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Simulation of a Communication Channel Assisted by an Intelligent Reflecting Surface for Vehicular Scenarios

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ABSTRACT

An Intelligent Reflecting Surface (IRS) is a sophisticated technology that utilizes an array of tunable reflective elements to modulate the amplitude, phase, and direction of the reflected electromagnetic wave. This capability has the potential to enhance the range and efficiency of communications networks to a considerable extent. Vehicular Ad-hoc Networks (VANETs), are a type of communication network that utilizes vehicles as nodes to establish connections when they are in close proximity to each other. In areas characterized by limited coverage or unfavorable propagation conditions, such as intersections with obstacles, the IRS has the potential to enhance vehicle-to-vehicle (V2V) communications. The VANET Toolbox, an integrated vehicular network simulator developed in MATLAB, is a notable tool for testing before the deployment of systems. Despite its advantages, the absence of an IRS-assisted channel presents an opportunity to enhance its functionality and to include the analysis of IRS-enabled vehicular communications. This enhancement substantially advances the toolbox's ability to model coverage and quality of service in high-density urban environments, where conventional communication strategies often encounter significant limitations. This work implements both an IRS-assisted channel and a multipath channel. A series of tests were conducted to assess the efficacy of the IRS tool within the simulator.

Keywords: Intelligent Reflecting Surface, Vehicular Networks, MATLAB

1. -INTRODUCTION

In the context of the rapid advancements in communication technologies, the implementation of 5G and the Internet of Things (IoT) has led to a substantial proliferation of connected devices, resulting in network saturation and the exhaustion of radio spectrum. This proliferation has resulted in an escalation in interference and power consumption. The spread of IoT is driving a trend towards the interconnection of all elements of society, including vehicles. The future vision is moving towards an automated and efficient environment, where smart cities are a goal for countries with large metropolitan areas. These cities often experience dense traffic that is susceptible to congestion and frequent traffic accidents.

In order to address these issues, the development of vehicular ad hoc networks (VANETs) is underway to establish connectivity between vehicles and among vehicles and other infrastructure. However, in urban environments characterized by a plethora of buildings, obstacles, and interference, wireless communication poses a significant challenge. In this context, Intelligent Reflecting Surfaces (IRS) emerge as a pivotal solution. These surfaces possess the capability to redirect electromagnetic signals in a dynamic and programmable manner, thereby mitigating issues related to inadequate coverage. These surfaces are designed to address the global energy problem by consuming significantly less energy without compromising signal strength.

The IRS constitutes an advanced technology that utilizes an array of tunable reflective elements to govern the amplitude, phase and direction of the reflected electromagnetic wave. This capability has the potential to enhance the coverage and efficiency of communication networks to a considerable extent. The architecture of the IRS is typically comprised of three layers, in addition to an intelligent controller, as illustrated in Figure 1. The first/outer layer comprises a large number of

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tunable/reconfigurable metal patches printed on a dielectric substrate, with the purpose of directly manipulating the incident signals. The second layer, or middle layer, typically consists of a copper plate, which is utilized to minimize signal energy leakage during IRS reflection. The third and final layer is constituted by a control circuit board, the function of which is to excite the reflecting elements and to tune their reflection amplitudes and/or phase shifts in real time. In addition, the reflection adaptation is triggered and determined by an intelligent controller connected to each IRS, which can be implemented by an FPGA [1].

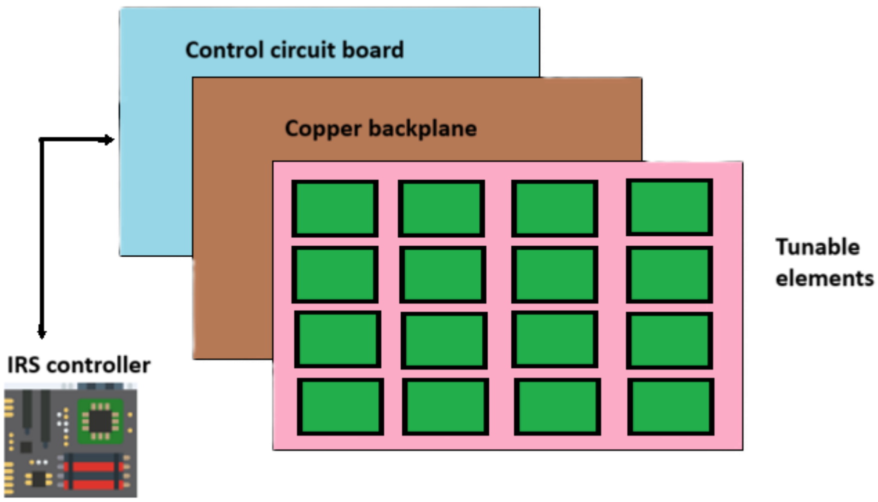


Figure 1. IRS architecture.

Ad-hoc networks (VANETs) are a type of communication network that uses vehicles as nodes to establish connections when they are in close proximity to each other. This is critical for road safety, traffic management, and accident prevention. These networks are foundational to the development of intelligent transport systems and the future of autonomous vehicles. In areas with limited coverage or unfavorable propagation conditions, such as traffic intersections with obstructions, the Intelligent Road System has been shown to enhance vehicle-to-vehicle (V2V) communication. This is particularly beneficial for vehicles positioned on perpendicular streets, which otherwise face challenges in effective communication. It is important to note that throughout this work, IRS refers to Intelligent Reflecting Surface, and should not be confused with the acronym of Intelligent Road System.

The VANET Toolbox is a comprehensive vehicular network simulator developed in MATLAB, which incorporates a Simulink library containing the fundamental components of the vehicular communication protocol stack. Nevertheless, its applicability to emerging research domains has been constrained by the absence of support for IRS. The principal contribution of this work lies in the integration of an IRS-assisted channel model into the simulator, thereby extending its functionality to encompass the analysis of IRS-enabled vehicular communications. This enhancement substantially advances the toolbox's ability to model coverage and quality of service in high-density urban environments, where conventional communication strategies often encounter significant limitations. Specifically, an IRS-assisted channel model, combined with a multipath fading channel, has been designed and implemented. A series of test scenarios were conducted to demonstrate the effectiveness of the proposed extension, confirming its added value as a robust tool for the study and planning of IRS-enhanced vehicular networks.

The remainder of the paper is structured as follows: Section 2 introduces the use cases of IRS-assisted vehicular networks and reviews related work. Section 3 compares different VANET simulators. Section 4 details the architecture of the utilized software. Section 5 describes the implementation of novel communication channels within the software framework. The subsequent sections, namely Section 6 and Section 7, present the simulation scenarios and the ensuing results, respectively. The paper concludes with Section 7.

2.- Use cases for IRS-assisted vehicular networks and related works

IRS offers attractive advantages from an implementation standpoint. First, IRS are generally manufactured with a low profile, light weight, and compliant geometry, which facilitates their mounting/dismounting on walls, ceilings, building facades, and advertising panels. Since the IRS is a complementary device in wireless networks, implementing it in existing wireless systems (e.g., cellular or WiFi) does not require changing their standardization and hardware. As a result, the integration of the IRS into wireless networks can be made transparent to users, thus providing great flexibility and superior compatibility with existing wireless systems. Therefore, the IRS can be implemented and integrated into wireless networks at low cost [2].

Several use cases for IRS-assisted vehicular networks are:

- Underground tunnels: Tunnels present challenges for wireless communication due to the lack of line of sight. The IRS can reflect signals from the tunnel entrance into the interior [3].
- Offloading tasks in vehicle networks: In intelligent transportation systems, vehicles connect to the network to process critical and urgent tasks, such as safety and navigation. Mobile edge computing (MEC) enables offloading services, but its efficiency depends on stable communication. The IRS supports achieving such communication [4].
- Physical layer security: Connectivity in vehicular networks increases physical security risks. IRS can enhance the desired signal or suppress unwanted signals, constructing new propagation paths and improving security against eavesdroppers by controlling the reflected signal. In [5] and [6], the security of vehicle networks using IRS is studied. In [7], the approach to canceling the signal filtered to the eavesdropper in IRS-assisted mobile networks is studied.
- Doppler mitigation: The IRS can compensate for Doppler shift in V2X systems, improving signal quality and reliability. This is crucial for advanced applications such as autonomous driving and traffic management [8].
- Enabling coverage in dark areas: In areas with limited coverage or unfavorable propagation conditions, such as traffic intersections with obstructions, the IRS can improve V2V communication by reflecting signals and increasing coverage installed on the surfaces of buildings around the intersection. This is especially useful for vehicles on perpendicular streets that would otherwise not communicate well with each other. Figure 2 illustrates an IRS-assisted vehicle communication scenario similar to the one intended for implementation in the simulation, the latter being the use case chosen for the IRS in this research [9], [10].

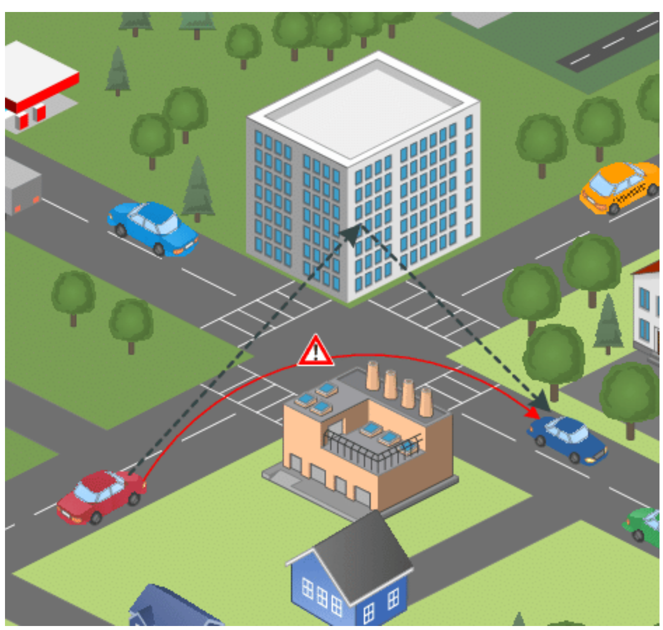


Figure 2. Intelligent Reflecting Surface in the intersection [11]**.**

There is extensive research into the development of intelligent reflective surfaces in millimeter bands, where the dimensions of the prototypes are only a few square centimeters, which facilitates their experimental implementation. As an example, [12] presents a 100 mm × 100 mm IRS, composed of 20 × 20 elements with a spacing of 5 mm, designed to operate at 28.5 GHz. In [13], a 200 mm × 200 mm IRS with 1600 elements and a spacing of λ/2 is reported, also at 28.5 GHz. Meanwhile, in [14], an 86 mm × 86 mm IRS is manufactured, with 16 × 16 elements, operating at 27.2 GHz. Finally, [15] presents an IRS with 20 × 20 elements, each one with size of 3.85 mm x 3.85 mm and total surface area of 77 mm × 77 mm and a center frequency of 27.5 GHz.

At the same time, significant advances have also been made in IRS operating at lower frequencies, such as those corresponding to the sub-6 GHz band with great importance for VANET and the 802.11p standard. In [16], a 55 × 20 element IRS (1100 in total) is described, with dimensions of 800.8 mm × 313 mm and a frequency of 5.8 GHz. In [17], a 10 × 10 element IRS is reported, spaced λ/2, with a frequency of 5.3 GHz and approximate dimensions of 304 mm × 304 mm. In [18], an IRS with 2430 elements and a surface area of 1140 mm × 1116 mm is presented, designed to operate at 3.5 GHz. This study shows that such entities can be used in 5G as well as future 6G networks for ensuring an enhanced coverage footprint and a seamless connectivity to the users [18]. Similarly, [19] describes a 3.5 GHz IRS composed of 10 × 10 elements measuring 42 mm × 42 mm, resulting in an area of 420 mm × 420 mm. Finally, in [20], two IRSs are manufactured: the first at 2.3 GHz, with 16 × 16 elements, spaced 50 mm apart and with a size per element of 37 mm × 37 mm, reaching an area of 800 mm × 800 mm; the second, at 28.5 GHz, does not specify dimensions, but it is noted that a similar design philosophy is followed, using elements of size λ/3.5.

Additionally, other frequency bands have been explored. In [21], three IRSs are reported: the first, with 100 × 102 elements measuring 10 mm × 10 mm, with a surface area of 1000 mm × 1020 mm and a frequency of 10.5 GHz; the second, with 50 × 34 elements with the same dimensions per element and operating frequency, reaching an area of 500 mm × 340 mm; and the third, with 8 × 32 elements measuring 12 mm × 12 mm, with an area of 96 mm × 384 mm and a frequency of 4.25 GHz.

In summary, the literature shows a wide diversity of operating frequencies, configurations, and dimensions in IRS design. However, the key point to highlight is that this technology is still in an experimental stage and is being validated using laboratory prototypes. To date, no actual deployment in practical scenarios has been documented, and the available evaluations are based primarily on simulations and controlled measurements. Consequently, there are no verified implementations in real VANET network environments.

3.- COMPARISON BETWEEN VANET SIMULATORS

A plethora of VANET simulation frameworks, encompassing both commercial and open-source models, exist. These frameworks diverge in their implementation of the wireless stack, the network, and mobility. To select the most suitable tool, a comprehensive analysis of the advantages and disadvantages is necessary to ascertain the optimal choice for a given application. Two broad categories of VANET simulators have been identified: The first category is that of integrated simulation frameworks, while the second is that of joint simulation frameworks.

Integrated frameworks incorporate network and traffic simulators into a unified simulator, enabling comprehensive interaction. Examples include Matlab's VANET Toolbox [22], MoVes [23], the NCTUns simulator [24], and VISSIM [25]. In contrast, joint frameworks encompass a multitude of simulation components. The primary components of joint frameworks can be classified according to [26] in: (1) Network simulators, which are the most frequently used in simulation of VANET, OMNeT+ [27], NS-2 [28], NS-3 [29], and JiSt [30]; (2) Mobility generators, among which are SUMO [31], MOVE [32], CityMob [33], PARAMICS [34], and MoNoTrac [35]; and (3) Interface to associate traffic mobility simulators with existing network simulators. Examples of such simulators include Veins, VENTOS [36], iTETRIS [37], and TraNS [38].

In order to comprehend the distinction between the joint and integrated frameworks, a comparative study will be conducted between two frameworks that represent the two directions. The first is a networked vehicle simulator known as Veins, which is a joint simulation framework, and the second is MATLAB's VANET Toolbox, which is an integrated framework. The Table 1 offers a synopsis of the salient contrasts between these two frameworks.

It is evident that both frameworks exhibit a commendable simulation of the vehicular network stack, particularly in the lower layers. However, the implementation of the physical (PHY) layer in the VANET Toolbox can be more accurate than in Veins. This discrepancy can be attributed to the use of abstractions in Veins, which facilitates the omission of specific details related to wireless communication implementation, such as channel estimation, frequency offset estimation and correction, and waveform modulation and demodulation [36]. A thorough comparison of seven VANET simulators can be found in [36], which provides further insights into the subject.

Table 1 Comparison between Veins and VANET Toolbox [19].

Aspect	Veins	VANET Toolbox
Supported applications	V2V and V2X	V2V
Network simulator	OMNeT++	MATLAB/SIMULINK
Simulator availability	Open source	Commercial
Code availability	Open source	Open source
Simulation languages	C++ and NED	MATLAB
Mobility generators	SUMO	Does not use external simulators
Road map	Real and user-defined maps	Customized (Road and Crossroads)
Framework Extensions	Available	Not available
VANET Protocols	IEEE 802.11p /802.11e/1609.4	IEEE 802.11p/802.11a/1609.4
Ease of use	More difficult	Easier

The VANET Toolbox simulator was chosen for this research because it provides access to individual bits within a waveform, allowing for accurate simulations of the PHY layer and channel models, which are omitted by other simulators that work at the network packet level. This is essential for this research, as the aim is to analyze the signal-to-noise ratio received in the proposed communications system, and this parameter is analyzed using bit energy. Furthermore, its ease of use, as it is based on MATLAB, gives it an advantage in terms of accessibility and rapid deployment of simulations and scenarios.

4.- VANET SOFTWARE STRUCTURE

This section describes the process of implementing the IRS-assisted channel and the multipath channel within the chosen VANET simulator in order to fulfill the research objective: to simulate an IRS-assisted communication channel for vehicular environments in MATLAB. The fundamental purpose of this section is to understand the operation and structure of the simulator in order to decide in which segment of code the new communication channel models should be added.

VANET Toolbox is an integrated vehicular network simulator developed using MATLAB SimEvents and MATLAB Discrete Event System (DES). This combination allowed the creation of a hybrid simulation system controlled by time and events. The framework includes a Simulink library with the basic components for the vehicular network stack (APP – MAC – PHY), as well as network nodes such as vehicles and traffic lights, as shown in Figure 3 [39].

VANET does not use any external tools for mobility simulation, but rather implements mobility algorithms in the application layer. It supports lane changes, conservative lane changes, car tracking, regular braking, and emergency braking. Currently, the framework supports two route maps for mobility simulation: a road map and a traffic intersection map [22].

Figures 4 and 5 show the internal structures of each component block used in the simulations. It can be seen that the component blocks are composed of one or more network layer blocks. Each network layer block is composed of its corresponding network layer class. For example, the Vehicle block contains an application layer block and an OBU (On- Board Unit) block, the latter containing an access layer block, which communicates with the physical layer block via connected inputs and outputs.

The APP DES application layer is responsible for generating basic safety messages (BSM) at fixed intervals (0.1 s) and critical safety messages in response to different traffic scenarios, such as emergency braking situations. When it receives messages from the MAC layer, the APP DES extracts the message information and forwards it to the mobility models according to their types.

The MAC layer in VANET Toolbox manages Enhanced Distributed Channel Access (EDCA) (assigning priorities to various messages so that messages with higher priority have less delay in channel disputes), according to the IEEE 802.11p standard, transforming payloads into frames and handling acknowledgments (ACK) and retransmissions. It integrates with the PHY layer, where the PHY Tx is responsible for converting binary message information into wireless waveform symbols, while the PHY Rx is used to reverse the process. This process follows the standards established by IEEE 802.11a, which are implemented by the WLAN tool system. Both PHY Tx and Rx operations are based on bit-level processing, so they are continuous over time rather than event-driven. In the simulator, a series of functions are created to perform bit-level processing operations [22].

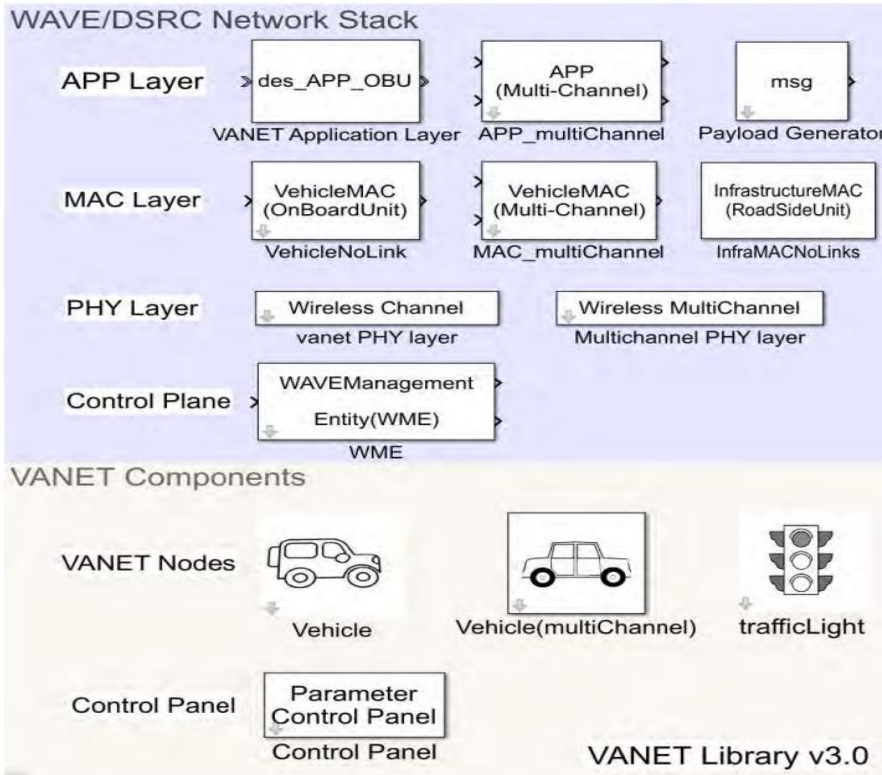


Figure 3. VANET Toolbox consists of a Simulink library [22]**.**

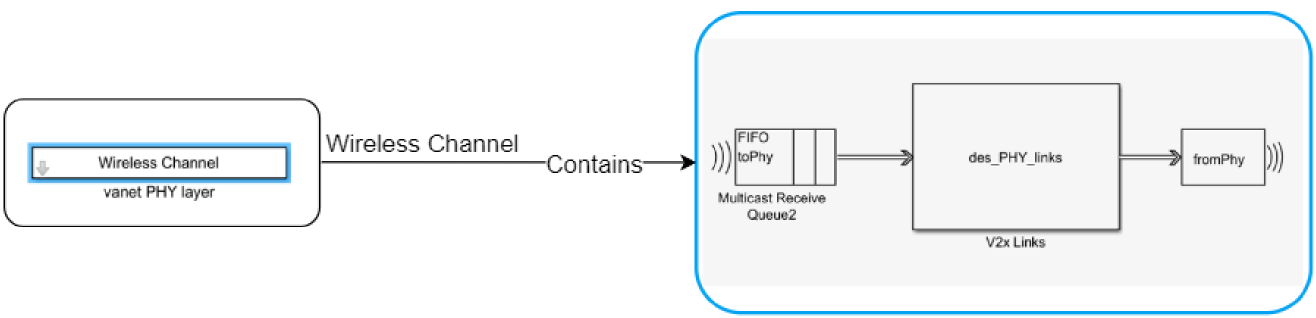


Figure 4. Internal structure of the Wireless Channel block.

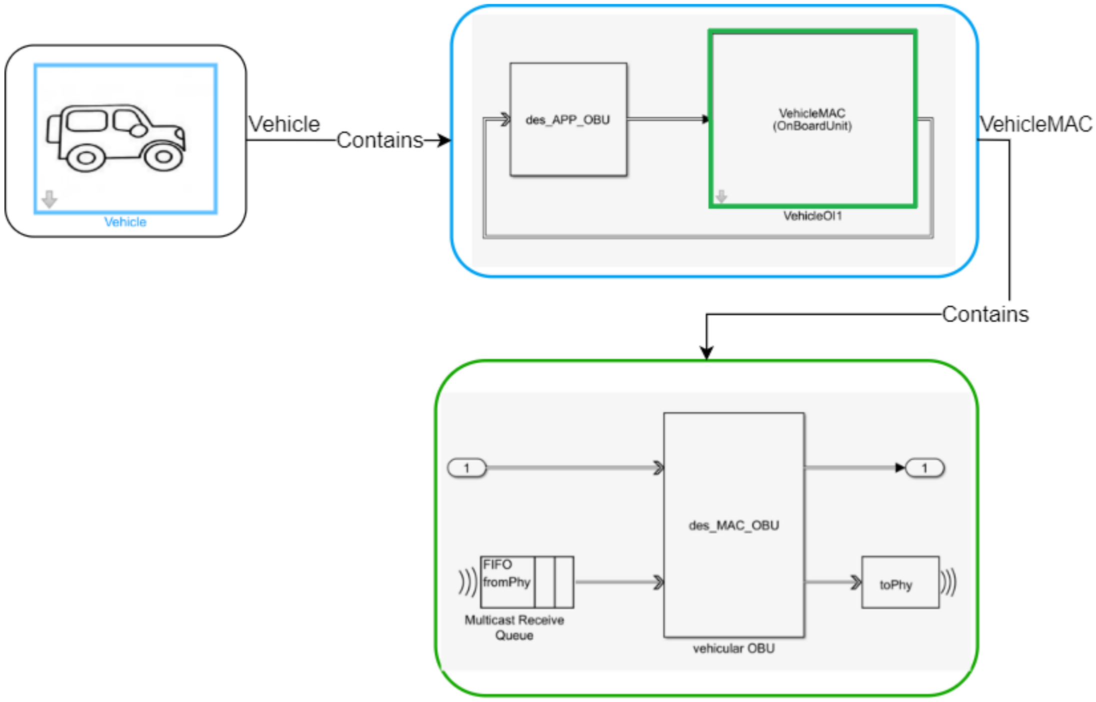


Figure 5. Internal structure of the Vehicle block.

The DES of the PHY layer implements the link that transmits the waves to the receivers after a propagation delay. The PHY layer supports AWGN channel models and the new ones added by this research: multipath and IRS-assisted. This process is implemented by functions within the PHY Rx, rather than DES [22].

As illustrated in Figure 6.a, the design framework of two vehicular nodes communicating over a wireless channel consists of three modules. The framework is composed of three main modules. The first module, designated as the Application Layer Discrete Event Systems Module (APP DES), integrates vehicle mobility models with message generation. Conversely, the Access Layer Discrete Event Systems Module (MAC DES) executes MAC layer operations and undertakes bit-level processing at both the transmitter (Tx) and receiver (Rx), where the functions supporting the channel models are implemented. Finally, the Physics Layer Discrete Event Systems Module (PHY Link DES) simulates only wireless propagation channels [22].

As illustrated in Figure 6.b, the basic wireless PHY link model converts the frame received from the MAC layer into a wireless waveform, which is then transmitted through the wireless channel. The interaction between the PHY layer and the MAC layer is managed by the Physical Layer Convergence Protocol (PLCP). The wireless channel is modeled as a multipath channel, an IRS-assisted channel, and an additive white Gaussian noise (AWGN) model. The latter is the common standard and is based on the investigation of the line-of-sight (LOS) conditions [40]. The implementation of the IRS in the simulator introduced the other channel models. It is noteworthy that the PHY channel is the only component designed in DES, while both the transmit (Tx) and receive (Rx) functions are implemented through the use of WLAN Toolbox functions and are integrated with the MAC DES module [22]. The red squares in Fig. 5 indicate the places where the channels are implemented within the simulator structure.

5.- IMPLEMENTATION OF IRS CHANNEL

So far, we have discussed which block of the simulator implements the IRS-assisted channel. In this section, we will discuss the methods and tools used to carry out this implementation.

A MATLAB system object, designated as "helperRISSurface," is employed to illustrate the IRS for wireless communications [41]. In order to implement an IRS-assisted channel environment, the function 'waveformTimer' belonging to the des_MAC_OBU has been modified. This modification introduces a novel IRS-assisted channel model while preserving the existing additive white Gaussian noise (AWGN) model.

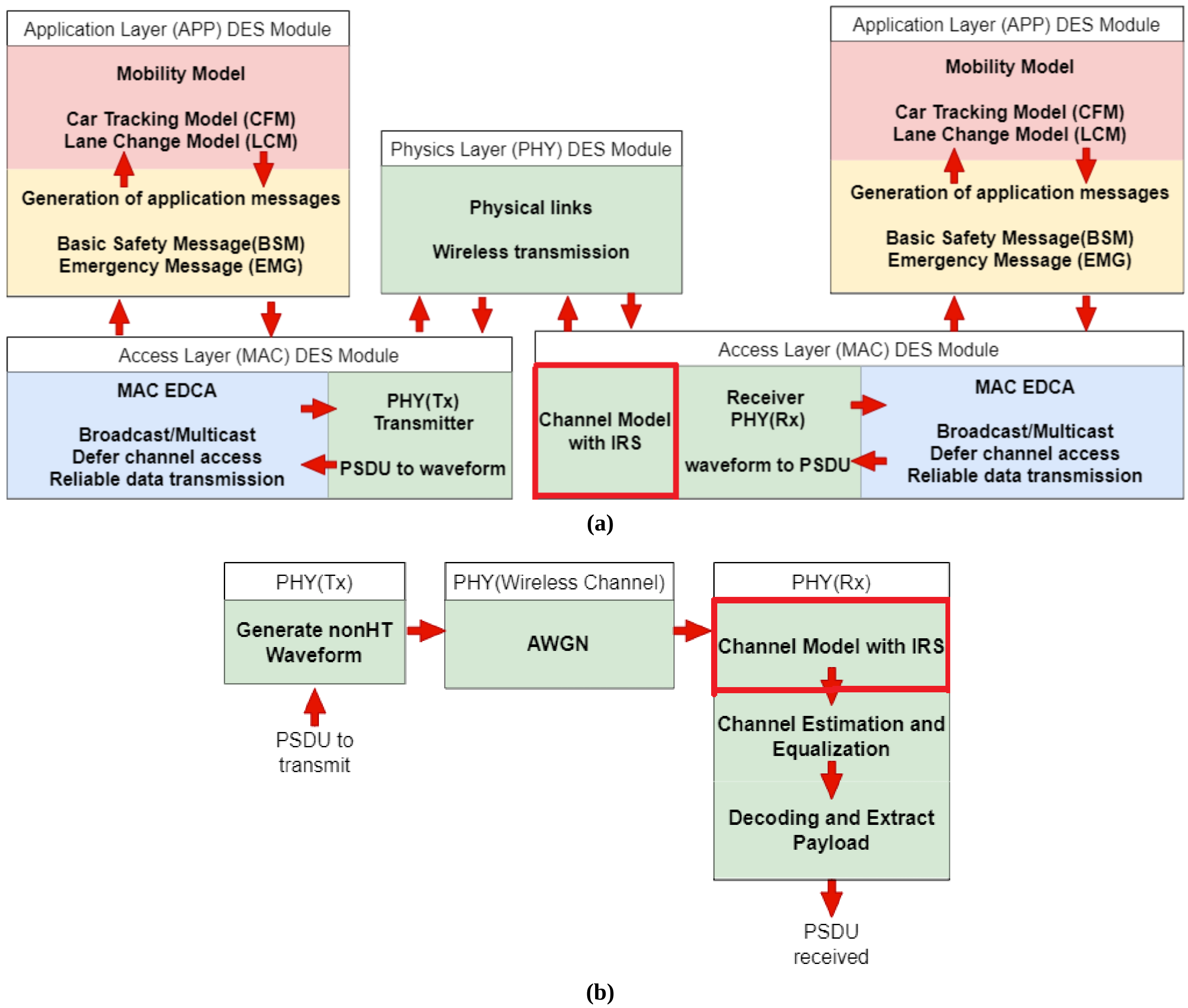


Figure 6. Design structure of VANET Toolbox (a) and link modelling VANET PHY (b), both with the implemented channels models.

The flowchart in Figure 7 illustrates the procedure of the implemented "functionIRS" to add the necessary channel models. The function was developed using the following inputs: the received signal, the locations of the transmitter and receiver, and their respective speeds. Basic parameters such as the carrier frequency and the dimensions of the IRS were also defined. The MATLAB "helperRISSurface" function was then employed to create an object representing the IRS surface. The positions and velocities of the vehicles and the IRS were defined. The propagation channels of the vehicles with each other and with the IRS were configured. The distance and the angle of incidence between the transmitter-IRS and IRS-receiver are computed using the "rangeangle" function of Matlab [42].

Finally, a selector is implemented to choose the channel test scenarios, including:

- Line-of-sight: The signal is transmitted from Tx to Rx via the LOS channel.
- IRS with random reflection coefficients: The signal is transmitted through the Tx-IRS channel to obtain the input signal to the IRS. The IRS is configured with random reflection coefficients. The signal is then processed by the IRS, and finally, the IRS-Rx channel is applied to the IRS output signal.

- IRS with adjusted reflection coefficients: The Tx-IRS and IRS-Rx channels are estimated using the 'getSteeringVector' [43] and 'fspl' [44] functions. The fitted reflection coefficients are calculated with the previously estimated gains, and the IRS is configured with these. Subsequently, the Tx-IRS channel is applied to the signal, and the signal is processed by the IRS with the adjusted reflection coefficients. Finally, the IRS-Rx channel is applied to the output of the IRS.
- Two IRS with adjusted reflection coefficients without LOS: A secondary IRS is generated with a distinct configuration of position, number of elements, and independent reflection coefficients. The vehicles communicate with the nearest IRS, which is then connected to the other IRS, which transmits to the Rx. The channel between the transmitter (Tx) and the first IRS, the channel between the second IRS and the receiver (Rx), and the channel between the IRSs are estimated using the methods mentioned in the previous bullet, but now with the two IRSs configured.
- Multipath: The signal is transmitted over a multipath channel without LOS from the Tx to the Rx. The MATLAB function "raytraicing" [45], [46] was employed to calculate the primary propagation paths of the wave towards the Rx. This function is instrumental in simulating multipath channels, as it can model either the Rayleigh or Rician distribution, depending on the presence or absence of LOS in the environment, respectively.

6.- RESULTS AND DISCUSSION

The aim is to calculate the signal-to-noise ratio obtained in the proposed communications system. This parameter is sampled every 0.1 seconds during the 30 seconds that the simulation lasts. The simulation scenario is a traffic light intersection where two different cars approach from intersecting streets, stop or continue depending on the traffic light, and continue straight ahead until they reach the end of the street. This route is repeated twice.

The simulation environment was configured on a map that represented a 200-meter by 200-meter road intersection, as illustrated in part (a) of Figure 8. This environment is depicted in part (b) of Figure 8 and comprises two vehicles, a semaphore, a communication channel, and a control panel. The duration of the simulation is 30 seconds, and all of the aforementioned elements are represented by blocks within Simulink using the VANET Toolbox.

The configuration of the semaphore's light times is imperative: 15 seconds for the green and red lights, and 3 seconds for the yellow light. The vehicles are set to an initial velocity of 3 km/h, with a subsequent acceleration from 0 to 100 km/h within 4 seconds. It is noteworthy that both vehicles possess the capacity to both transmit and receive messages, thereby facilitating two-way communication. It is noteworthy that the maximum velocity permitted for the vehicles is 60 km/h. The transmitters installed in the vehicles possess a power output of 23dBm and an antenna gain of 3 dBi. The maximum allowed EIRP is 33 dBm [47]. In [48], [49], [50] the same power and gain values are used.

Our IRS, which is composed of 200 elements, is strategically positioned in the lower right corner of the intersection. Other works use 256 elements [20], [21], so the approximate number 200 was chosen to simplify calculations. The spacing between these elements is equivalent to half a wavelength, at which the IRS operates. The antenna elements are isotropic, and all parameters can be adjusted within the same function that generates the IRS. The IRS would measure 510mm x 255mm for a frequency of 5.9GHz.

The VANET simulator incorporates the LOS model as the sole channel, with the multipath channel serving as the initial channel model extension. This model aims to delineate wireless propagation through the complex urban environment, characterized by numerous buildings and obstacles. This channel was created using MATLAB's 'raytracing' function, which allows the different communication paths to be calculated. The scenario was configured such that the buildings and streets were constructed of concrete, with the objective of calculating signal reflections. The current position of each vehicle is used to calculate the attenuation on each path.

The VANET Toolbox operates under the assumption that vehicles function as both transmitters and receivers. It is further assumed that the signal's propagation path from vehicle 1 to vehicle 2 is consistent in both directions. Consequently, the signal-to-noise ratio (SNR) received by both vehicles is presumed to be equivalent.

The received SNR plots for each of the aforementioned scenarios are illustrated in Figure 9. Initially, a comparison is made between the multipath channel and the LOS channel. The figure reveals a substantial loss due to multipath effects, which is evident in the points where vehicles intersect or are in close proximity to each other. In contrast, LOS channels, devoid of obstacles, exhibit an enhancement in SNR. The distance of each vehicle with respect to the IRS during the simulation time is also shown at the lower part of the figure. It is evident that both vehicles are approaching the intersection in a straight line.

V2V communications use OFDM modulations. In IEEE 802.11p, data rates range from 3 to 27 Mbps (BPSK/QPSK/16QAM/64QAM with different codes). The Table 2 summarizes the approximate SNR thresholds for each mode (for block error rate BLER≲10%, according to link simulations [51]).

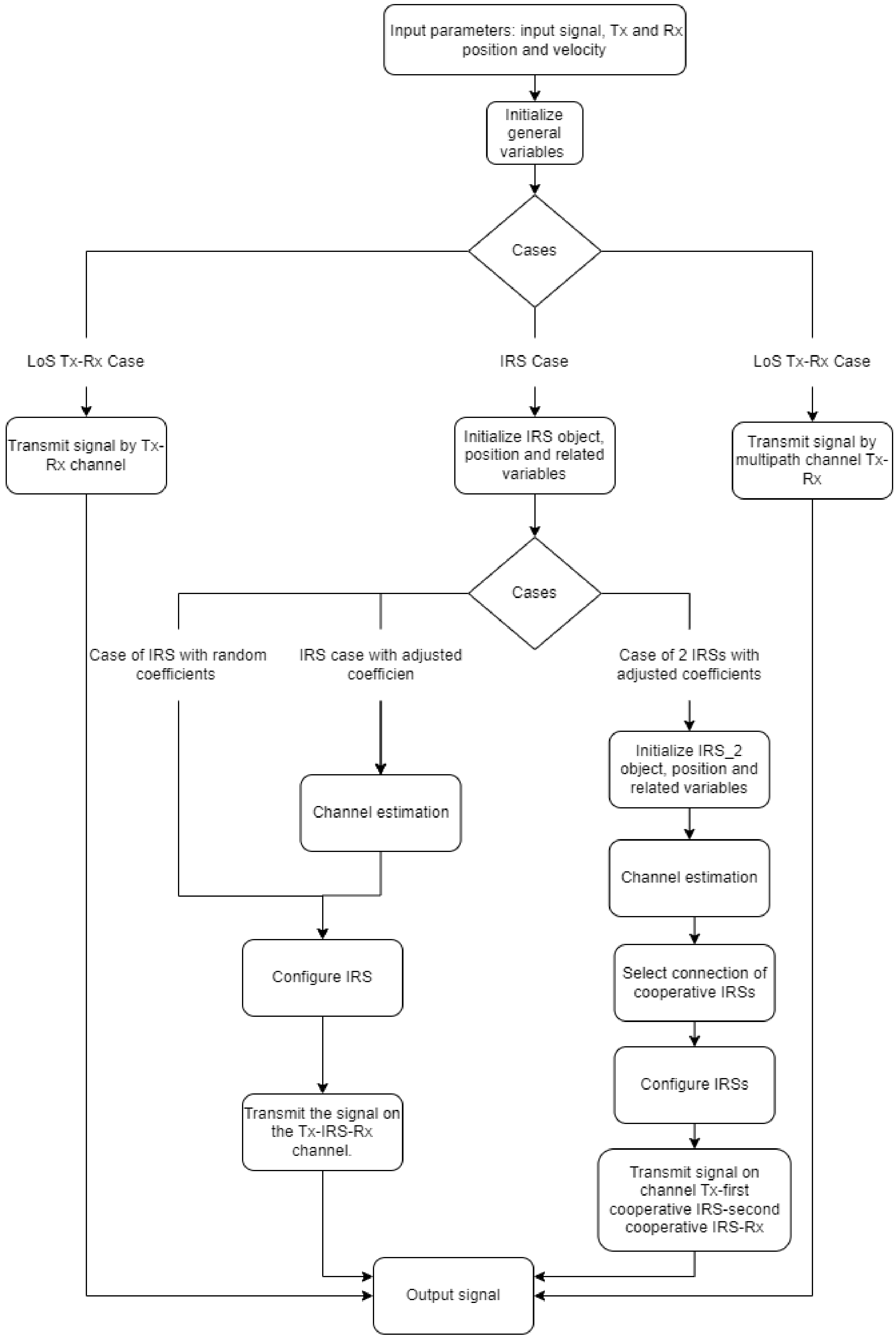
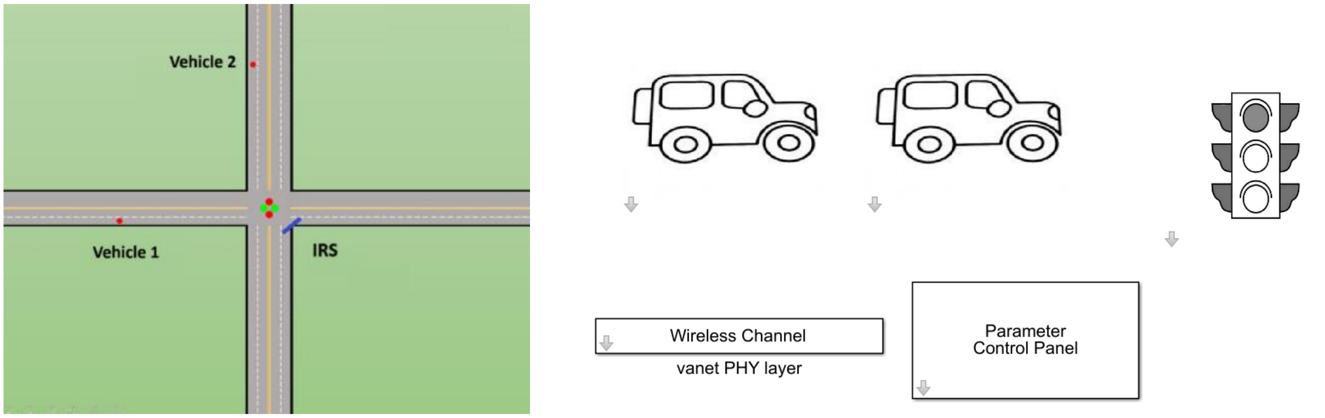


Figure 7. Flowchart of ‘functionIRS’, which implements the IRS channel models.



(a) **(b)**

Figure 8. Simulation map with the elements in their initial position (a) and Simulink environment with the blocks used in the simulation (b)

Table 2. IEEE 802.11p data rate and SNR threshold.

Modulation	BPSK 1/2	BPSK 3/4	QPSK 1/2	QPSK 3/4	16QAM 1/2	16QAM 3/4	64QAM 2/3
Data Rate (Mbps)	3	4.5	6	9	12	18	24
SNR (dB)	5	6	8	10	13	15	20

The physical environment strongly affects the SNR: on open roads or highways with long lines of sight, losses are lower and the SNR received is usually high. For example, field studies show SNRs greater than 20 dB at a distance of 40 m in open environments. In contrast, in dense urban environments there is often non-line-of-sight propagation and strong fluctuations. There, the SNR can fall well below 10–15 dB in many links. V2V systems typically operate at SNRs over a wide range, from a few dB in weak links to over 20 dB in short, clean links [52], [53].

The preceding analysis underscores the necessity to implement a channel in urban environments devoid of LOS option, thus giving rise to a channel assisted by an IRS. A comparison of the aforementioned channels and the IRS channel lacking configuration, which presents random reflection coefficients, reveals that the SNR behaves similarly to or worse than the multipath. This observation suggests that implementing an IRS without proper configuration does not offer any advantages in terms of communication.

Conversely, incorporating a channel with reflection coefficients of the IRS configured based on vehicle position leads to enhanced SNR. Figure 9 presents the results of this channel, in comparison with the LOS and multipath scenarios. It is evident from this figure that the SNR with the adjusted IRS coefficients is considerably higher than in a multipath channel without LOS. The enhancement in SNR is approximately 30 dB.

The analysis of the data reveals the presence of two local maxima in the plot of both channels. These peaks signify the temporal instances when the vehicles are in closest proximity to each other. At the initial peak, vehicle 1 is passing adjacent to the IRS, while vehicle 2 is situated 20 meters away. The second peak corresponds to a scenario where the vehicles are equidistant from the IRS, with a shorter distance separating them. This observation indicates that, in the context of installing smart surfaces, it is advantageous to position them in close proximity to one of the two elements intended to be connected.

The SNR between the IRS channel with adjusted reflection coefficients and the LOS channel is also compared. The results indicate that the LOS channel typically exhibits superior performance in comparison to the IRS channel. Initially, the distinction between the channels is discernible, attributable to the initial separation between the two vehicles and the IRS. Subsequently, a notable peak in SNR is observed, attributable to vehicle 1's proximity to the IRS. The remaining time periods feature a difference between the channels of approximately 5 dB, attributable to the proximity of at least one of the vehicles to the IRS.

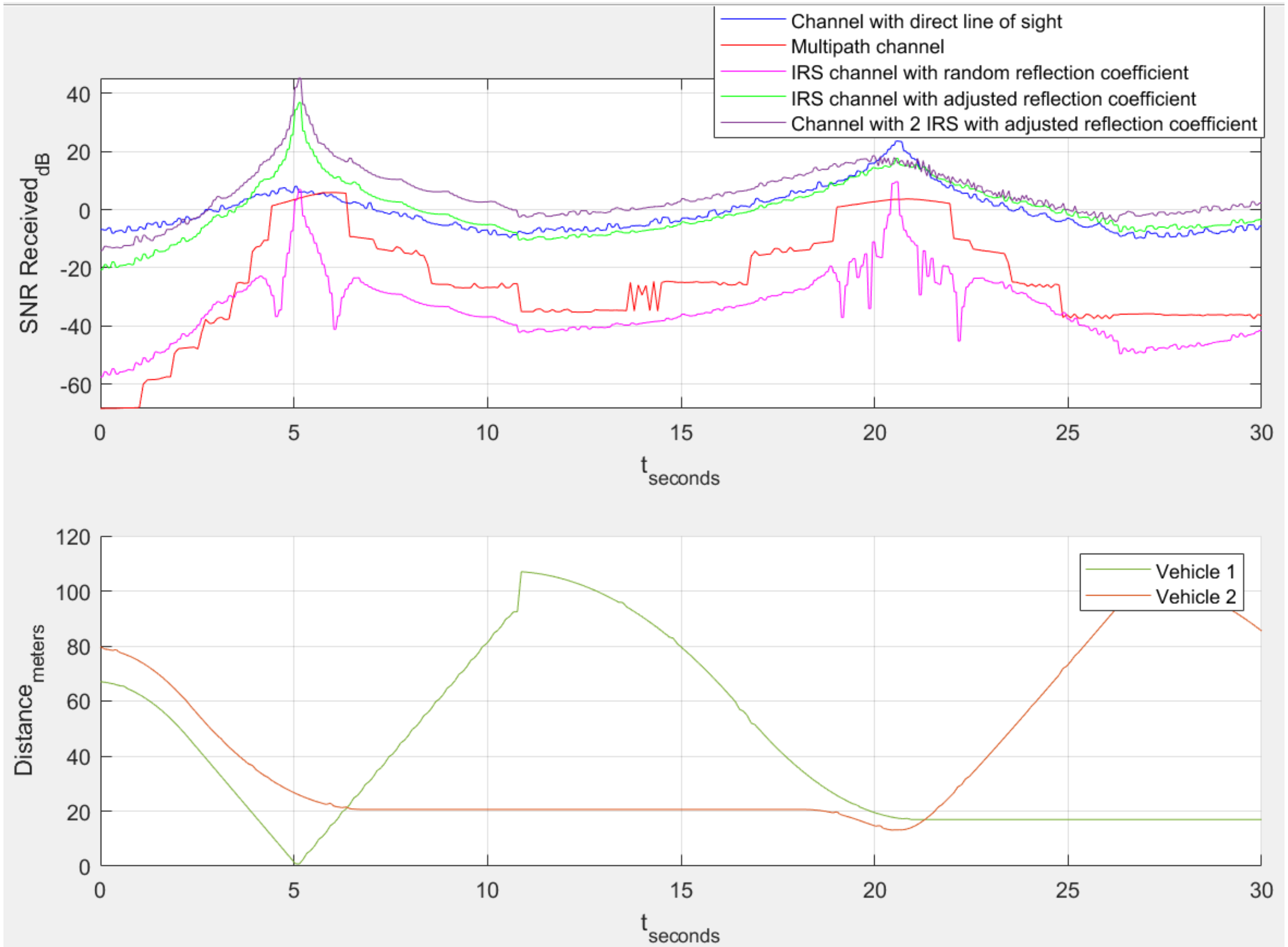


Figure 9. Upper graph: Comparison of the Signal-to-Noise Ratio of all the implemented channels. Lower graph: Distance of each vehicle to the IRS during the simulation.

In order to develop the last case, certain modifications were made to the simulation environment. The previously utilized 200-element IRS was substituted with one comprising half the number of elements, i.e., 100, situated in the same location. Additionally, an additional IRS with an equal number of elements was incorporated and positioned in the upper right corner of the intersection. The configuration of the IRS parameters remains unaltered from their previous settings, including the element spacing, operating frequency, and antenna element specifications.

Instead of a given number of IRS reflectors forming a single IRS, as discussed above, the IRS reflectors can form multiple smaller IRSs. This approach exhibits both advantages and disadvantages when compared with deploying a single IRS. On the one hand, the deployment of multiple IRSs within the user-AP link results in enhanced reflections between the IRSs, leading to a more pronounced decrease in signal strength. Conversely, the formation of multiple IRSs can yield cooperative passive beams, thereby facilitating multiplicative gains. A comparison is presented between the single IRS-assisted channel and the new two IRS-assisted channel. The results demonstrate that the two IRS-assisted channels exhibit a 10 dB enhancement in received SNR. Access to the code can be done through [54].

7.- CONCLUSIONS

In the present study, the integration of IRS in the context of vehicular ad hoc networks has been addressed through simulations in the VANET Toolbox library of MATLAB. To validate the newly proposed channels, IRS-assisted and multipath simulations were performed. The chosen simulation scenario is a semaphore intersection, where the obstruction of visibility between different roads by buildings is a salient feature. In this scenario, communication is facilitated through multipath signals, thereby enabling a comparison of the benefits from the incorporation of an IRS to enhance communication. The results of this study demonstrate that the implementation of an IRS enhances the signal-to-noise ratio (SNR) by approximately 5 dB, in comparison to the scenario where direct visibility is present. The improvement in SNR due to IRS deployment was found to be approximately 20 dB, in comparison to the multipath channel. The efficacy of employing two IRSs in a cooperative manner was also demonstrated, further enhancing the SNR value at the receivers.

A VANET simulator that integrates IRS technology is helpful for exploring and optimizing vehicular communications in complex environments. The incorporation of IRS technology in VANET simulations can offer valuable insights into enhancing the efficiency and safety of urban traffic. Furthermore, the capacity to simulate diverse IRS configurations and their impact on vehicular communication is imperative for the advancement of sophisticated intelligent transportation systems. The future use of this tool would be to validate scenarios for the implementation of IRS in dense metropolitan areas before carrying out such implementation, thereby saving material resources and time.

REFERENCES

[1] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent Reflecting Surface-Aided Wireless Communications: A Tutorial," *IEEE Trans. Commun.*, vol. 69, no. 5, pp. 3313–3351, May 2021, doi: 10.1109/TCOMM.2021.3051897.

[2] Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network," *IEEE Communications Magazine*, vol. 58, no. 1, pp. 106–112, Jan. 2020, doi: 10.1109/MCOM.001.1900107.

[3] A. Shakeel, A. Iqbal, A. Nauman, R. Hussain, X. Li, and K. Rabie, "6G driven Vehicular Tracking in Smart Cities using Intelligent Reflecting Surfaces," in *2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring)*, Jun. 2023, pp. 1–7. doi: 10.1109/VTC2023-Spring57618.2023.10199356.

[4] Y. Zhu, B. Mao, and N. Kato, "A Dynamic Task Scheduling Strategy for Multi-Access Edge Computing in IRS-Aided Vehicular Networks," *IEEE Transactions on Emerging Topics in Computing*, vol. 10, no. 4, pp. 1761–1771, Oct. 2022, doi: 10.1109/TETC.2022.3153494.

[5] A. U. Makarfi, K. M. Rabie, O. Kaiwartya, X. Li, and R. Kharel, "Physical Layer Security in Vehicular Networks with Reconfigurable Intelligent Surfaces," in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, May 2020, pp. 1–6. doi: 10.1109/VTC2020-Spring48590.2020.9128438.

[6] Y. Ai, F. A. P. deFigueiredo, L. Kong, M. Cheffena, S. Chatzinotas, and B. Ottersten, "Secure Vehicular Communications Through Reconfigurable Intelligent Surfaces," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 7, pp. 7272–7276, Jul. 2021, doi: 10.1109/TVT.2021.3088441.

[7] X. Yu, D. Xu, and R. Schober, "Enabling Secure Wireless Communications via Intelligent Reflecting Surfaces," in *2019 IEEE Global Communications Conference (GLOBECOM)*, Dec. 2019, pp. 1–6. doi: 10.1109/GLOBECOM38437.2019.9014322.

[8] E. Basar, "Reconfigurable Intelligent Surfaces for Doppler Effect and Multipath Fading Mitigation," *Front. Comms. Net.*, vol. 2, May 2021, doi: 10.3389/frcmn.2021.672857.

[9] J. Chen, Y.-C. Liang, Y. Pei, and H. Guo, "Intelligent Reflecting Surface: A Programmable Wireless Environment for Physical Layer Security," *IEEE Access*, vol. 7, pp. 82599–82612, 2019, doi: 10.1109/ACCESS.2019.2924034.

[10] M. Alsenwi, M. Abolhasan, and J. Lipman, "Intelligent and Reliable Millimeter Wave Communications for RIS-Aided Vehicular Networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 11, pp. 21582–21592, Nov. 2022, doi: 10.1109/TITS.2022.3190101.

[11] Md. Noor-A-Rahim *et al.*, "6G for Vehicle-to-Everything (V2X) Communications: Enabling Technologies, Challenges, and Opportunities," *Proceedings of the IEEE*, vol. 110, no. 6, pp. 712–734, Jun. 2022, doi: 10.1109/JPROC.2022.3173031.

[12] J.-B. Gros, V. Popov, M. A. Odit, V. Lenets, and G. Lerosey, "A Reconfigurable Intelligent Surface at mmWave Based on a Binary Phase Tunable Metasurface," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1055–1064, 2021, doi: 10.1109/OJCOMS.2021.3076271.

[13] V. Popov *et al.*, "Experimental Demonstration of a mmWave Passive Access Point Extender Based on a Binary Reconfigurable Intelligent Surface," *Front. Commun. Netw.*, vol. 2, Oct. 2021, doi: 10.3389/frcmn.2021.733891.

[14] A. S. Shekhawat, B. G. Kashyap, R. W. Raldiris Torres, F. Shan, and G. C. Trichopoulos, "A Millimeter-Wave Single-Bit Reconfigurable Intelligent Surface With High-Resolution Beam-Steering and Suppressed Quantization Lobe," *IEEE Open Journal of Antennas and Propagation*, vol. 6, no. 1, pp. 311–325, Feb. 2025, doi: 10.1109/OJAP.2024.3506453.

[15] R. Wang, Y. Yang, B. Makki, and A. Shamim, "A Wideband Reconfigurable Intelligent Surface for 5G Millimeter-Wave Applications," *IEEE Transactions on Antennas and Propagation*, vol. 72, no. 3, pp. 2399–2410, Mar. 2024, doi: 10.1109/TAP.2024.3352828.

[16] X. Pei *et al.*, "RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials," *IEEE Transactions on Communications*, vol. 69, no. 12, pp. 8627–8640, Dec. 2021, doi: 10.1109/TCOMM.2021.3116151.

[17] M. Rossanese, P. Mursia, A. Garcia-Saavedra, V. Sciancalepore, A. Asadi, and X. Costa-Perez, "Open Experimental Measurements of Sub-6GHz Reconfigurable Intelligent Surfaces," *IEEE Internet Computing*, vol. 28, no. 2, pp. 19–28, Mar. 2024, doi: 10.1109/MIC.2024.3376772.

[18] A. Araghi *et al.*, "Reconfigurable Intelligent Surface (RIS) in the Sub-6 GHz Band: Design, Implementation, and Real-World Demonstration," *IEEE Access*, vol. 10, pp. 2646–2655, 2022, doi: 10.1109/ACCESS.2022.3140278.

[19] B. Rana, S.-S. Cho, and I.-P. Hong, "Parameters and Measurement Techniques of Reconfigurable Intelligent Surfaces," *Micromachines*, vol. 13, p. 0, Oct. 2022, doi: 10.3390/mi13111841.

[20] L. Dai *et al.*, "Reconfigurable Intelligent Surface-Based Wireless Communications: Antenna Design, Prototyping, and Experimental Results," *IEEE Access*, vol. 8, pp. 45913–45923, 2020, doi: 10.1109/ACCESS.2020.2977772.

[21] W. Tang *et al.*, "Wireless Communications with Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 421–439, Jan. 2021, doi: 10.1109/TWC.2020.3024887.

[22] L. Wang, R. Iida, and A. Wyglinski, "Vehicular Network Simulation Environment via Discrete Event System Modeling," *IEEE Access*, vol. PP, pp. 1–1, Jun. 2019, doi: 10.1109/ACCESS.2019.2922766.

[23] L. Bononi, M. Di Felice, G. D'Angelo, M. Bracuto, and L. Donatiello, "MoVES: A framework for parallel and distributed simulation of wireless vehicular ad hoc networks," *Computer Networks*, vol. 52, no. 1, pp. 155–179, Jan. 2008, doi: 10.1016/j.comnet.2007.09.015.

[24] "Nctuns simulator for wireless vehicular AD Hoc network research," ResearchGate. Accessed: Oct. 27, 2024. [Online]. Available: https://www.researchgate.net/publication/326254434_Nctuns_simulator_for_wireless_vehicular_AD_Hoc_network_research

[25] M. Killat *et al.*, "Enabling efficient and accurate large-scale simulations of VANETs for vehicular traffic management," in *Proceedings of the fourth ACM international workshop on Vehicular ad hoc networks*, Montreal Quebec Canada: ACM, Sep. 2007, pp. 29–38. doi: 10.1145/1287748.1287754.

[26] B. Ahmed, A. W. Malik, T. Hafeez, and N. Ahmed, "Services and simulation frameworks for vehicular cloud computing: a contemporary survey," *J Wireless Com Network*, vol. 2019, no. 1, p. 4, Jan. 2019, doi: 10.1186/s13638-018-1315-y.

[27] A. Varga, "OMNeT++," in *Modeling and Tools for Network Simulation*, K. Wehrle, M. Güneş, and J. Gross, Eds., Berlin, Heidelberg: Springer, 2010, pp. 35–59. doi: 10.1007/978-3-642-12331-3_3.

[28] M. H. Rehmani and Y. Saleem, "Network Simulator NS-2," in *Encyclopedia of Information Science and Technology, Third Edition*, IGI Global, 2015, pp. 6249–6258. doi: 10.4018/978-1-4666-5888-2.ch615.

[29] G. F. Riley and T. R. Henderson, "The ns-3 Network Simulator," in *Modeling and Tools for Network Simulation*, K. Wehrle, M. Güneş, and J. Gross, Eds., Berlin, Heidelberg: Springer, 2010, pp. 15–34. doi: 10.1007/978-3-642-12331-3_2.

[30] R. Barr, Z. J. Haas, and R. van Renesse, "JiST: an efficient approach to simulation using virtual machines," *Software: Practice and Experience*, vol. 35, no. 6, pp. 539–576, May 2005, doi: 10.1002/spe.647.

[31] D. Krajzewicz, "Traffic Simulation with SUMO – Simulation of Urban Mobility," in *Fundamentals of Traffic Simulation*, J. Barceló, Ed., New York, NY: Springer, 2010, pp. 269–293. doi: 10.1007/978-1-4419-6142-6_7.

[32] K.-C. Lan, "MOVE: A Practical Simulator for Mobility Model in VANET," in *Telematics Communication Technologies and Vehicular Networks: Wireless Architectures and Applications*, IGI Global, 2010, pp. 355–368. doi: 10.4018/978-1-60566-840-6.ch021.

[33] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "CityMob: A Mobility Model Pattern Generator for VANETs," in *ICC Workshops - 2008 IEEE International Conference on Communications Workshops*, May 2008, pp. 370–374. doi: 10.1109/ICCW.2008.76.

[34] G. D. B. Cameron and G. I. D. Duncan, "PARAMICS—Parallel microscopic simulation of road traffic," *J Supercomput*, vol. 10, no. 1, pp. 25–53, Mar. 1996, doi: 10.1007/BF00128098.

[35] M. Güneş, F. Juraschek, B. Blywis, and C. Graff, "MoNoTrac — A mobility trace generator based on OpenStreetMap geo-data," in *The 7th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2010)*, Nov. 2010, pp. 618–623. doi: 10.1109/MASS.2010.5663869.

[36] J. S. Weber, M. Neves, and T. Ferreto, "VANET simulators: an updated review," *Journal of the Brazilian Computer Society*, vol. 27, no. 1, p. 8, May 2021, doi: 10.1186/s13173-021-00113-x.

[37] M. Rondinone *et al.*, "iTETRIS: A modular simulation platform for the large scale evaluation of cooperative ITS applications," *Simulation Modelling Practice and Theory*, vol. 34, pp. 99–125, May 2013, doi: 10.1016/j.simpat.2013.01.007.

[38] M. Piórkowski, M. Raya, A. L. Lugo, P. Papadimitratos, M. Grossglauser, and J.-P. Hubaux, "TraNS: realistic joint traffic and network simulator for VANETs," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 12, no. 1, pp. 31–33, Jan. 2008, doi: 10.1145/1374512.1374522.

[39] S. Zhang and R. Zhang, "Intelligent Reflecting Surface Aided Multiple Access: Capacity Region and Deployment Strategy," in *2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, May 2020, pp. 1–5. doi: 10.1109/SPAWC48557.2020.9153884.

[40] B. Aygun, "Distributed Adaptation Techniques for Connected Vehicles," Worcester Polytechnic Institute, 2016.

[41] "Introduction to Reconfigurable Intelligent Surfaces (RIS) - MATLAB & Simulink." Accessed: Oct. 25, 2024. [Online]. Available: https://www.mathworks.com/help/phased/ug/introduction-to-reconfigurable-intelligent-surfaces.html

[42] "rangeangle - Range and angle calculation - MATLAB." Accessed: Oct. 25, 2024. [Online]. Available: https://www.mathworks.com/help/phased/ref/rangeangle.html

[43] "phased.SteeringVector - Sensor array steering vector - MATLAB." Accessed: Oct. 25, 2024. [Online]. Available: https://www.mathworks.com/help/phased/ref/phased.steeringvector-system-object.html

[44] "fspl - Free space path loss - MATLAB." Accessed: Oct. 25, 2024. [Online]. Available: https://www.mathworks.com/help/phased/ref/fspl.html

[45] "raytrace - Display or compute RF propagation rays - MATLAB." Accessed: Oct. 25, 2024. [Online]. Available: https://www.mathworks.com/help/comm/ref/txsite.raytrace.html

[46] Z. Yun and M. F. Iskander, "Ray Tracing for Radio Propagation Modeling: Principles and Applications," *IEEE Access*, vol. 3, pp. 1089–1100, 2015, doi: 10.1109/ACCESS.2015.2453991.

[47] "IEEE Standards Association," IEEE Standards Association. Accessed: Sep. 25, 2025. [Online]. Available: https://standards.ieee.org/ieee/802.11p/3953/

[48] H. Schumacher *et al.*, "Vehicle-to-Vehicle IEEE 802.11p performance measurements at urban intersections," in *2012 IEEE International Conference on Communications (ICC)*, Jun. 2012, pp. 7131–7135. doi: 10.1109/ICC.2012.6364714.

[49] S. Maaloul, H. Aniss, L. Mendiboure, and M. Berbineau, "Performance Analysis of Existing ITS Technologies: Evaluation and Coexistence," *Sensors*, vol. 22, no. 24, p. 9570, Jan. 2022, doi: 10.3390/s22249570.

[50] M. H. Manshaei, M. Krunz, and A. Youssef, "Performance Evaluation of DSRC and C-V2X Coexistence in the 5.895-5.925 GHz Spectrum," in *2024 International Conference on Computing, Networking and Communications (ICNC)*, Feb. 2024, pp. 862–867. doi: 10.1109/ICNC59896.2024.10556134.

[51] A. Paier, D. Faetani, and C. F. Mecklenbrauker, "Performance evaluation of IEEE 802.11p physical layer infrastructure-to-vehicle real-world measurements," in *2010 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL 2010)*, Roma, Italy: IEEE, Nov. 2010, pp. 1–5. doi: 10.1109/ISABEL.2010.5702844.

[52] M. Boban, W. Viriyasitavat, and O. Tonguz, "Modeling Vehicle-to-Vehicle Line of Sight Channels and its Impact on Application-Level Performance Metrics".

[53] M. Boban, J. Barros, and O. K. Tonguz, "Geometry-Based Vehicle-to-Vehicle Channel Modeling for Large-Scale Simulation," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 9, pp. 4146–4164, Nov. 2014, doi: 10.1109/TVT.2014.2317803.

[54] AnaP-Suarez, *AnaP-Suarez/Matlab-simulation-of-vehicular-communications-channel-with-Intelligent-Reflecting-Surface*. (Aug. 31, 2025). MATLAB. Accessed: Aug. 31, 2025. [Online]. Available: https://github.com/AnaP-Suarez/Matlab-simulation-of-vehicular-communications-channel-with-Intelligent-Reflecting-Surface

CONFLICT OF INTEREST

Authors declare no conflicts of interest.

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