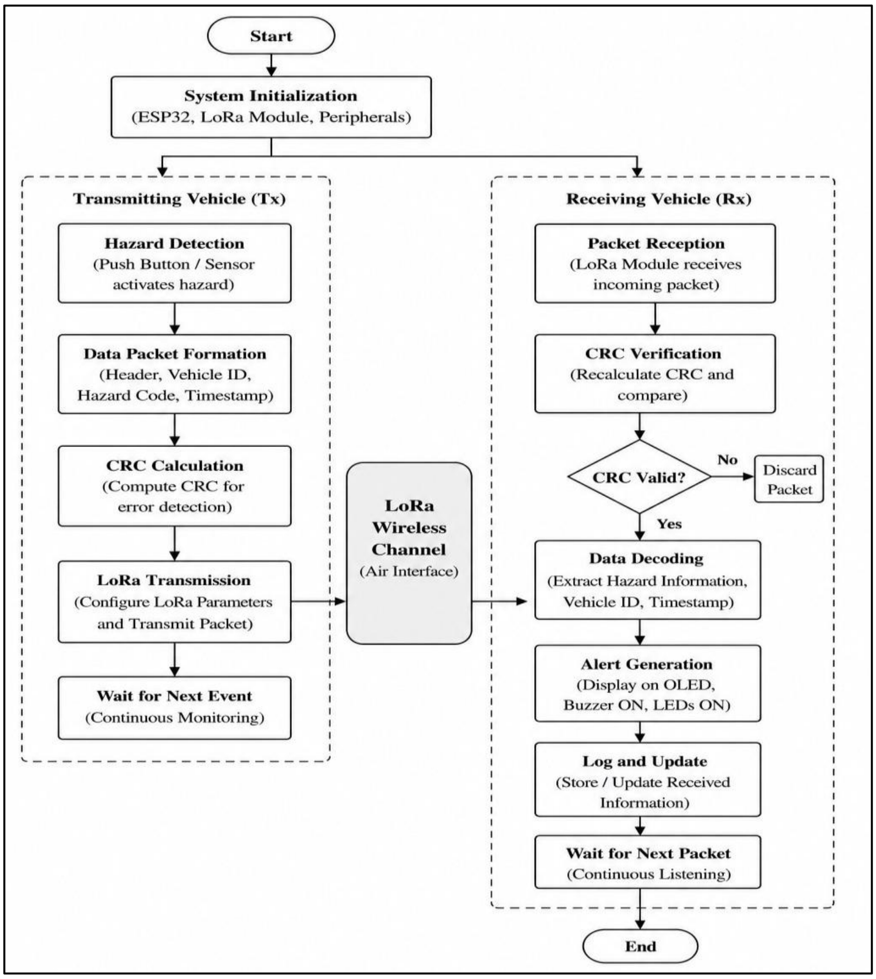


**Figure 3.** Workflow of the Proposed V2V Safety Communication

**Table 1.** Hazard Alert Packet Structure

| Field | Description |
|---|---|
| Header | Synchronization and packet identification |
| Vehicle ID | Unique identifier of transmitting vehicle |
| Hazard Code | Encoded hazard information |
| Timestamp | Time of packet generation |
| CRC | Error detection bits |

The LoRa transceiver is configured with efficient communication parameters to ensure maximum coverage and reliability of wireless communication. The complete set of communication parameters of the LoRa employed in the experimentation is shown in Table 2 below. A larger spreading factor will improve the sensitivity of the receiver and the distance of the communication, but it will increase the transmission time.

**Table 2.** LoRa Communication Parameters

| **Parameter** | **Value** |
|---|---|
| Operating Frequency | 466 MHz |
| Bandwidth (BW) | 125 kHz |
| Spreading Factor (SF) | 12 |
| Coding Rate (CR) | 4/5 |
| Transmission Power | 17 dBm |
| Communication Mode | Peer-to-Peer |

Packet transmission delay is based on the LoRa Time-on-Air (ToA) that is affected by the following factors:

The symbol duration is expressed as:

$$T_{\text{sym}} = \frac{2^{SF}}{BW} \quad (1)$$

where:

- $T_{\text{sym}}$ = LoRa symbol duration,
- $SF$ = spreading factor,
- $BW$ = communication bandwidth.

The total packet airtime is calculated as:

$$T_{\text{packet}} = T_{\text{preamble}} + T_{\text{payload}} \quad (2)$$

where:

- $T_{\text{packet}}$ = nmtotal packet transmission time,

- $T_{\text{preamble}}$ = preamble transmission duration,
- $T_{\text{payload}}$ = payload transmission duration.

The end-to-end latency is represented as:

$$L_{\text{total}} = L_{\text{proc}} + L_{tx} + L_{\text{prop}} + L_{rx} \tag{3}$$

where:

- $L_{\text{proc}}$ = processing delay at ESP32
- $L_{tx}$ = LoRa packet transmission delay
- $L_{\text{prop}}$ = wireless propagation delay
- $L_{rx}$ = packet decoding and alert generation delay

Communication reliability is evaluated using Packet Delivery Ratio:

$$PDR = \frac{N_{\text{rocositard}}}{N_{\text{transmitted}}} \times 100 \tag{4}$$

where:

- $N_{\text{received}}$ = successfully received packets
- $N_{\text{transmitted}}$ = total transmitted packets

Signal attenuation is modeled using the log-distance path loss equation:

$$PL(d) = PL(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) \tag{5}$$

where:

- $PL(d)$ = path loss at distance $d$
- $n$ = path loss exponent
- $d_0$ = reference distance

At the receiving node, the LoRa transceiver always listens to the wireless channel for incoming packets that contain information about hazards. On receiving a valid packet, the

ESP32 checks the validity of the packet by performing an error-checking algorithm known as cyclic redundancy check (CRC). CRC is employed to ensure data integrity in wireless communication by detecting errors that might be introduced during transmission due to noise and interference. In this study, the implementation of a CRC error detection method based on a 16-bit CRC scheme is carried out at the packet level.

The CRC operation can be represented as:

$$CRC(x) = \text{Remainder}\left(\frac{M(x)\cdot x^r}{G(x)}\right) \tag{6}$$

where:

- $M(x)$ = message polynomial
- $G(x)$ = generator polynomial
- $r$ = degree of the generator polynomial

Valid packets are analyzed to obtain data on hazards, which are displayed on the OLED display unit. At the same time, buzzer alarms and LED alarms are initiated to send audio-visual alerts to the driver. These multimodal methods ensure that the awareness of drivers is improved, thus improving road safety.

To evaluate the proposed methodology experimentally, various environments were considered including open field LOS, campus LOS, and NLOS environments. The analysis was done with regard to PDR, RSSI, latency, communication range, and reliability based on different distances between vehicles and other environmental obstacles.

## 4. Results And Discussion

Experimental tests have been carried out on the proposed V2V communication network utilizing LoRa technology in order to assess the ability of the system to transmit hazard alerts in real time under varied environmental conditions. In this regard, the test has been conducted in open field, LOS, campus, LOS, and NLOS conditions in order to assess how the level of signal obstructions and communication distance affect system performance. The key parameters considered during experimental analysis include packet delivery ratio, RSSI, latency, and effective communication distance.

The developed model for V2V communications has successfully managed to facilitate wireless communication between nodes without dependence on infrastructure. In this regard, hazard alerts that have been generated from the transmitting vehicle have been transmitted in real time in order to be picked up by the receiving node, which receives and displays the message through an OLED display and also through buzzer and LED lights.

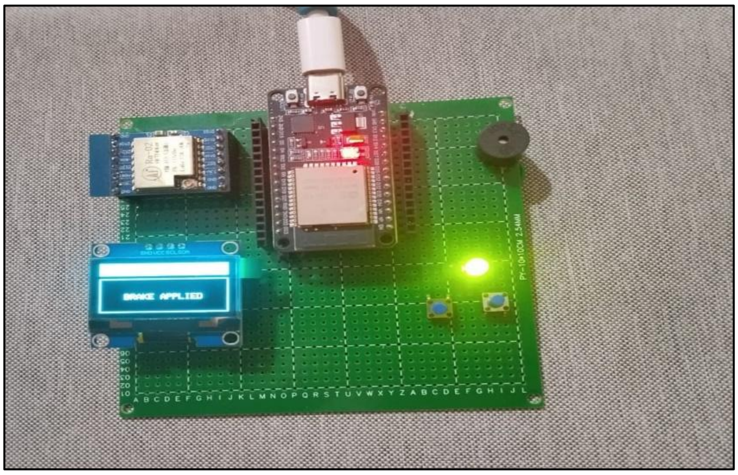


**Figure 4.** Experimental Setup for LoRa-Based V2V Communication Validation

Figure 4 demonstrates the testbed employed to verify the suggested scheme in real-world communication scenarios. Transmitter and receiver nodes were placed at different distances, and the performance was evaluated for each scenario. It was demonstrated through the experimentation that the LoRa technology could be employed for hazardous information exchange in a peer-to-peer network fashion without any dependency on cellular network or roadside infrastructures.

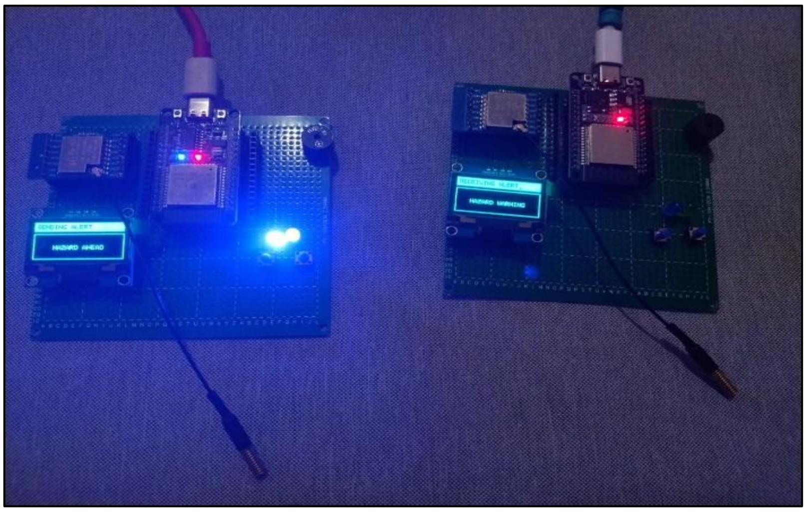

**Figure 5.** Real-Time Hazard Alert Transmission Between Vehicle Nodes

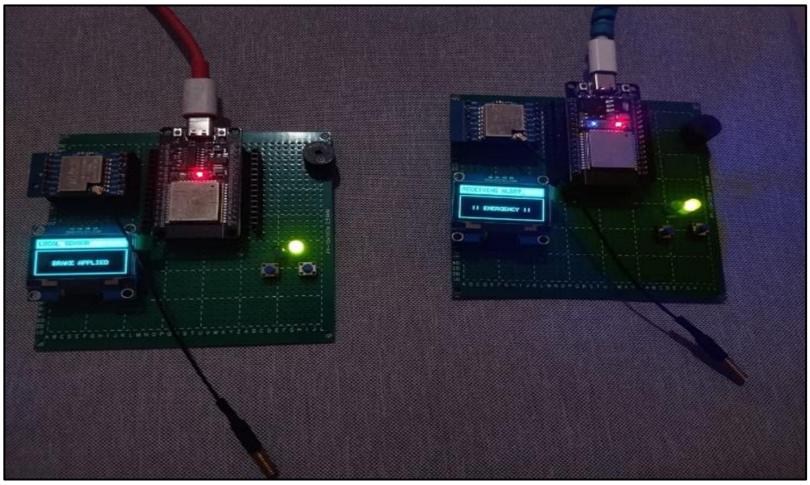


**Figure 6.** Emergency Alert Reception and Driver Notification Mechanism

Figure 5 depicts the real-time exchange of warning message packets among the vehicle nodes. The sent warning messages were properly received and processed without much communication delay in LOS environments. Likewise, Figure 6 shows the emergency alert reception process where the warning messages trigger both auditory and visual alerts to enhance the drivers' awareness and reaction times.

Table 3 highlights the system performance assessment under varying environmental conditions. From the results, it can be seen that the proposed communication framework delivered consistent communication performance in LOS environments. This was evidenced by a packet delivery ratio exceeding 95% with a communication radius of 600 meters. RSSI readings ranged from -90 dBm to -110 dBm, which showed an appropriate level of communication signal strength. On the other hand, end-to-end latency was measured between 180 ms and 240 ms, proving that it was appropriate for non-critical vehicular warning applications.

**Table 3.** Performance Evaluation of the Proposed LoRa-Based V2V System Under Different Environmental Conditions

| Environment | Distance Range (m) | PDR (%) | RSSI (dBm) | Average Latency (ms) | Remarks |
|---|---|---|---|---|---|
| Open Field (LOS) | 0–600 | >95 | -90 to -110 | 180–240 | Stable communication |

| | | | | | |
|---|---|---|---|---|---|
| Campus (LOS) | 400–500 | >90 | -95 to -115 | 260–340 | Moderate attenuation |
| Campus (NLOS) | ~300 | <80 | -110 to -125 | 450–620 | High packet loss |

Communication distance was shortened to about 400-500 m due to partial structural obstructions and multipath interference under campus LOS scenarios. Despite the system having a PDR above 90%, slight increments were recorded in terms of latency and attenuation. For NLOS cases, communication efficiency was drastically reduced since there was heavy obstruction and increased path loss. There was a drop in the PDR value to below 80%, and also RSSI readings were lowered to -125 dBm under longer distances.

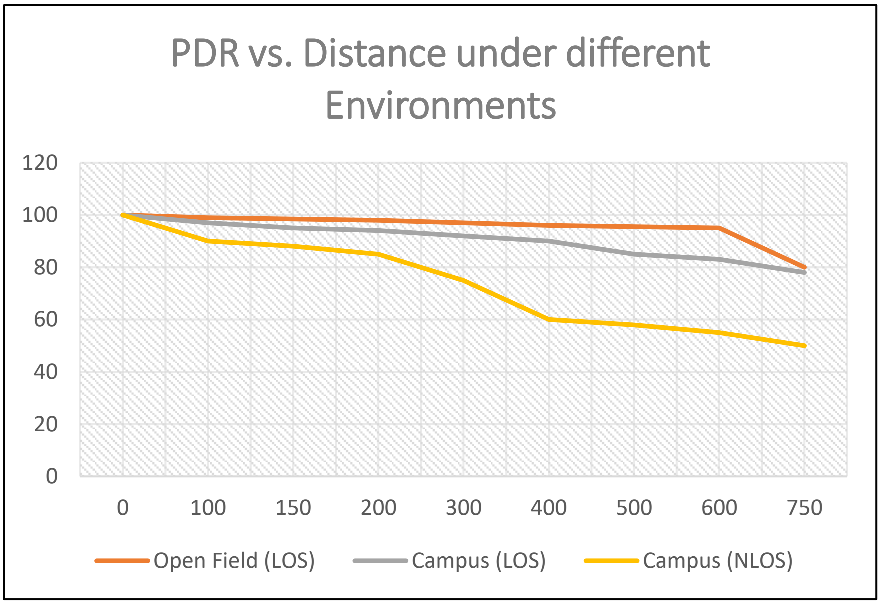


**Figure 7.** Variation of PDR with Communication Distance Under Different Environmental Conditions

Figure 7 depicts the effect of communication distance on PDR in varying environmental conditions. As can be seen from Figure 7, the PDR decreases as the communication distance increases. This is especially true for an environment obstructing the communication process. However, for open field LOS, the communication process remained stable until the 600 m distance point. However, at distances greater than 600 m, there was considerable degradation in communication performance because of signal attenuation. For NLOS, rapid degradation of communication performance occurred due to attenuation of obstacles and multipath effects.

As can be seen from above experiments, it is evident that the communication environment affects the propagation characteristics of LoRa signals used in the system. Moreover, the findings of the experiment coincide with the log-distance path loss model used in the methodology section of the study. In summary, the proposed LoRa-based V2V communication system is capable of reliable long-range communication with minimal energy consumption and independence from infrastructure.

## 5. Conclusion

The current study has created an effective LoRa-based V2V communication architecture capable of transmitting information about the hazardous conditions in real-time through the use of ESP32 microcontroller and SX1278 LoRa modules. The proposed communication network allows for direct transmission of information among different nodes without depending on the existence of a cellular network or any roadside infrastructure, and therefore it can be employed in ITS in both urban and rural areas. The experiment conducted under diverse environmental conditions indicated high success in terms of data transmission, especially in scenarios where there was visibility, as the distance reached in such cases was 600 meters and PDRS. This communication system provides a reliable and economical means of increasing road safety by disseminating information among various vehicles. Future research can investigate methods of preventing accidents in high vehicular density environments and efficient communication systems in huge vehicular networks.

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