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Performance Analysis of Static Vehicle-to-Vehicle Communication Systems Using Software Defined Radio

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Abstract – *Vehicle-to-Vehicle (V2V) communication is a key component of Smart Transportation Systems (STS), enabling improved road safety, traffic efficiency, and cooperative driving. However, developing flexible, cost-effective, and experimentally validated V2V platforms remains challenging, particularly under varying propagation conditions such as Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS). This paper presents the design and experimental evaluation of a static V2V communication system using a Software-Defined Radio (SDR) platform. The system operates at 2.7 GHz and employs Binary Phase Shift Keying (BPSK) modulation, implemented using the GNU Radio framework. Performance is evaluated under LOS and NLOS conditions at varying distances using Packet Loss (PL), Bit Error Rate (BER), and Signal-to-Noise Ratio (SNR) as key metrics. The main contributions of this work are threefold: (1) the practical implementation of an SDR-based V2V communication system, (2) controlled experimental validation under both LOS and NLOS scenarios, and (3) a comprehensive performance analysis highlighting the impact of distance and environmental conditions. Experimental results show that the system achieves reliable performance under LOS conditions, with zero PL, negligible BER, and SNR up to 13.9 dB at short distances, remaining reliable up to 25 m. In contrast, performance degrades under NLOS conditions due to signal obstruction and multipath effects. These findings demonstrate the feasibility of SDR-based V2V systems and provide insights for improving their robustness in real-world environments.*

***Keywords**: Vehicle-to-Vehicle Communication, Software Defined Radio, Smart Transportation System*

I. Introduction

The rapid advancement of information and communication technology (ICT) has significantly transformed various sectors, particularly the transportation domain. One of the most prominent outcomes of this evolution is the emergence of Smart Transportation Systems (STS), which aim to enhance transportation efficiency, safety, and user convenience [1]. As a globally recognized concept, STS contributes to reducing traffic accidents, alleviating congestion, and minimizing environmental impacts [2]. By integrating advanced communication technologies and intelligent systems, STS enables real-time monitoring and anomaly detection in transportation networks.

Vehicle-to-Vehicle (V2V) communication is a fundamental component of STS, facilitating the exchange of real-time information, such as vehicle position, speed, and environmental conditions [3]. This capability supports collision avoidance, traffic flow optimization, and improved decision-making for both drivers and autonomous systems [4]. Recent studies have highlighted the importance of secure and efficient V2V communication, including the development of authentication mechanisms based on digital vehicle identification and comprehensive analyses of V2V contributions to traffic efficiency and safety [5][6]. Nevertheless, V2V systems must operate under stringent requirements, including low latency, high reliability, and robustness in dynamic and often unpredictable environments.

These challenges have driven the adoption of Software-Defined Radio (SDR) as a flexible and efficient platform for modern wireless communication systems [7][8]. SDR enables the implementation and modification of communication functionalities through software, thereby supporting adaptive protocols, improving resource utilization, and reducing the need for hardware modifications [9][10]. Among the available SDR platforms, GNU Radio has gained considerable attention due to its open-source architecture and support for programming languages such as C++ and Python [11]. Its graphical interface, GNU Radio Companion, further simplifies system development by enabling the design of signal processing chains using intuitive block diagrams [12][13]. These features make SDR particularly suitable for both experimental validation and practical implementation of V2V communication systems.

In addition, prior studies have demonstrated the effectiveness of SDR in various wireless applications, including the integration of OFDM and line coding techniques, multi-antenna system measurements, and applications in Tire Pressure Monitoring Systems (TPMS) [14–19]. These works further confirm the versatility and applicability of SDR-based approaches in real-world scenarios.

Based on these considerations, this paper presents the design and experimental evaluation of a static V2V communication system using SDR within the STS framework. The proposed system employs a computationally efficient modulation scheme, namely Binary Phase Shift Keying (BPSK), and operates at 2.7 GHz. Performance is evaluated under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions across varying distances, using Packet Loss (PL), Bit Error Rate (BER), and Signal-to-Noise Ratio (SNR) as key metrics. The experimental results demonstrate that both transmission distance and environmental conditions significantly affect V2V communication performance.

II. Method

This study develops a static V2V communication system based on an SDR platform to support STS. This section presents the system's design and implementation.

A. Design System

The proposed system consists of two main components, namely the transmitter and the receiver, as illustrated in Figure 1. At the transmitter side, input data are first converted into a binary bit stream and subsequently modulated using Binary Phase Shift Keying (BPSK), in which each bit is represented by a phase shift of 0° or 180°. The resulting symbols are then transformed into baseband in-phase and quadrature (IQ) samples using GNU Radio. Before transmission, these IQ samples may undergo pulse shaping to mitigate inter-symbol interference. The processed samples are then delivered to the HackRF One via a USB interface, where digital-to-analog conversion and upconversion are performed to generate a radio frequency (RF) signal at the designated operating frequency. The RF signal is subsequently transmitted through an antenna. The system operates at a carrier frequency of 2.7 GHz, selected based on experimental performance across the 2.7–5.8 GHz frequency range. The results indicate that 2.7 GHz provides the best transmission performance, in terms of reliability and maximum achievable distance. A detailed summary of these findings is presented in Table 1.

TABLE I
PERFORMANCE TESTING RESULTS OF SIGNAL TRANSMISSION ACROSS FREQUENCY VARIATIONS (2.7–5.8 GHZ)

Test No.	**Frequency (GHz)**	**Success**	**Failure**	**Maximum distance (m)**
1	5.8		✓	0
2	5.7		✓	0
3	5.6		✓	0
4	5.5		✓	0
5	5.4		✓	0
6	5.3		✓	0
7	5.2		✓	0
8	5.1		✓	0
9	5.0		✓	0
10	4.9		✓	0
11	4.8		✓	0
12	4.7		✓	0
13	4.6		✓	0
14	4.5		✓	0
15	4.4		✓	0
16	4.3		✓	0
17	4.2		✓	0
18	4.1		✓	0
19	4.0		✓	0
20	3.9		✓	0
21	3.8		✓	0
22	3.7		✓	0
23	3.6		✓	0
24	3.5		✓	0
25	3.4		✓	0
26	3.3		✓	0
27	3.2		✓	0
28	3.1		✓	0
29	3.0	✓		4
30	2.9	✓		6
31	2.8	✓		7
32	2.7	✓		45

At the receiver side, the transmitted RF signal is captured by an antenna and processed by another HackRF One device, which performs downconversion from RF to baseband, followed by analog-to-digital conversion to produce digital IQ samples. These samples are then transferred back to the software environment, where BPSK demodulation is carried out using GNU Radio Companion. The demodulation process includes synchronization, carrier recovery, and symbol detection to reconstruct the original data bits. Finally, the recovered data is used to evaluate system performance using reliability metrics such as Packet Loss (PL), Bit Error Rate (BER), and Signal-to-Noise Ratio (SNR). This architecture enables a flexible and real-time SDR-based implementation suitable for experimental V2V communication scenarios.

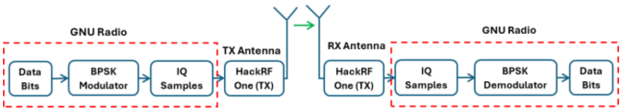

Fig. 1. System Architecture

B. *Implementation System*

The system design is deliberately straightforward and low-cost: one laptop with a HackRF One on both the transmit and receive sides, as depicted in Figure 2. Flow graphs written using GNU Radio run on the laptops to generate signals, modulate, demodulate, and process data. The HackRF Ones act as the RF front ends. This design provides a versatile, configurable system architecture, perfect for implementing and experimenting with V2V communication ideas. This setup provides a flexible, reconfigurable platform for prototyping and evaluating V2V communication systems across various configurations.

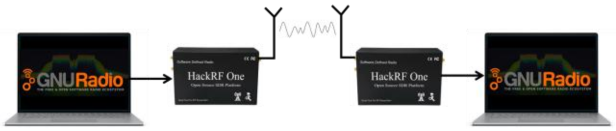

Fig. 2. Hardware Configuration

V2V communications use a proprietary software stack that handles packet framing, synchronization, and error correction. The modular software-defined radio (SDR) approach enables us to rapidly evaluate different wireless environments, ranging from line-of-sight to non-line-of-sight. Such an approach is highly suitable for practical evaluation purposes.

Given the design of our transmitter, we first load a file and convert the resulting sequence into a tagged sequence, enabling dynamic packet processing. Then, a CRC code is calculated to prevent corruption during transmission. After the framing procedure is applied according to the protocol, the generated bit sequence is modulated using BPSK. Filtering and resampling are required to match the receiver's sampling rate. The shaped signal will be broadcast via the HackRF One transceiver with proper gain adjustment.

From figure 3, it is evident that the transmitted signal uses BPSK modulation. It can be observed that the wave changes its polarity depending on the phase at which it oscillates. The I-Q diagram also confirms the presence of two distinct points on the real axis. This demonstrates the reliability of BPSK, which, although less efficient in terms of bandwidth utilization, offers good noise immunity.

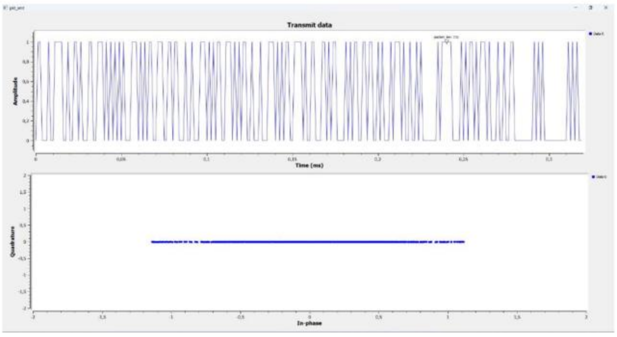

Fig. 3. Transmitted Signal

The signal on the receiver side enters the SDR frontend module. It undergoes several processing stages: resampling, Automatic Gain Control (AGC), frequency alignment via a Frequency Locked Loop (FLL), and synchronization. Following demodulation, the data are decoded using constellation and differential decoding methods, and verified using the Cyclic Redundancy Check (CRC) error-detection mechanism. Certain processing blocks are responsible for shaping the data and visualizing the signal behavior in real time.

Figure 4 displays the analysis of the received signal, demonstrating that the proposed design can recover the transmitted data despite real-world channel conditions. Although there is some noise in both the frequency response and constellation plots, the demodulated signal is quite reliable. The correlation process significantly reduces noise, providing stable results.

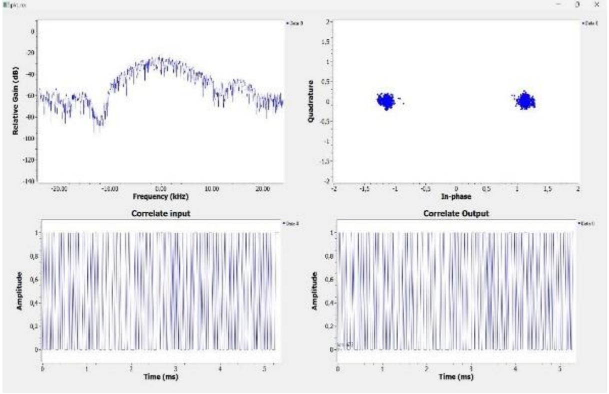

Fig. 4. Received Signal

These experiments were conducted under two propagation scenarios: LOS and NLOS. The primary purpose of these experiments is to evaluate the effectiveness of the vehicular communication system from a practical perspective, using parameters such as packet loss (PL), bit error rate (BER), and signal-to-noise ratio (SNR).

Packet loss is an essential measure of data transfer efficiency in vehicular communication. It denotes the percentage of data packets that fail to be delivered to the receiver. Thus, by evaluating this parameter, one may identify potential areas of underperformance due to interference, signal transmission obstacles, low signal levels, or technical limitations. The formula used to compute Packet Loss (P) is given in (1). Overall, P reflects link reliability; thus, its high values are associated with difficult signal reception conditions.

$$P = \frac{P_{tx}-P_{rx}}{P_{tx}} \times 100 \tag{1}$$

where

P : Packet Loss (%)

P_{tx} : Number of packets transmitted

P_{rx} : Number of packets received

BER is an important metric used to assess the precision and reliability of a digital communication system. BER can be defined as the ratio of the number of bits that are in error upon reception to the number of bits transmitted. In vehicles, maintaining a low BER is important for reliable communication. This metric is calculated using (2).

$$B = \frac{N_e}{N_{tx}} \tag{2}$$

where:

B : Bit Error Rate

N_e : Number of Erroneous Bits

N_{tx} : Number of Transmitter Bits

III. Results

This chapter presents the experimental results for two types of propagation: LOS and NLOS. Experiments have been conducted to measure the performance of vehicular communication with respect to its parameters, PL, BER, and SNR. In all experiments, Vehicle 1 sends information to Vehicle 2, including the license plate number, vehicle type, and vehicle color.

A. LOS Condition

In this section, the efficiency of the static V2V communication model will be examined under the assumption of LOS between two cars. In other words, a direct connection between the two antennas minimizes the effects of signal shadowing, fading, and interference. Therefore, LOS represents the optimal conditions for this system and serves as the basis for measuring its performance.

To avoid the influence of other factors and observe the effects of distance alone, vehicles remain stationary during the experiments. Thus, this approach enables the identification of the main characteristics of communication channel operation, such as path loss and noise level. In this respect, packet loss rate, BER, and SNR serve as major indicators.

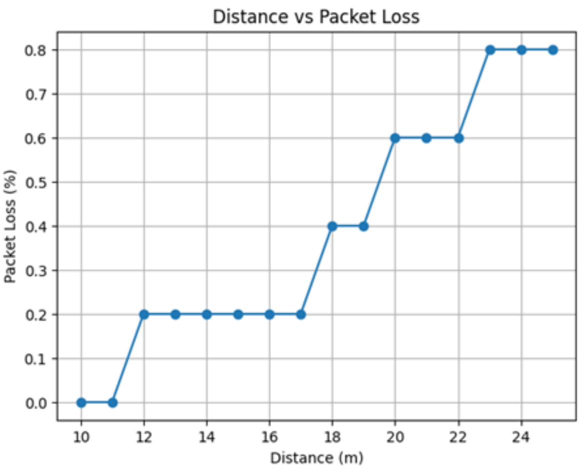

Fig. 5. Distance vs Packet Loss under LOS Condition

The relationship between vehicle separation and the frequency of packet losses is seen to deteriorate performance as the separation increases. Based on the results in figure 5, at a very small vehicle separation (between 10-11 m), no packet loss is observed, implying a highly reliable channel with strong received signal power and minimal interference. When the separation exceeds 12 m, packet losses begin to occur, increasing slowly to about 0.8% at separations greater than 23 m. The phenomenon can be explained by path loss: as separation increases, signal strength attenuates, leading to lower signal power and a higher probability of packet loss. The results are consistent with theoretical knowledge of wireless communication, since packet errors arise from attenuation and noise, which increase with distance. Despite the increase in losses, their value remains fairly low (less than 1%), highlighting the channel's reliability and the modulation scheme's efficiency.

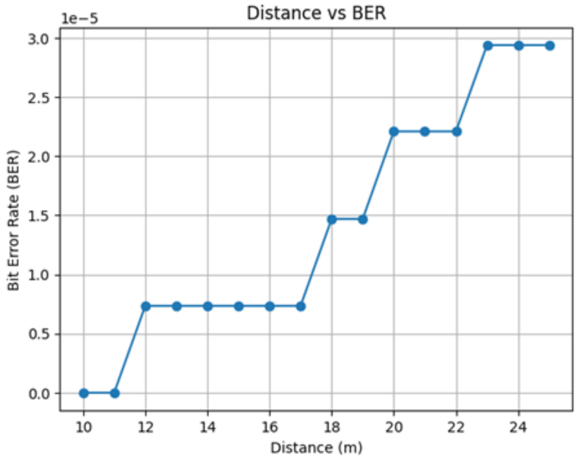

Fig. 6. Distance vs Estimated Bit Error Rate under LOS Condition

From the results in figure 6, as the link is extended, the BER increases in steps, mirroring the degradation in signal quality with increasing distance. At the beginning, there was no communication error, as the BER was zero due to the high SNR. As the distance increases, the BER rises from $7.35 \times 10^{-6}$to 2.94×10^{-5} because the probability of bit errors increases. This clearly indicates how BER, SNR, and distance influence each other, where with an increase in distance, the value of BER increases while that of received signal strength and hence SNR decreases. This gradual increase in the BER values reflects the robustness of BPSK modulation to channel noise.

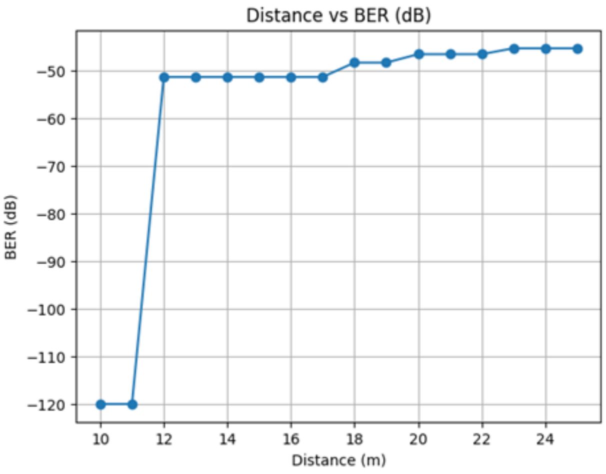

Fig. 7. Distance vs Estimated Bit Error Rate (dB) under LOS Condition

Based on figure 7, a logarithmic scale for BER provides a much more accurate view of the impact of distance on the link. In dB, the BER increases as you move farther from the source, indicating that the error performance deteriorates. At very short distances, the BER is extremely low, approaching −120 dB, indicating that communications are nearly perfect. As distance increases, the BER rises to −45 dB, highlighting the impact of signal degradation and noise accumulation. The trend is highly similar to the decreasing SNR observed due to signal attenuation at greater distances, while noise remains nearly constant. On a logarithmic scale, minor linear variations in BER have a significant effect on the link's relative performance. However, it still operates well within the acceptable range.

B. NLOS Condition

However, in practice, establishing a line-of-sight path between the two communicating vehicles may not be feasible due to obstructions from buildings, other vehicles, and the environment. This leads to challenges such as signal fading, shadowing, multipath, and interference, among others, that affect the system's performance. Therefore, it becomes essential to assess the performance of the V2V communication system under NLOS conditions for practical applicability.

This section presents the performance analysis of the proposed SDR-based V2V communication system, in which the direct propagation path between the transmitter and receiver is either partially or entirely obstructed. In an NLOS environment, the signal from the transmitter to the receiver propagates via diffraction, reflection, and scattering. This reduces the received signal strength and increases the wireless channel's variability, which would negatively affect system performance metrics such as packet loss rate and bit error rate.

As in the LOS experimental setups, stationary vehicles are used to distinguish between the effects of environmental interference and movement. The purpose of this experiment is to provide a thorough description of the behavior of the communication system in realistic radio-wave propagation environments by comparing results obtained in NLOS and LOS environments. The expected outcome is to determine the system's constraints and identify critical factors affecting its performance.

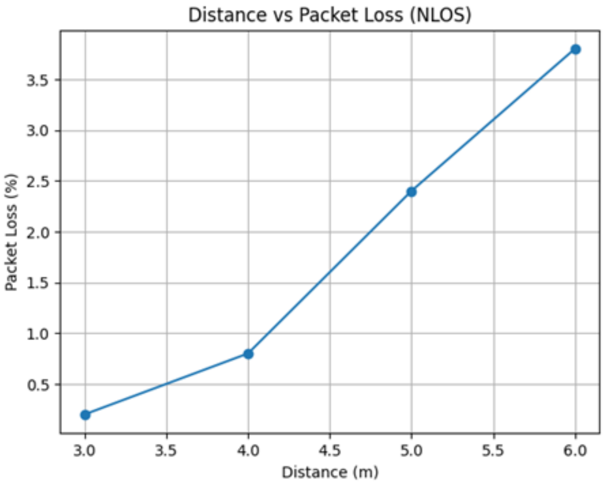

Fig. 8. Distance vs Packet Loss under NLOS Conditions

The correlation between vehicle spacing and the number of lost packets under NLOS conditions is highly inconsistent and nonlinear. Even at a mere 3 meters, nearly 0.2% of packets will fail, underscoring the need for line-of-sight communication for reliable information transmission. Increase the separation to 6 meters and expect the loss rate to surge to 3.8%, far beyond what one would expect in the LOS case. Such behavior is due to signal obstruction and multipath propagation – reflection, diffraction, and scattering distort the original signal on its way to the recipient. Interference and fading induced by such movements significantly increase the probability of corruption of the packet.

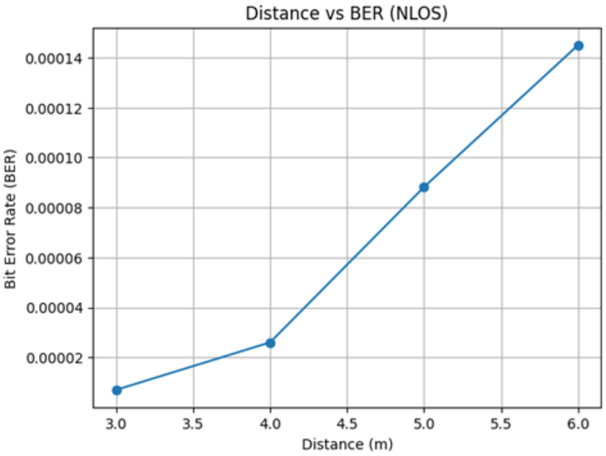

Fig. 9. Distance vs Estimated Bit Error Rate under NLOS Condition

BER in NLOS mode exhibits exponential degradation with increasing distance. At the mark of 3 meters, the BER value is equal to 10^{-6}, while it increases sharply to 1.45×10^{-4} by reaching 6 meters. This indicates that any increase in distance increases the probability of erroneous information reception. This trend is consistent with the concept of fading channels and is mainly due to multipath effects that lead to symbol detection failures. This is in contrast to LOS scenarios, where BER remains insignificant at greater distances. In contrast, in NLOS cases, the phase and amplitude of the transmitted signals exhibit randomness, which negatively impacts demodulation. Even BPSK cannot escape from the problem of communication breakdown in such an environment.

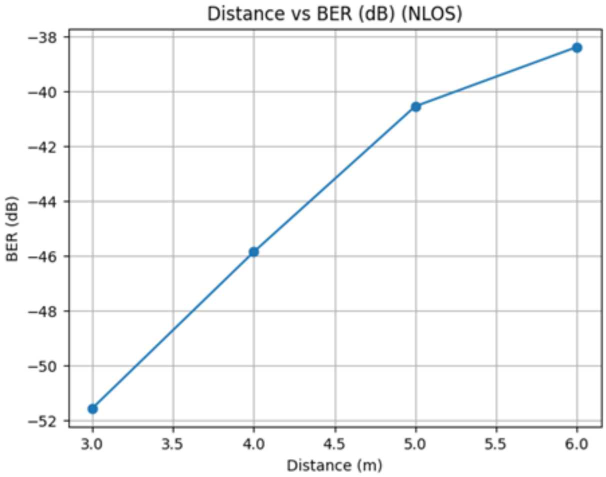

Fig. 10. Distance vs Estimated Bit Error Rate (dB) under NLOS Conditions

Regarding the BER graph plotted on a logarithmic scale, it is quite evident that performance degradation is significant in the NLOS scenario. As we see, as we move from 3 meters to 6 meters, the BER (in dB) increases from about -52 dB to roughly -38 dB, reflecting a significant decline in transmission quality after a very short distance. In this respect, the increase accounts for the impact of the impairments mentioned, resulting in reduced SNR values. With regard to the linear trend observed on the logarithmic graph, one can conclude that channel impairments strongly affect the communication process in question, leading to a constant degradation in performance. On the contrary, the BER level does not change significantly in the LOS scenario. Therefore, the degradation slope becomes quite steep in the NLOS scenario.

A clear distinction in V2V communication performance is evident between LOS and NLOS configurations, demonstrating that the environment has a significant influence on the process. In LOS communication, the link remains very stable and reliable at long distances, with negligible packet losses, close to zero BER, and constant SNR values, regardless of whether the distance exceeds 20 meters. However, in NLOS communication, performance has already decreased rapidly at short distances, such as 3-6 meters, due to higher packet losses, higher BER, and reduced SNR. This happens because, in the latter case, there is no direct line of sight, leading to greater attenuation, interference, and multipath effects. It means that environmental obstacles have a stronger effect on V2V communication than distance alone. In such a manner, LOS is considered optimal for communication, whereas NLOS corresponds to reality and calls for more complex measures.

IV. Conclusion

The present work details our process for designing, implementing, and evaluating the performance of a static V2V communication setup using an SDR-based platform in the context of a smart transportation system (STS). Performance was tested in both LOS and NLOS propagation scenarios, with PL, BER, and SNR as the primary performance metrics. Our results reveal that, in LOS propagation scenarios, our system provides highly reliable performance by maintaining extremely low PL, a BER close to zero, and a constant SNR, irrespective of distance, which reached up to 25 meters in our tests. However, in NLOS environments, our system experiences a significant reduction in performance, as PL and BER increase rapidly as distance decreases. The results suggest that environmental factors, such as the presence of obstacles, have a greater influence on system performance than distance alone. It may therefore be concluded that SDRs can be used successfully for V2V communications in STS, but there is a need to increase system robustness.

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