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PAPER

Implementation of IEEE 802.11p for Vehicular Communication: Utilizing NI USRP N321 to Advance Mobile Interactive Technologies

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ABSTRACT

This paper aims to comprehensively implement the Institute of Electrical and Electronics Engineers (IEEE) 802.11p transceiver using the Universal Software Radio Peripheral (USRP) device N321 series for teaching undergraduates. It is a standard in the 802.11 family designed explicitly for wireless access in vehicular environments (WAVE). This process involves configuring the USRP N321 device with IEEE standards, such as adjusting the frequency, amplitude, transmitter gain, direction of the radiation pattern, receiver gain, etc. This transceiver uses an orthogonal frequency division multiplexing (OFDM) modulation scheme. This IEEE 802.11p transceiver provides a practical approach for students and researchers in the real-world platform to analyze wireless communication technologies such as OFDM transceiver, peak-to-average power ratio (PAPR) values, and constellation diagrams for various modulation schemes such as binary phase shift keying (BPSK), quadrature amplitude modulation (QAM), and quadrature phase shift keying (QPSK) with different code rates. The bit error rate values were calculated for the modulation coding schemes index, and data rates of 24 Mbps were achieved for this transceiver.

KEYWORDS

Institute of Electrical and Electronics Engineers (IEEE) 802.11p, wireless fidelity (Wi-Fi), orthogonal frequency division multiplexing (OFDM), software defined radio (SDR), NI USRP N321

1 INTRODUCTION

The Institute of Electrical and Electronics Engineers (IEEE) 802.11 was introduced in 1999, which sets the protocols for WLANs and defines the medium access control layer (MAC) and physical layer (PHY) specifications. It supports the frequency of 2.4 GHz and 5 GHz bands and supports data transmission rates. So basically, this

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standard provides a clear foundation for WLAN technology [1]. This paper uses USRP devices to enhance network performance using time-sensitive network algorithms. It also addresses challenges in latency and synchronization, and the proposed method design uses software-defined radio (SDR) flexibility to adapt to network conditions [2]. The full-duplex transmission system is utilized in IEEE 802.11p standards in GNU Radio open-source software, and the performance evaluation is tested in the indoor wireless environment. Some metrics are packet delivery ratio and physical layer time latency [3]. This paper helps with understanding wireless fidelity (Wi-Fi) standards and their deployment in system-on-chip architecture, and it aims to provide flexible solutions for open Wi-Fi with real-time capabilities [4]. The investigation of different waveform configurations is implemented in SDR platforms, and performance metrics such as efficiency and integrity are used in this system [5]. The system uses ZigBee and Wi-Fi devices for dynamic protocol and uses a gateway between two network types and various signal processing blocks. The simulation results show that the SDR approach efficiently integrates Wi-Fi and Zigbee networks [6].

This paper shows that the SDR protects Wi-Fi networks under de-authentication and spoofing attacks, which use GNU blocks to generate malicious traffic and exploit vulnerabilities in Wi-Fi networks [7]. This paper uses visible light communication, which is also one of the IEEE standards for vehicular environments. The author addresses different challenges, such as different modulation schemes and synchronization in outdoor environments. The results show the high-speed communication in vehicular environments [8]. The Vehicle to Everything (V2X) interactions in traffic management and coordination at intersections play a significant role in latency and data throughput. This aims to improve self-driving car applications to enhance safety and efficiency [9].

This paper examines the security of V2V communication by using various security protocols and vectors in the SDR environment. The evaluation of different security measures for different attacks and vulnerabilities is discussed [10]. This paper evaluates the performance of IEEE 802.11p in vehicular environments, considering the impact of realistic channel conditions, mobility, and interference. The authors propose methods to improve communication reliability and reduce delays in safety-critical applications [11]. This paper addresses the challenges of resource allocation in IEEE 802.11p-based vehicular networks. The authors introduce adaptive techniques for efficient spectrum and power management to enhance network capacity and reliability in high-speed environments [12].

2 SYSTEM DESCRIPTION

2.1 Universal software radio peripheral N321

Ettus Research developed this USRP device for advanced communication system research and development. It has a field-programmable gate array and a flexible RF front end, and it supports signal processing blocks in the range of 70 MHz to 6 GHz. This device supports a 10 Gigabit Ethernet interface for massive data transfer and ensures extensive bandwidth support. This device is compatible with MATLAB GNU Radio and supports flexibility for different signal processing applications. It supports various applications such as radio detection and ranging (RADAR), global positing system (GPS), global navigation satellite system (GNSS), frequency modulation (FM) RADIO, digital video broadcasting (DVB), and digital audio broadcasting (DAB). It has robust performance and a wide range of various applications in wireless technology development.

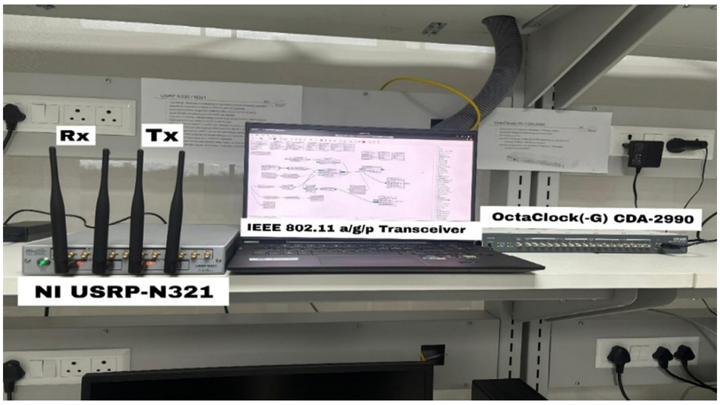


Fig. 1. Experimental setup using N321 and Octa-clock CDA 2990

The labelled "Rx" and "Tx" antennas indicate the receiver and transmitter chains used in wireless communication experiments. The Octa Clock unit provides a clock distribution for synchronizing multiple USRP devices. Clock synchronization ensures coherent operation across different SDR units, especially in applications such as MIMO or distributed communication systems. The CDA-2990 ensures that all USRP devices receive the same clock signal, minimizing phase noise and improving signal quality, as shown in Figure 1. The N321 and Octa-Clock CDA 2990 were interconnected via standard signal cables (e.g., BNC), with the N321 providing a master timing signal. Synchronization was achieved using a shared clock reference, ensuring accurate phase alignment across all connected devices.

2.2 Hands-on exposure to SDR technology

- The USRP N321 allows students to interact directly with an SDR, which enables real-time signal processing, modulation, and communication. This hands-on experience helps students in bridging the gap between theoretical concepts in signal processing and their practical applications.
- Students can configure the system for different communication protocols (e.g., LTE, 5G, Wi-Fi) and experiment with adjusting parameters such as modulation schemes, power levels, and bandwidth. This flexibility empowers students to apply theoretical knowledge in designing, implementing, and testing real-world communication systems.

2.3 IEEE 802.11 a/g/p standards

IEEE 802.11a was introduced in 1999, and standards support different WLAN communications protocols, each operating with different frequency bands. IEEE 801.11a has a different range of channels and supports a 2.4 GHz band and a data rate of 54 Mbps, and this data rate is much higher than the older IEEE 802.11b standard. It uses OFDM technology, which reduces congestion and improves overall performance. The indoor range is around 75 meters due to high signal attenuation from other 2.4 GHz systems. It uses 64 QAM modulation to achieve high data rates and less co-channel interference. It is mostly used in offices and enterprise networks.

IEEE 802.11g, introduced in 2003, supports the 2.4 GHz band and a maximum data rate of 54 Mbps, utilizes OFDM modulation, and is compatible with 802.11b. This standard divides the 2.4 GHz band into overlapping channels and increases the interference compared to non-overlapping channels of 802.11a. The indoor range is only 30 to 50 meters.

IEEE 802.11p, released in 2010, is tailored for vehicular communication, operating in the 5.9 GHz band. It supports data rates up to 27 Mbps in 10 MHz bandwidth and is designed to facilitate V2X communication, which includes Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) interactions. It has some advantages, such as low latency and high throughput support between vehicles and V2X for different roadside infrastructures. It is used in applications such as collision avoidance, real data exchange, and traffic signal control to improve road safety and traffic efficiency. With various robust communication frameworks, the IEEE 802.11p plays a significant role in intelligent transport systems (ITS).

2.4 Contributions to IEEE 802.11p implementations for vehicles

This study provides a comprehensive performance evaluation of IEEE 802.11p under realistic vehicular conditions, leveraging the advanced capabilities of the USRP N321 platform. The study demonstrates how factors such as mobility, interference, and environmental variations impact communication reliability by analyzing key metrics such as BER (bit error rate), latency, and throughput.

Unlike previous studies that rely on idealized channel models (e.g., AWGN or simple Rayleigh fading), this research incorporates more realistic channel conditions, including multipath fading, non-line-of-sight (NLOS) propagation, and urban interference. These models provide a more accurate representation of vehicular communication environments.

2.5 IEEE 802.11p transmitter and receiver block diagram

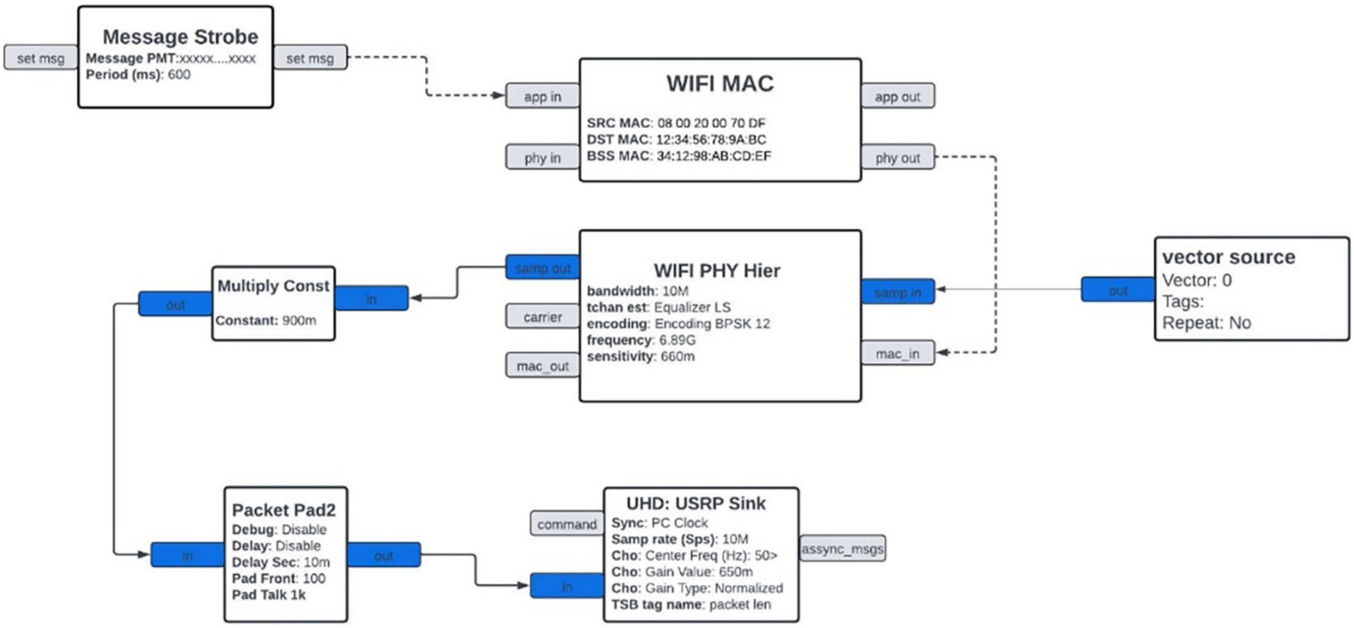


Fig. 2. IEEE 801.11p transmitter block diagram in GNU Radio software

Figure 2 shows a block diagram representing a Wi-Fi transmitter chain implemented using GNU Radio, a toolkit for building software-defined radios.

1. **Message Strobe:** This block generates periodic messages at a 600 ms interval, subsequently fed into the Wi-Fi MAC block. The PMT format (polymorphic type) suggests a flexible message type for further processing.
2. **Wi-Fi MAC:** The Wi-Fi medium access control (MAC) layer block takes in the periodic messages and encapsulates them in MAC frames. The source MAC address is set to 08:00:20:00:70:DF, the destination MAC address is set to 12:34:56:78:9A:BC, and the BSS MAC address (used for network association) is 34:12:98:AB:CD:EF. The MAC block outputs a stream fed to the Wi-Fi PHY hierarchy block.
3. **Wi-Fi PHY Hier:** This block represents the Wi-Fi physical (PHY) layer, configured with a 10 MHz bandwidth, a BPSK modulation scheme, and operating at a frequency of 6.89 GHz. The block uses an LS equalizer for channel estimation. The output of the PHY block is sent as sample data for transmission.
4. **Multiply Const:** This block scales the signal by a constant factor of 900 m, representing a gain adjustment or a scaling factor before feeding it into the packet pad block.
5. **Packet Pad2:** This block adds padding to the signal, which is crucial for ensuring that packets are aligned and maintain proper timing. Padding parameters include a 100-sample front padding and 1k-sample tail padding, with the debug and delay functions disabled.
6. **UHD: USRP Sink:** The final block in the chain, the UHD (USRP hardware driver) Sink, transmits the processed signal through a USRP device. The block is synchronized to the PC clock, with a sample rate of 10 MHz and a center frequency set just above 50 Hz. Gain parameters include a 650 m gain value, a normalized gain type, and the TSB tag name for packet length management.

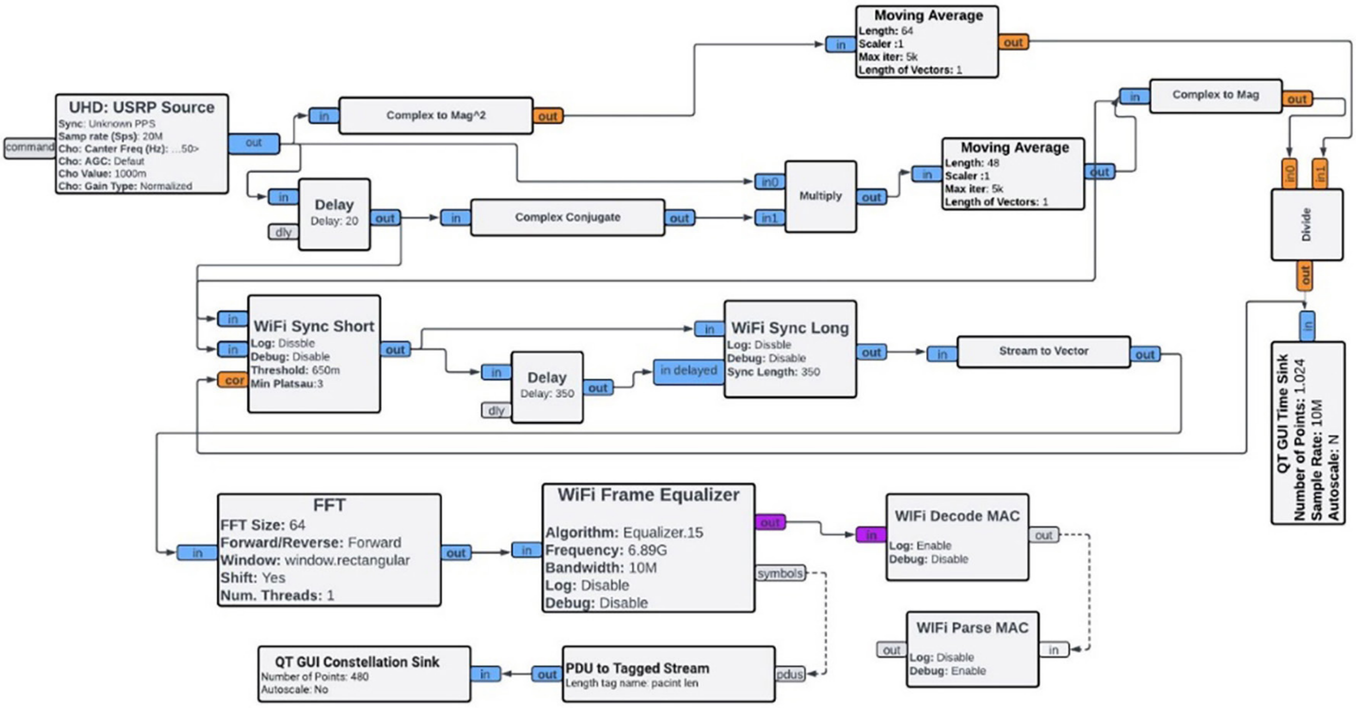


Fig. 3. IEEE 802.11p receiver using GNU radio blocks

Figure 3 shows the receiver block diagram illustrating a Wi-Fi receiver chain implemented using GNU Radio, designed to process signals captured by a USRP device.

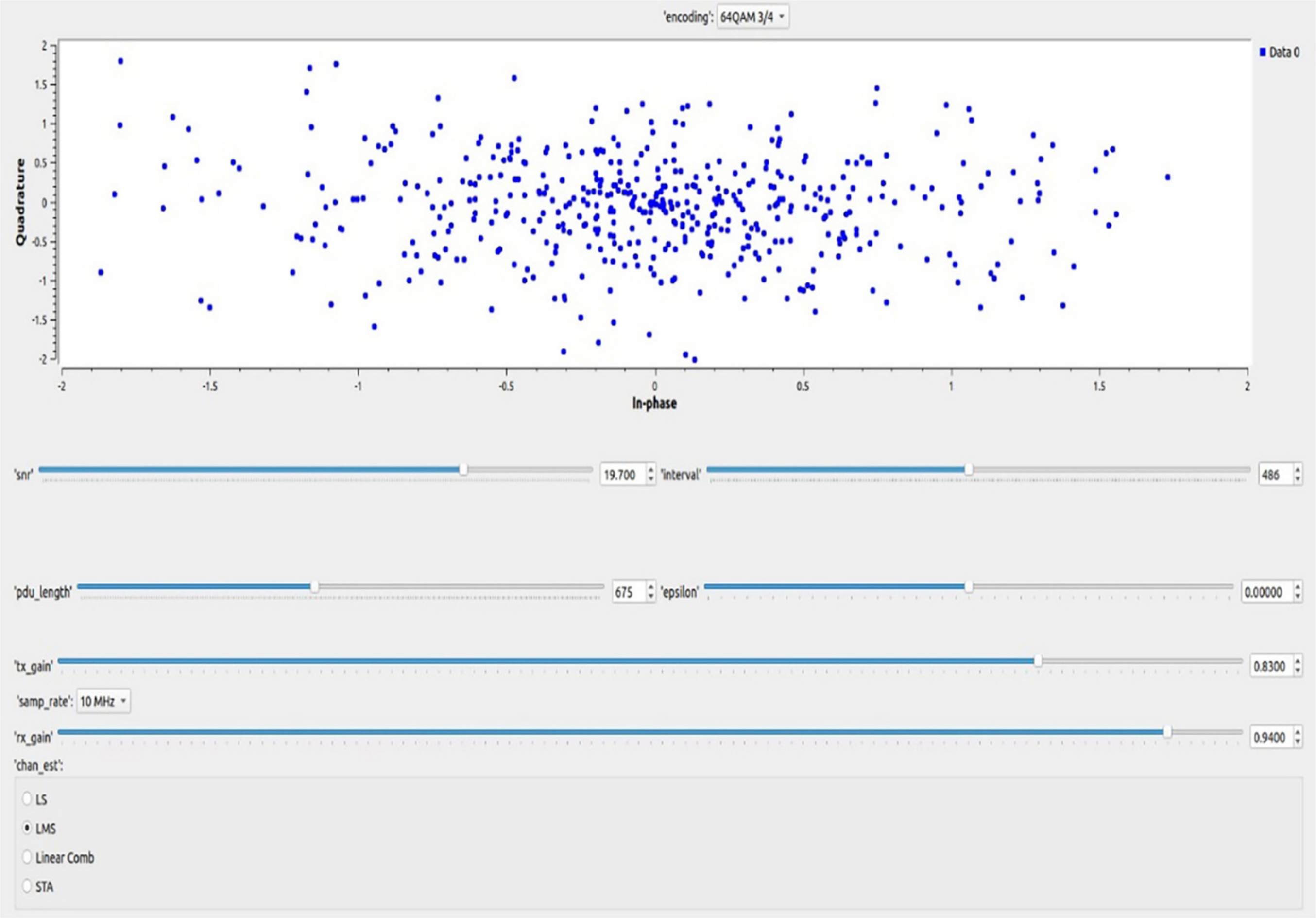
1. **UHD: USRP Source:** The receiver chain begins with the USRP Source block, which captures the RF signals. The sample rate is 20 MSps, with the center frequency slightly above 50 Hz. Gain is normalized, and AGC is set to default.
2. **Complex to Mag^2:** This block calculates the magnitude squared of the incoming complex signal, which is helpful for power detection and synchronization tasks.
3. **Moving Average:** Two moving average blocks smooth the signal to assist with detection. The first has a length of 64 and is directly connected to the complex to Mag^2 block. The second has a length of 48 and is used with magnitude calculations for finer adjustments.
4. **Complex Conjugate and Multiply:** This combination of blocks performs correlation for signal synchronization. The complex conjugate block processes the signal, and the resulting output is multiplied by the original signal to aid synchronization.
5. **Wi-Fi Sync Short:** This block performs short preamble synchronization, helping to detect the start of Wi-Fi packets. It is configured with a threshold of 650 m and a minimum plateau of 3 to ensure reliable detection.
6. **Wi-Fi Sync Long:** Following the short sync, the long sync block aligns the signal more precisely using a longer preamble. A delay of 350 samples is introduced to align the incoming signal correctly before processing.
7. **FFT:** The FFT block converts the time-domain signal into the frequency domain using a 64-point FFT with a rectangular window, essential for decoding the OFDM subcarriers in the Wi-Fi signal.
8. **Wi-Fi Frame Equalizer:** This block equalizes the received Wi-Fi frame to compensate for channel impairments. It uses an equalizer algorithm (Equalizer 15) with a bandwidth of 10 MHz centered at 6.89 GHz.
9. **Wi-Fi Decode MAC:** After equalization, the signal is passed to the Wi-Fi Decode MAC block, where the MAC layer frames are extracted from the PHY layer.
10. **Wi-Fi Parse MAC:** Finally, the parsed MAC frames are processed to retrieve the original data packets, and debug logs are enabled for verification.
11. **QT GUI Time Sink:** The processed signal is visualized in real-time using the QT GUI Time Sink, with parameters set to monitor a sample rate of 10 MSps over 1024 points.
12. **QT GUI Constellation Sink:** This block provides a constellation diagram of the received signal, which is crucial for analyzing modulation schemes and ensuring proper demodulation.

This receiver chain is designed to capture, synchronize, equalize, and decode Wi-Fi signals, effectively recovering transmitted data for further processing and analysis.

3 RESULTS AND DISCUSSIONS

Figure 4 shows the constellation diagram of a communication system, most likely for a wireless signal using 64-QAM (Quadrature Amplitude Modulation) with a 3/4 coding rate. The diagram plots signal points (symbols) in I/Q plane, representing different symbol states transmitted over the communication channel. The signal's in-phase (I) and quadrature (Q) components are shown on the x and y axes, respectively.

The scatter of the points indicates the modulation quality and the presence of noise and distortion. Ideally, the points would cluster tightly in a noise-free environment at specific coordinates corresponding to the ideal symbol locations. However, in this case, the spread of points around each ideal location suggests some signal degradation, potentially due to channel impairments, noise, or imperfect synchronization.



'encoding': 64QAM 3/4

'snr' 19.700

'interval' 486

'pdu_length' 675

'epsilon' 0.00000

'tx_gain' 0.8300

'samp_rate': 10 MHz

'rx_gain' 0.9400

'chan_est':

○ LS
● LMS
○ Linear Comb
○ STA

Fig. 4. Screenshot of QAM-based in-phase quadrature phase plot in receiver

The other parameters allow the users to fine-tune the transmission and reception characteristics. These include SNR (signal-to-noise ratio), pdu_length (protocol data unit length), tx_gain (transmit gain), rx_gain (receive gain), and samp_rate (sampling rate). These settings influence the quality and reliability of the transmitted signal.

Different channel estimation algorithms are available, such as LMS (least mean squares), LS (least squares), linear combination, and STA (space-time adaptive). The selected method, LMS, aims to minimize error by adjusting the weights in the system based on the error between the predicted and actual received symbols. The interface also controls the interval and epsilon parameters, which might relate to timing or threshold settings critical for the system's performance.

Table 1. Data rate calculation for different modulation schemes and coding rate

MCS Index	Modulation Type	Coding Rate	Data Rate (Mbps)
0	BPSK	½	3
1	QPSK	½, ¾	6,9
2	16-QAM	½, ¾	12,18
3	64-QAM	⅔, ¾, ⅚	24,27,30

Table 2. BER vs. SNR for different modulation schemes and coding rate

MCS Index	Modulation Type	SNR	BER	Coding Rate
0	BPSK	10	10^{-3}	1/2
1	QPSK	12	10^{-4}	1/2
2	QPSK	14	10^{-5}	3/4
3	16-QAM	16	10^{-6}	1/2
4	16-QAM	18	10^{-7}	3/4
5	64-QAM	20	10^{-8}	2/3
6	64-QAM	22	10^{-9}	3/4
7	64-QAM	24	10^{-10}	5/6

$$\text{Data Rate} = \text{Symbol Rate} \times \text{Bits per Symbol} \times \text{Coding Rate} \tag{1}$$

$$BER_{bpsk} = \frac{1}{2} erfc(sqrt(SNR)) \tag{2}$$

$$BER_{qpsk} = \frac{1}{2} erfc(sqrt(SNR/2)) \tag{3}$$

$$BER_{bpsk} = \frac{3}{2} erfc(sqrt(SNR/10)) \tag{4}$$

The specific real-time data can vary depending on the environment, equipment, and testing conditions. The SNR to BER relationship in IEEE 802.11p demonstrates how the clarity of the signal (SNR) impacts the likelihood of bit errors (BER). The modulation scheme and coding rate influence this relationship, and theoretical models or empirical data are used to predict and analyze this relationship for different operating conditions. The calculations of Tables 1 and 2 are derived from Equations [1], [2], [3], and [4].

3.1 Testing conditions

1. Hardware platform: The experiments were performed using the USRP N321 hardware, a high-performance SDR platform suitable for advanced wireless communication research are shown in Table 3.
2. Software environment: The tests were implemented and executed using GNU Radio, a versatile open-source framework for SDR development.
3. Modulation schemes: The system employed quadrature phase shift keying (QPSK) and various QAM levels, such as 16-QAM and 64-QAM, to evaluate performance under different modulation complexities.
4. Signal parameters: The following parameters were configured using standard values:
    - Signal bandwidth: 15 MHz
    - Carrier frequency: 2.4 GHz for the hardware
    - Sampling rate: 10 MS/s, as per design
5. Channel models: The channel conditions assumed were AWGN (Additive White Gaussian Noise), Rayleigh fading, or real-world over-the-air testing].

6. Environment setup and measurement tools: The tests were conducted in a controlled environment to minimize interference and ensure repeatability. Real-world testing conditions were emulated where necessary. BER values were calculated based on the received data streams and compared against transmitted sequences to quantify errors accurately.
7. Assumptions and simplifications: All testing was conducted under the assumption of ideal synchronization between transmitter and receiver, with no consideration of hardware imperfections such as phase noise or oscillator drift.

Table 3. Comparison between existing methods and proposed methods

Aspect	Existing Methods	Proposed Method
Hardware Platform	Use of USRP N210 and earlier SDR platforms. Studies such as [13], [14] use older USRP models for V2X communication research.	USRP N321 is a more advanced platform offering higher bandwidth, improved signal processing capabilities, and better support for 5G.
Communication Protocols	Focus on protocols such as IEEE 802.11p, LTE-V2X, and 5G NR V2X, mainly using basic modulation schemes such as QPSK and OFDM [15].	Evaluation of 5G NR V2X and advanced SDR modulation schemes such as MIMO and adaptive modulation, with improved interference management and data throughput in dynamic environments.
Testing Environments	Often simulated or semi-controlled environments with simplified channel models such as AWGN or Rayleigh fading [16], [17], [18], [19], [20], [21].	Realistic channel models simulating multi-path fading, non-line-of-sight (NLOS), and urban interference, reflecting true vehicular communication.

4 CONCLUSION AND FUTURE SCOPE

This project effectively utilized a SDR testbed to evaluate the security of V2V communications. By configuring the SDR environment to simulate various V2V scenarios, we assessed the performance of multiple security protocols against a range of potential attack vectors. The study confirms that robust security mechanisms are essential for mitigating risks and ensuring secure V2V interactions, thus enhancing the integrity of vehicular communication systems in practical deployments.

Future research can explore integrating adaptive modulation techniques and dynamic resource allocation algorithms to optimize communication in dense urban traffic and high-mobility scenarios. Advanced channel modelling can be extended to include weather-related interference, such as rain fade or fog, and the impact of high-speed vehicular scenarios (e.g., highways) on IEEE 802.11p performance.

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