Journal of Al-Azhar University Engineering Sector

Vol.17, No.65, October 2022,1348- 1361

VIRTUAL MIMO FOR VEHICULAR COMMUNICATION SYSTEMS

Sara Sameeh Shokry[1], Osama Abdelfattah[2] and Gamal Mabrouk[3]

[1] School of Engineering, Canadian International College, Cairo, Egypt

[2] Department of Electrical Engineering, Al-Azhar University, Cairo, Egypt

[3] Department of Communications Engineering, Military Technical College, Cairo, Egypt.

Corresponding: sara_sameeh@cic-cairo.com

Received :16 July 2022 Accepted: 20 September 2022

ABSTRACT

This paper provides a simulation study for the quality of vehicle communication system by using a Virtual Multiple-Input Multiple-Output (VMIMO) used in Ultrawide Band (UWB) wireless communication, merged with orthogonal pulse shaping using modified Hermite polynomial. The simulation compares between Zero-Forcing (ZF) and Minimum Square Error (MMSE) Detection Techniques performance through bit-error-rate analysis. The simulation includes different scenarios for vehicular communication: The Vehicle to Vehicle (V2V) and the Vehicle to Infrastructure (V2I). Firstly, the Non-Line-of-Sight (NLOS), secondly the Line-of-Sight (LOS) scenarios. Moreover, the simulation considers the effect of path-loss and noise on transmitted signal, besides the comparison with QAM (Quadratic amplitude modulation), QPSK (quadratic pulse shift keying) and (Binary pulse shift keying) BPSK modulations. The simulation result is useful for the design of vehicle communication system including several cases of vehicles communication such as the V2V and V2I. The final results recommend BPSK-MMSE communication for both the LOS and NLOS scenarios for the V2V and V2I.

KEYWORDS: Vehicle communication, The Vehicle to Vehicle (V2V), the Vehicle to Infrastructure (V2I), Virtual Multiple-Input Multiple-Output (VMIMO), path loss, Non-Line-of-Sight (NLOS), and Line-of-Sight (LOS).

مخرجات متعددة المدخلات الافتراضية في أنظمة اتصالات المركبات

سارة سميح شكري[١]، أسامة جاد[٢]، جمال مبروك عبدالحميد[٣]

١ كلية الهندسة، المعهد الكندي لتكنولوجيا الهندسة والإدارة، مقر القاهرة الجديدة، مصر

٢ قسم الهندسة الكهربائية، كلية الهندسة، جامعة الأزهر، مصر.

٣ قسم هندسة الاتصالات، الكلية الفنية العسكرية، مصر

البريد الإلكتروني للمؤلف الرئيسي: sara_sameeh@cic-cairo.com

الملخص

تركز الورقة البحثية على تعزيز الاتصـالات بين المركبات باسـتخدام تقنية نظام متعدد المداخل والمخارج الافتراضـي. يتم تقديم مقارنة الأداء بين تقنيتين للمعادلات هما التأثير الصـفري (ZF) والحد الأدنى لمتوسـط الخطأ التربيعي (MMSE)،

بالإضافة إلى أثر تقنيات أنظمة التضمين (التعديل) المختلفة. يوجد في اتصالات المركبات عدة سيناريوهات تؤثر على جودة وأداء الاتصالات بين العربات والمركبات المحيطة. تعتمد هذه السيناريوهات على عدة عوامل بما في ذلك الانتشار، والعرقلة، ونوع الموقع في المناطق الحضرية أو الطرق السريعة، وقد تم تضمينها في الدراسة على أنها مع خط الرؤية وبدون خط رؤية. تتم محاكاة أداء كل نظام مقترح في جميع السيناريوهات ومقارنته بمقياسين هما معدل الخطأ في البت (BER) والإنتاجية. تم النظر في ثلاث تعديلات وكان أفضلها في مقارنة معدل الخطأ في البت هو مفتاح إزاحة الطور الثنائي، ولكن الأفضل في تحليل الصبيب هو مفتاح إزاحة الطور التربيعي، علاوة على ذلك، فإن استخدام تقنية الكشف عن متوسط الحد الأدنى للخطأ التربيعي يتفوق على تقنيات التأثير الصفري. تضمنت الدراسة عدة حالات لاتصالات المركبات مثل من مركبة لمركبة ومن مركبة لشبكات الاتصال.

الكلمات المفتاحية:التأثير الصفري، متوسط الحد الأدنى للخطأ التربيعي، مركبة لمركبة، مركبة لشبكات الاتصال

1. INTRODUCTION

The many ITS communication channels include (V2V), (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N). One of the key forces behind the development of 5G and other wireless communication technologies is vehicle-to-everything (V2X) communication. Relevant V2X communication scenarios include the efficient delivery of web and entertainment services to passengers of cars and trains, as well as information sharing relating to traffic safety and efficiency between vehicles and with infrastructure nodes along roadways. The advantages of implementing V2X include a sharp decline in traffic-related fatalities, a reduction in running costs for fleets of vehicles, and the opening up of new business models [1]. Research regarding ITS communications has been aimed at supporting applications ranging from fully autonomous vehicle operation and essential road-safety support to traffic flow optimization and in-car infotainment services.

In this study, we explore various propagation situations to improve the communication between V2V and V2I. For intelligent transportation and rail traffic management systems, which are anticipated to significantly improve road traffic efficiency and safety, V2I communication is a key enabler. Modern technologies may struggle to meet the dependability requirements of such systems for the wireless communication link. Transmissions in the UWB band have the potential to offer enough bandwidth to support web and entertainment applications for passengers on trains and cars in addition to traffic management services.
In these scenarios we study the cases of: urban, sub-urban and rural highway communication channel environment to identify their effects on path loss of line and non-line of sight signal propagation [2-5]. Also, we study the effect of vehicle speed on the signal propagation [6-8].The underground communication scenario was studied recommending the extended simulation of Multi-Input-Multi-Output (MIMO) V2V and V2I communication.

Some researchers show that the shadowing and the fading are critical factors affecting the communication system and the antenna selection for V2V and V2I communication [9]. Others, show that road barrier and the road type have great effects on channel characterization in urban and highway road, these studies were dedicated to characterizing V2X directly without assistance, the characterization was conducted using simulation or field measurements [10]. However, the concept of using assistant system to improve the characteristics of V2X was introduced by [11]. Also, the effect of fading channel communication channel with systems have pulse shaping, and detection techniques are studied [12-26].

Cooperative vehicular networks will play a vital role in the coming years to implement various ITS related applications. Both V2V and V2I communications will be needed to reliably disseminate information in a vehicular network [39]. A roadside unit (RSU) with several antennas can increase network capacity in this aspect. While conventional methods presume that fading occurs independently for each antenna. Virtual MIMO refers to the application of MIMO in a single antenna system. Virtual MIMO takes advantage of MIMO's diversity gain and spatial multiplexing in a fading channel. Single input, single output (SISO), single input, multiple output (SIMO), multiple-input, single output (MISO), and virtual MIMO are the four modes that make up virtual MIMO (MIMO). Typically, a wireless vehicular network has a SISO topology. Since the others are created virtually, we can also refer to MISO, SIMO, and MIMO as V-MISO, V-SIMO, and V-MIMO, respectively. VMIMO, which is developed for wireless communications and improves wireless vehicle networks, integrates MISO, SIMO, and MIMO techniques into one technique. They are especially helpful in applications where traditional MIMO technologies are impractical because of limitations imposed by the physical or energy consumption of the device. In order to take use of a MIMO system, VMIMO combines the concepts of cooperative behavior between mobile stations and virtual antenna array. It comprises of various mobile stations, each equipped with a single antenna. The key disadvantage of VMIMO is that station cooperation may require greater energy investment for signaling purposes [27]. VMIMO shows better results in the BER analysis than MIMO. But need a good detection technique to improve and enhance the its performance [28]. According to IEEE802.16e describing the uplink VMIMO (UL-VMIMO), each user is equipped with a single antenna and shares the same channel resources with other users [29]. In a wireless vehicular network for energy saving we mostly prefer multi-hop communication than single hop communication for long haul transmission. Therefore, in Figure 1, we have shown a two-hop communication of different virtual topology.

2. PROPOSED SYSTEM DESCRIPTION

The proposed system simulates two scenarios of V2V and V2I communication by including the path loss effect, then studying the detection and modulation techniques effect on the bit error and throughput. The channel matrix consists of elements which are the complex transmission coefficients for the links between the transmit (Tx) antenna and receive (Rx) antenna. The VMIMO implies parallel data streams on orthogonal sub-channels increasing the channel capacity. In simulation, random binary sequence of modulated symbols is generated and groups them into pairs according to different modulation scheme in one time slot. Then the symbols are multiplied with the Rayleigh channel which is used for simulation. In the channel, average white Gaussian noise (AWGN) is added to transmitted symbols. At receiver, detection technique is deployed to improve the quality of signal. For V2I communication, traffic mode affects the communication between the infrastructure antenna (T_x) and the vehicle antenna (R_x). There are two scenarios for the V2I communication, where the vehicle has NLOS with the T_x, and the vehicle has good LOS with T_x. According to the data extracted from the previous publications, condition of LOS is the data of the vehicle located in the nearest lane, and the vehicle in far lane is the condition of NLOS [17]. The V2V communication is affected by the traffic mode. The first mode is when vehicle communicates to the other vehicle while there is a large obstruction between them such as a bus or truck. This case is defined as the NLOS V2V communication. In the second mode which is LOS. The data collected from previous publication depends on road measurements. The transmitter and receiver are moving independently of one another between the test vehicles at a distance of 5 to 150 meters on the road. Otherwise, a bus about 10 meters in length is stationary on the roadside, and the Tx vehicle is just behind the obstacle bus and remains stationary [30]. The different scenarios and communication cases in the vehicle communication and intelligent transportation systems are shown in the following Figure 2.

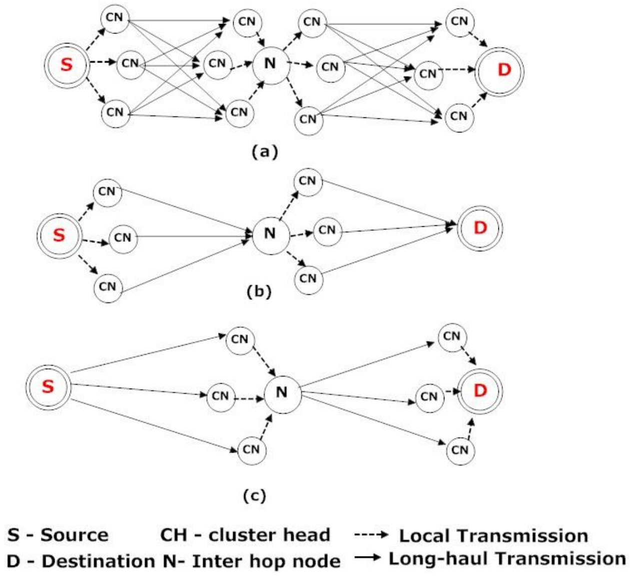

Figure 1: Topologies for V-MIMO, V-SIMO, and V-MISO: (a) V-MIMO (b) V-MISO (c) V-SIMO

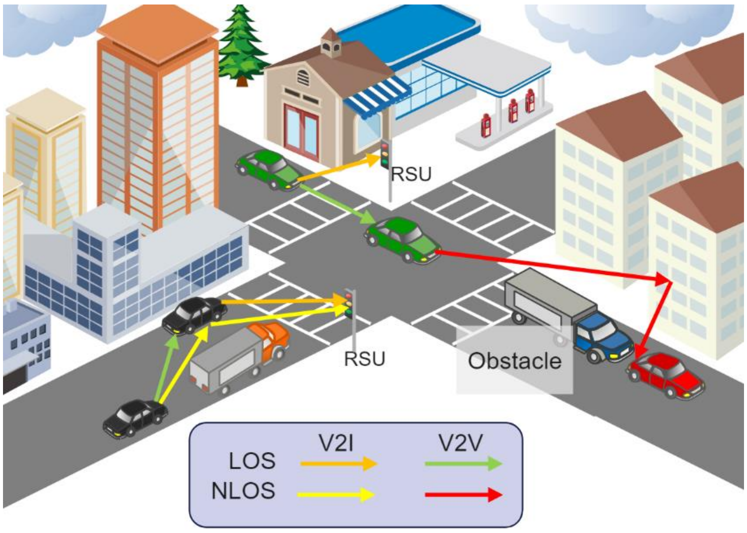

Figure 2: Schematic illustration for the four scenarios simulated showing the difference between the V2X systems, and the difference between LOS and NLOS.

3. SYSTEM MODEL

The block diagram of the system model for simulation V2V and V2I is shown in Figure 3.

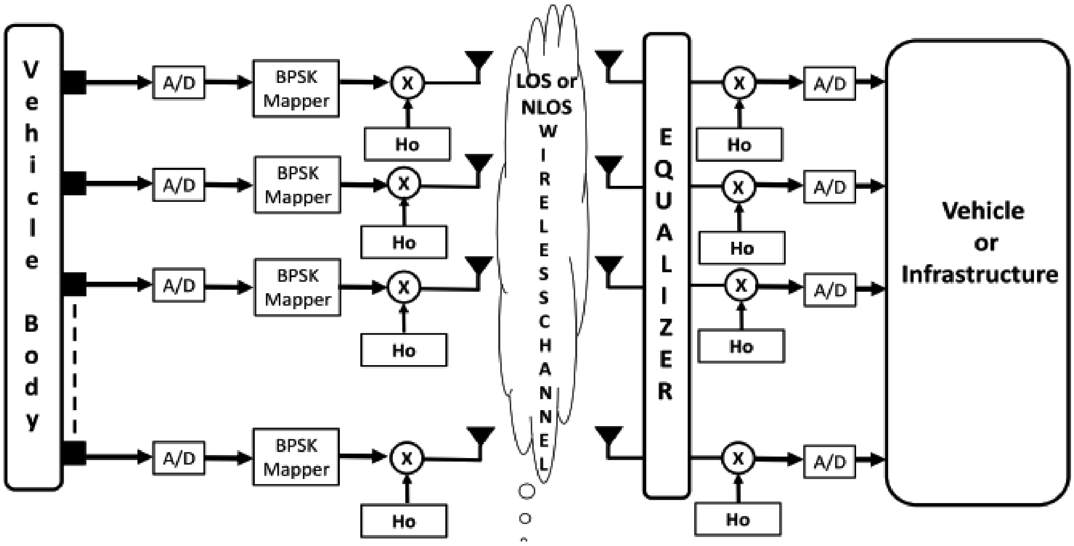

Figure 3: the block diagram of the proposed V2V/V2I system model.

3.1 Propagation Model

For V2X channel environments, there are two types of signal propagations:

Line-of-Sight (LOS): In LOS, no obstructions, such as buildings or cars, prevent a signal from travelling over the air directly from a transmitter to a receiver. In LOS propagation, two vehicles are travelling down the same roadway, and path loss simply depends on the separation of the two. The route loss exponent n [30] is used to express the average large-scale path loss given an arbitrary T-R separation as a function of distance:

$$\overline{PL}(dB) = PL(d_0) + 10\,n\,\log\left(\frac{d}{d_0}\right) \tag{1}$$

Where: PL(d) Average path-loss for an arbitrary separation d (denoted in dB).

n Path-loss exponent. The value of n depends on the propagation environment: for free space it is 2.

d_o Vehicles reference distance (m).

The path loss at reference distance $PL(d_o)$ is a measured value for V2V scenarios, and for the V2I it is estimated using the following equation

$$PL(d_o) = 20\log\left(\frac{4\pi d_o f_c}{c}\right) \tag{2}$$

Where: c the speed of light and

f_c the carrier frequency

Non-Line-of-Sight (NLOS): NLOS is a situation in which a transmitter's signal must go around obstacles before it can reach the receiver; these transmissions can only do so through reflection, scattering, and diffraction. In order to characterize the change in signal propagation behavior between two different signal channels while assuming the same propagation distance and the ability to treat path loss independently of shadowing, the concept of shadowing has been established. Models for path loss and shadowing can be superimposed to capture power falloff versus distance along with the random attenuation about this path loss from shadowing and given by [31]:

$$\mathrm{PL}\left(\mathrm{dB}\right)=\overline{\mathrm{PL}}\left(\mathrm{d}_{0}\right)+10\mathrm{n}\log\left(\frac{\mathrm{d}}{\mathrm{d}_{0}}\right)+\mathrm{X}_{\sigma} \tag{3}$$

Where: X_σ is the shadowing parameter (zero mean Gaussian distributed random variable in dB with standard deviation σ also in dB).

3.2 VMIMO

The spectral efficiency (SE) of wireless communications can be increased via VMIMO systems, in which the transmitter has multiple antennas and each of the receivers has a single antenna. The notion is that some nearby receivers can contribute their antennas (act as relays) and assist the single-antenna destination to create a virtual antenna array and gain certain advantages of MIMO systems when channel state information (CSI) is only accessible at the receiver side. For terrestrial mobile communication systems, where physical restrictions may prevent mobile stations from having multiple antennas, VMIMO is a potential concept. MIMO and VMIMO were introduced for V2X communication in different form to meet the requirements of high data rate and enhance link reliability. In the 2X2 VMIMO channel, the received signal is given by [32]

$$Y = HX + N \tag{4}$$

Where

Y is the received symbols,

H is the channel matrix and

N is the antenna noise.

and in matrix form

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{5}$$

Then, the received signal on the first antenna and on the second antenna are described by equation [32].

$$y_1 = h_{1,1}x_1 + h_{1,2}x_2 + n_1 = \left[h_{1,1}h_{1,2}\right]\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + n_1 \tag{6}$$

$$y_2 = h_{2,1}x_1 + h_{2,2}x_2 + n_2 = \left[h_{2,1}h_{2,2}\right]\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + n_2 \tag{7}$$

Where

$\boldsymbol{h}_{\mathbf{i,j}}$ is the channel gain from i virtual transmit antenna to j virtual received antenna.

$\boldsymbol{n_1}$, $\boldsymbol{n_2}$ are the first and second receive antennas noise.

$\boldsymbol{x_1}$, $\boldsymbol{x_2}$ are the transmitted symbols, and

$\boldsymbol{y_1}$, $\boldsymbol{y_2}$ are the received symbol on the first and second antenna.

3.3 Detection Techniques with Equalization

For MIMO system, each transmit antenna, transmits various signals so that the receiver can easily receive the transmitted signals. All signals are transmitted from all elements once and therefore the receiver solves a linear equation system to demodulate the message. Zero forcing is a detection criterion used to create the filtering matrix; the method drawback is the noise enhancement and diversity loss. Otherwise, the MMSE consider the noise enhancement problem, hence, the MMSE shows better results compared to ZF [33]. ZF is a linear detection technique, which force the interference to zero without including the noise, however, the MMSE minimizes the mean square error between transmitted and received data, both uses the matrix of linear transformation. The ZF and MMSE equalizers are purely a function of the channel state or the channel matrix [34]. Solving for x is by finding a matrix W which satisfying

$$WH=I \tag{9}$$

Hence, ZF detector for meeting this constraint is given in following equation

$$W_z = (H^H H)^{-1} H^H \tag{10}$$

and MMSE detector for meeting this constraint is given in following equation

$$W_m = [H^H H + H_o I]^{-1} H^H \tag{11}$$

Where:

H is the channel matrix and

W_z and W_m are the equalization matrix.

Multiplying the received signal vector by ZF / MMSE matrices to get the data sub-streams decoupled, in the VMIMO channel the data sub-streams are mixed by the channel matrix.

$$\rho_{zf,n} = \frac{SNR}{[(H*H)^{-1}]_{nn}},\ 1 \le n \le M \tag{12}$$

$$\rho_{mmse,n} = \frac{SNR}{\left[\left(H*H+\frac{1}{SNR}I\right)^{-1}\right]_{nn}} - 1,\ 1 \le n \le M \tag{13}$$

For lower bandwidth models, and the orthogonal polynomial families to have non-symmetrical wave forms. The Hermit pulse shaping was the recommended one, and the modified Hermit pulse set generates higher order orthogonal pulses [35-37]. The proposed system utilizing Hermite pulses as the pulse shaping will be more robust against Rayleigh fading combined with shadowing to achieve a boost in the overall performance. The Hermit polynomial expressed by Rodrigue's formula is given by the equation.

$$h_n(t) = (-\tau)\frac{t}{e^2\tau^2}\frac{d^n}{dt^n}\left(\frac{-t^2}{e^2\tau^2}\right) \tag{14}$$

Where:

n is the nth derivative.

τ is the time scaling factor, and

t is the time in nano seconds.

4. Simulation Results

In each simulation run, 1000000 bits are generated. Simulation results in terms of bit error rate for QAM, QPSK, and BPSK as the modulation techniques with two detection techniques ZF and MMSE for the channel parameters given by table 1 and 2 for characterizing LOS and NLOS in the V2V and V2I communication for urban scenario are give in the following figures by using MATLAB [30-31,38].

Table 1: V2V communication scenarios path-loss and distance[30].

Scenario	Scope	$d_o(m)$	$d\ (m)$	$Pl_o\ (dB)$	X_δ	n
LOS	V2V	1.5	50	58	2.63	1.51
NLOS	V2V	1.5	200	69.8	3.20	1.55

Table 2: V2I communication scenarios path-loss and distance[31].

Scenario	Scope	$d_o(m)$	$d\ (m)$	X_δ	n	F_c (GHz)
LOS	V2I	1	200	4.6	1.95	7
NLOS	V2I	1	500	10.08	2.62	7

Figures 4 and 5 show the probability of error versus SNR for V2V LOS and NLOS scenarios with BPSK, QPSK and QAM modulation schemes, besides ZF and MMSE detection techniques. The results show that the BPSK and MMSE outperform other techniques in the case of V2V for both cases of LOS and NLOS.

Figures 6 and 7 show the probability of error versus SNR for V2I LOS and NLOS scenarios with BPSK, QPSK and QAM modulation schemes and ZF and MMSE detection techniques. The results show that the BPSK and MMSE outperform other techniques in the case of V2I for both cases of LOS and NLOS.

Figures 8 and 9 show the throughput versus SNR for V2V LOS and NLOS scenarios with BPSK, QPSK and QAM modulation schemes and ZF and MMSE detection techniques. The results show that the QPSK and MMSE outperform other techniques in the case of V2V for both cases of LOS and NLOS.

Figures 10 and 11 show the throughput versus SNR for V2I LOS and NLOS scenarios with BPSK, QPSK and QAM modulation schemes and ZF and MMSE detection techniques. The results show that the QPSK and MMSE outperform other techniques in the case of V2I for both cases of LOS and NLOS.

Three modulation techniques are discussed in the simulation results; the simulation was acquired at different distance between vehicles to ensure the efficiency of performance. Figures from 4 to 7 compare both the modulation and detection techniques according to BER analysis showing that the BPSK and MMSE outperform other techniques in the case of V2V/V2I for both cases of LOS or NLOS. The comparison between ZF and MMSE shows that BPSK and MMSE achieve BER less than 10-4 at lower SNR with 3 dB, however, the QPSK and QAM is out of the comparison in the four scenarios.

The throughput is compared for QAM, BPSK and QPSK modulation techniques in all cases of V2X including the LOS and NLOS, the QPSK showed better performance in the comparison for the other modulation methods, and the detection techniques MMSE which shows better performance rather than other modulation and detection techniques, as in figures 8-12. The results show that QPSK - MMSE is better than the other modulation and detection techniques in terms of time and throughput.

Comparing the enhancement due to usage of QPSK and BPSK with MMSE show that BPSK-MMSE achieves BER less than 10e-4 at SNR less than 20 dB, where the QPSK did not achieve BER less than 10e-4 at the SNR range. The throughput comparison shows that the QPSK show better performance compared to the BPSK with average difference of 9x10e4 bits per second; otherwise the BPSK with MMSE shows better results with difference average of 9x10e4 bits per seconds. Moreover, the modification using pulse shaping did not affect the performance of QAM and QPSK, and still have not achieved low BER. Furthermore, the scenarios of LOS and NLOS show slight effect on the performance of the modulation and detection scheme which means that the proposed models and final recommended model considering the detection using the MMSE and the BPSK modulation shall has better performance and stable conditions.

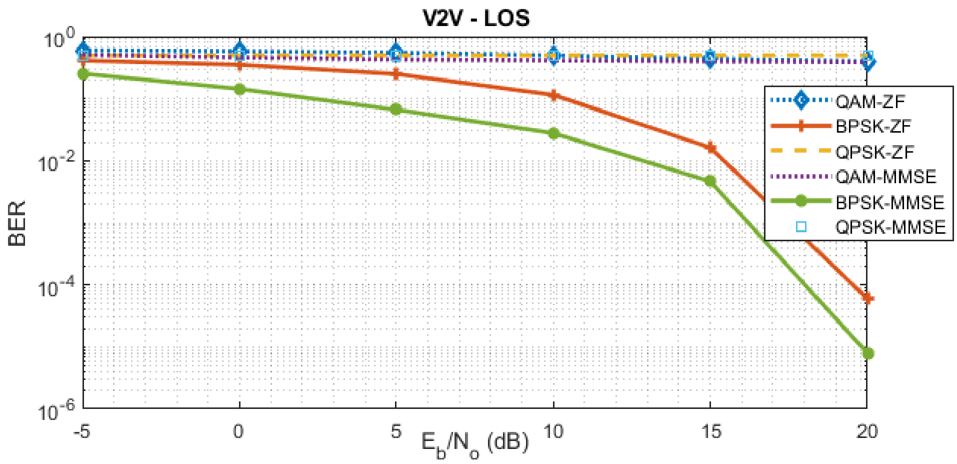

Figure 4: BER results for various modulations/detections techniques in case of V2V - LOS communication.

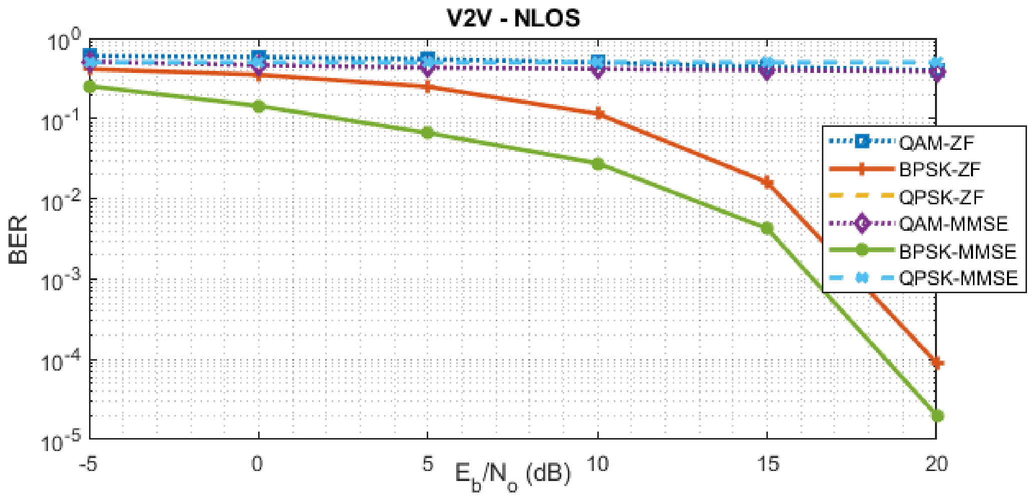

Figure 5: BER results for various modulations/detections techniques in case of V2V- NLOS communication.

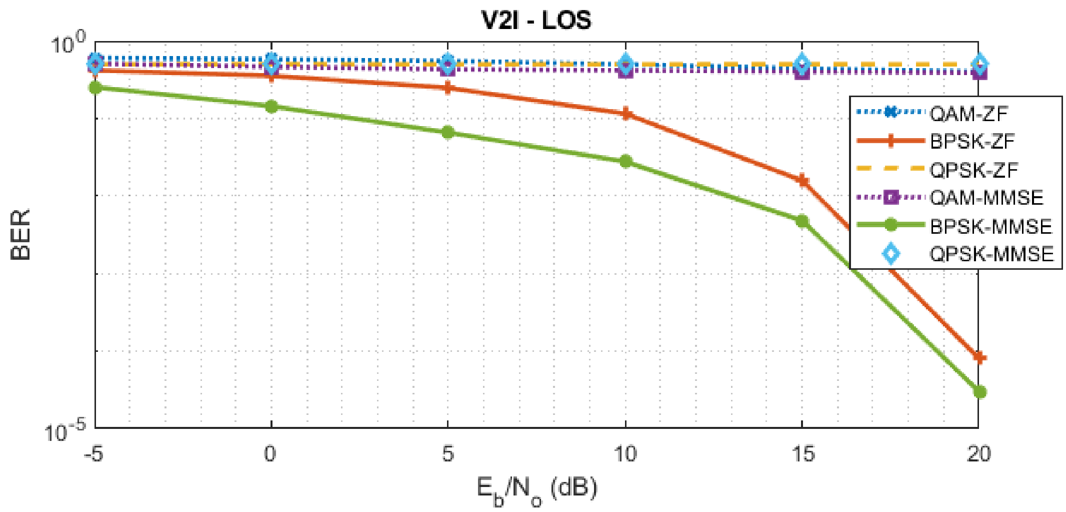

Figure 6: BER results for various modulations/detections techniques in case of V2I- LOS communication.

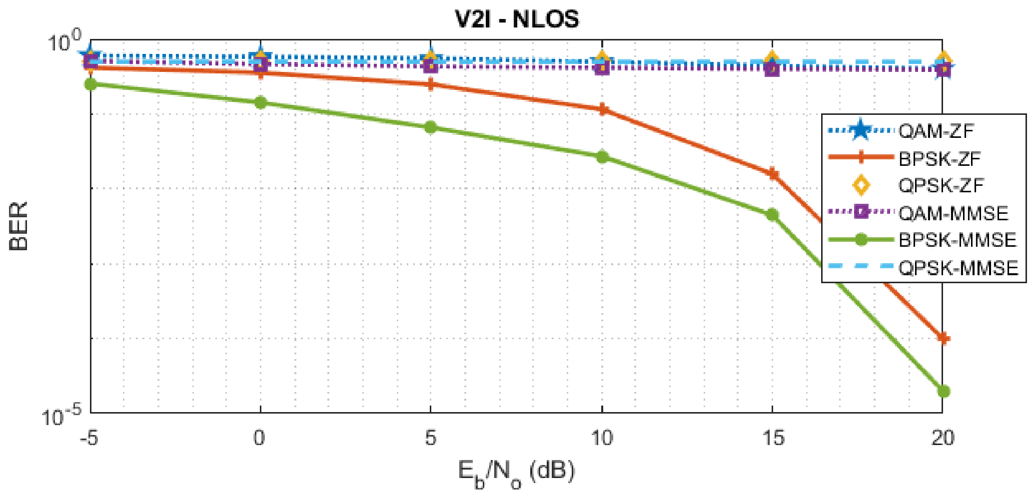

Figure 7: BER results for various modulations/detections techniques in case of V2I - NLOS communication.

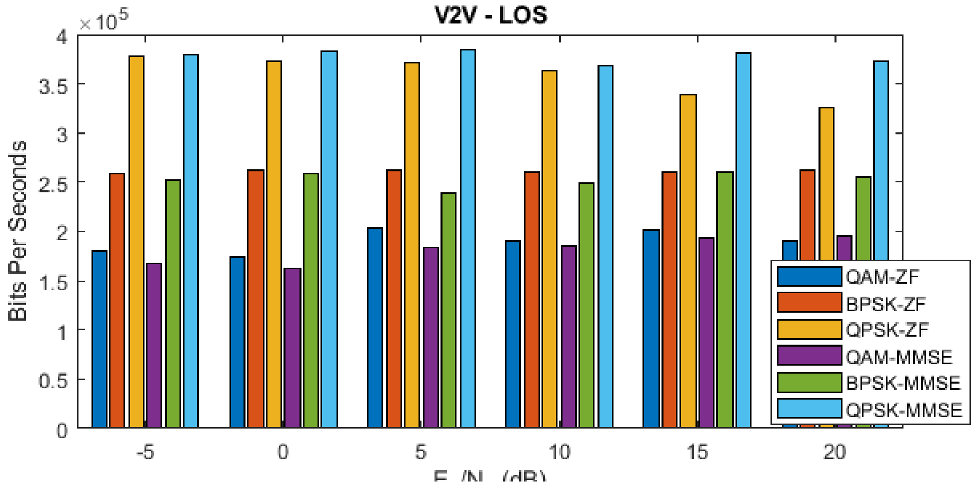

Figure 8: Throughput results for various modulations/detections techniques in case of V2V - LOS communication.

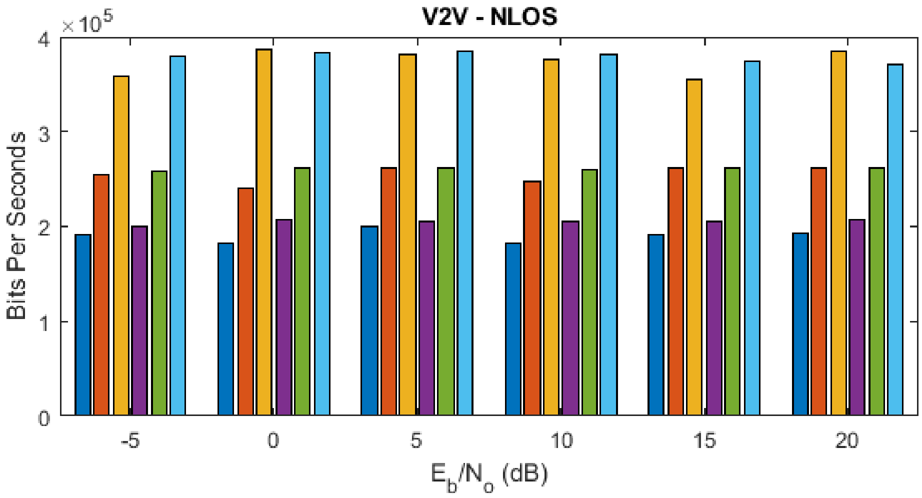

Figure 9: Throughput results for various modulations/detections techniques in case of V2V -NLOS communication.

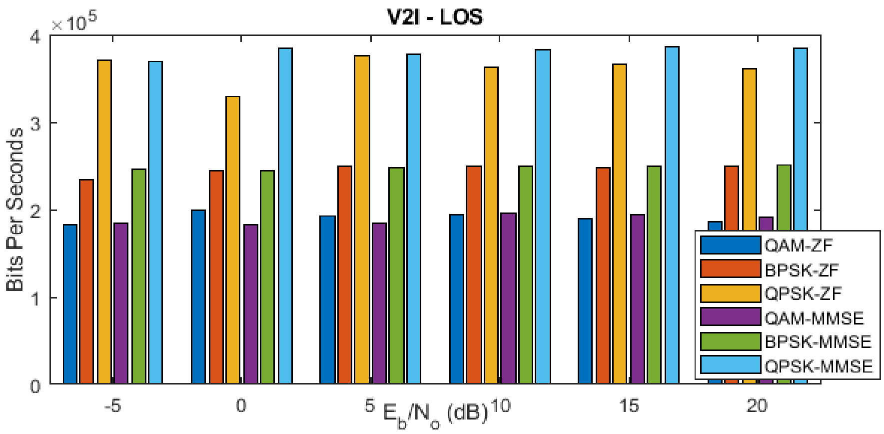

Figure 10: Throughput results for various modulations/detections techniques in case of V2I - LOS communication.

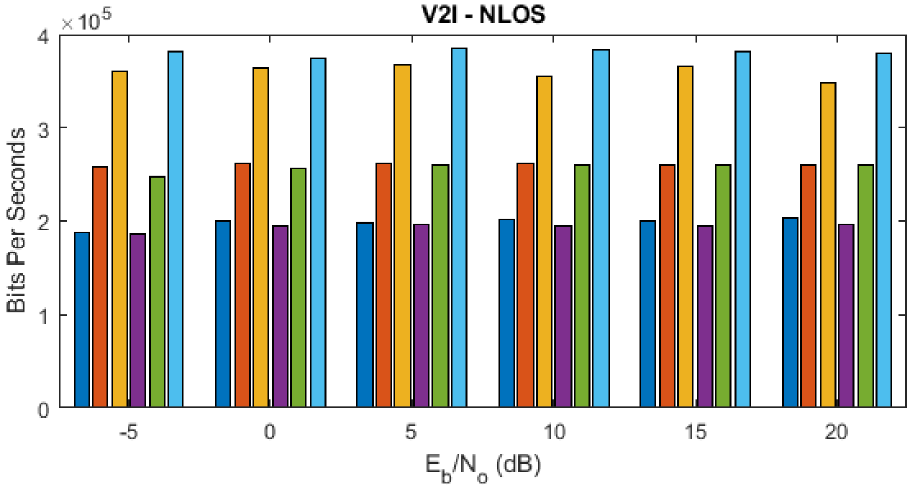

Figure 11: Throughput results for various modulations/detections techniques in case of V2I - NLOS communication.

CONCLUSION

The vehicle communication scenarios were simulated for proposed communication system. The vehicular scenarios cover the V2V and the V2I for both LOS and NLOS. Moreover, the BER analysis is used to compare the performance of ZF and MMSE detection techniques with BPSK, QPSK and QAM modulations schemes. The system proposed using VMIMO with orthogonal Hermite pulse shaping impulse ultra-wide band communication. The signal transmitted includes path loss, shadowing, and noise effect. Furthermore, the comparison for different modulation techniques including the QAM, QPSK, and BPSK, against the three metrics time, throughput, and BER.

The simulation results show that the ZF do not satisfy the requirement and that the MMSE is better than the ZF method. The results show that the MMSE is more superior to ZF. MMSE achieves lower BER compared to ZF, where the MMSE showed better performance compared to ZF in the case of VMIMO. Moreover, the usage of BPSK is the most recommended in the case of BER and QPSK in the case of throughput. However, the BPSK is the recommended over QPSK because the base of study is to improve the communication features using VMIMO. Furthermore, the scenarios of LOS and NLOS show slight effect on the performance of the modulation and detection scheme which means that the proposed models and final recommended model considering the detection using the MMSE and the BPSK modulation shall has better performance and stable conditions. The final results recommend BPSK-MMSE communication for both the LOS and NLOS scenarios for the V2V and V2I.

REFERENCE

[1] MacHardy, Z., Khan, A., Obana, K., & Iwashina, S. (2018). V2X access technologies: Regulation, research, and remaining challenges. IEEE Communications Surveys & Tutorials, 20(3), 1858-1877. https://doi.org/10.1109/comst.2018.2808444

[2] Giordani, M., Shimizu, T., Zanella, A., Higuchi, T., Altintas, O., & Zorzi, M. (2019, September). Path loss models for V2V mmWave communication: Performance evaluation and open challenges. In 2019 IEEE 2nd Connected and Automated Vehicles Symposium (CAVS) (pp. 1-5). IEEE. https://doi.org/10.1109/CAVS.2019.8887792

[3] Mir, Z. H., & Filali, F. (2017). Large-scale simulations and performance evaluation of connected cars-A V2V communication perspective. Simulation Modelling Practice and Theory, 73, 55-71. https://doi.org/10.1016/j.simpat.2017.01.004

[4] Hisham, A., Ström, E. G., Brännström, F., & Yan, L. (2019). Scheduling and power control for V2V broadcast communications with co-channel and adjacent channel interference. IEEE Access, 7, 67041-67058. https://doi.org/10.1109/access.2019.2916954

[5] Karedal, J., Czink, N., Paier, A., Tufvesson, F., & Molisch, A. F. (2010). Path loss modeling for vehicle-to-vehicle communications. IEEE transactions on vehicular technology, 60(1), 323-328. https://doi.org/10.1109/tvt.2010.2094632

[6] Al-Khalil, A. B., Turner, S., & Al-Sherbaz, A. (2015, May). Utilising SCM–MIMO channel model based on V-BLAST channel coding in V2V communication. In International Workshop on Communication Technologies for Vehicles (pp. 3-11). Springer, Cham. https://doi.org/10.1007/978-3-319-17765-6_1

[7] Jiang, G. X., Zhu, H. B., & Wei, C. A. O. (2006). A novel pulse design based on Hermite functions for UWB communications. The Journal of China Universities of Posts and Telecommunications, 13(1), 49-52. https://doi.org/10.1016/s1005-8885(07)60080-6

[8] Li, G., Zhou, Y., Bai, T., Lin, J., Pang, Y., Wu, W., ... & Jeon, G. (2018). Performance analysis for low-complexity detection of MIMO V2V communication systems. Computer Networks, 140, 92-100. https://doi.org/10.1016/j.comnet.2018.05.009

[9] Bithas, P. S., Kanatas, A. G., & Matolak, D. W. (2018). Exploiting shadowing stationarity for antenna selection in V2V communications. IEEE Transactions on Vehicular Technology, 68(2), 1607-1615. https://doi.org/10.1109/tvt.2018.2888802

[10] Yi, H., Guan, K., Ai, B., He, D., Zhu, F., Dou, J., & Zhong, Z. (2020, June). Channel characterization for vehicle-to-infrastructure communications at the terahertz band. In 2020 IEEE International Conference on Communications Workshops (ICC Workshops) (pp. 1-6). IEEE. https://ieeexplore.ieee.org/abstract/document/9145073

[11] Chehri, H., Chehri, A., & Hakem, N. (2019, September). Empirical radio channel characterization at 5.9 GHz for vehicle-to-infrastructure communication. In 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall) (pp. 1-6). IEEE. https://doi.org/10.1109/VTCFall.2019.8891344

[12] Ibrahim, A. S. (2020, May). Self-Interference Cancellation and Beamforming in Repeater-assisted Full-duplex Vehicular Communication. In 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring) (pp. 1-5). IEEE. https://ieeexplore.ieee.org/document/9128558

[13] Jameel, F., Javed, M. A., & Ngo, D. T. (2019). Performance analysis of cooperative V2V and V2I communications under correlated fading. IEEE Transactions on Intelligent Transportation Systems, 21(8), 3476-3484. https://doi.org/10.1109/tits.2019.2929825

[14] Khattabi, Y. M., & Alkhawaldeh, S. A. (2020, July). Spatial Modulation under Vehicular Rayleigh Fading Channels. In 2020 IEEE Symposium on Computers and Communications (ISCC) (pp. 1-6). IEEE. https://doi.org/10.1109/ISCC50000.2020.9219654

[15] Nguyen, B. C., & Hoang, T. M. (2019). Performance analysis of vehicle-to-vehicle communication with full-duplex amplify-and-forward relay over double-Rayleigh fading channels. Vehicular Communications, 19, 100166. https://doi.org/10.1016/j.vehcom.2019.100166

[16] Wang, L., Ai, B., He, D., Guan, K., Zhang, J., Kim, J., & Zhong, Z. (2019). Vehicle-to-infrastructure channel characterization in urban environment at 28 GHz. China Communications, 16(2), 36-48. https://doi.org/10.12676/j.cc.2019.02.002

[17] Yi, H., Guan, K., He, D., Ai, B., Dou, J., & Kim, J. (2019). Characterization for the vehicle-to-infrastructure channel in urban and highway scenarios at the terahertz band. IEEE Access, 7, 166984-166996. https://doi.org/10.1109/access.2019.2953890

[18] Caputo, S., Mucchi, L., Cataliotti, F., Seminara, M., Nawaz, T., & Catani, J. (2021). Measurement-based VLC channel characterization for I2V communications in a real

urban scenario. Vehicular Communications, 28, 100305. https://doi.org/10.1016/j.vehcom.2020.100305

[19] Eldeeb, H. B., Miramirkhani, F., & Uysal, M. (2019, July). A path loss model for vehicle-to-vehicle visible light communications. In 2019 15th International Conference on Telecommunications (ConTEL) (pp. 1-5). IEEE. https://ieeexplore.ieee.org/document/8848562

[20] Mir, Z. H., & Filali, F. (2016, January). Simulation and performance evaluation of vehicle-to-vehicle (V2V) propagation model in urban environment. In 2016 7th International Conference on Intelligent Systems, Modelling and Simulation (ISMS) (pp. 394-399). IEEE. https://doi.org/10.1109/ISMS.2016.56

[21] Nguyen, H., Xiaoli, X., Noor-A-Rahim, M., Guan, Y. L., Pesch, D., Li, H., & Filippi, A. (2020). Impact of big vehicle shadowing on vehicle-to-vehicle communications. IEEE Transactions on Vehicular Technology, 69(7), 6902-6915. https://doi.org/10.1109/tvt.2020.2994407

[22] Schwarz, S., Zöchmann, E., Müller, M., & Guan, K. (2020). Dependability of directional millimeter wave vehicle-to-infrastructure communications. IEEE Access, 8, 53162-53171. https://doi.org/10.1109/access.2020.2981166

[23] Tang, P., Wang, R., Molisch, A. F., Huang, C., & Zhang, J. (2019, September). Path loss analysis and modeling for vehicle-to-vehicle communications in convoys in safety-related scenarios. In 2019 IEEE 2nd Connected and Automated Vehicles Symposium (CAVS) (pp. 1-6). IEEE. https://doi.org/10.1109/WCSP.2018.8555605

[24] Wang, Y., Liu, F., & Wang, P. (2019, April). Performance Analysis of V2V Links in Highway Scenarios with Weibull-Lognormal Composite Fading. In 2019 IEEE Wireless Communications and Networking Conference (WCNC) (pp. 1-6). IEEE. https://ieeexplore.ieee.org/abstract/document/8885914/.

[25] Elbal, B. R., Schwarz, S., & Rupp, M. (2020, May). Relay selection and coverage analysis of relay assisted V2I links in microcellular urban networks. In 2020 IEEE Wireless Communications and Networking Conference (WCNC) (pp. 1-7). IEEE. https://doi.org/10.1109/WCNC45663.2020.9120458

[26] Shafiq, Z., Abbas, R., Zafar, M. H., Basheri, M.," Analysis and Evaluation of Random Access Transmission for UAV-Assisted Vehicular-to-Infrastructure Communications", IEEE Access, 7, 12427-12440, 2020. https://doi.org/10.1109/access.2019.2892776.

[27] Al-Basit, S. M., Al-Ghadhban, S., & Zummo, S. A. (2015). Performance Analysis of Virtual MIMO Relaying Schemes Based on Detect–Split–Forward. Wireless Personal Communications, 81(2), 711-724. https://doi.org/10.1007/s11277-014-2153-9.

[28] Zhang, M., Wen, M., Cheng, X., & Yang, L. (2016). A dual-hop virtual MIMO architecture based on hybrid differential spatial modulation. IEEE Transactions on Wireless Communications, 15(9), 6356-6370. https://doi.org/10.1109/twc.2016.2583423.

[29] Zhu, X., Song, Y., Yang, H., & Cai, L. (2009, April). 2-D switching diversity aided collaborative spatial multiplexing for uplink wireless access. In 2009 IEEE Wireless Communications and Networking Conference (pp. 1-4). IEEE. https://doi.org/10.1109/WCNC.2009.4917486

[30] Yang, M., Ai, B., He, R., Chen, L., Li, X., Huang, Z., ... & Huang, C. (2018, October). Path loss analysis and modeling for vehicle-to-vehicle communications with vehicle obstructions. In 2018 10th International Conference on Wireless Communications and Signal Processing (WCSP) (pp. 1-6). IEEE. https://ieeexplore.ieee.org/document/8555605.

[31] Wang, Q., Matolak, D. W., & Ai, B.," Shadowing Characterization for 5-GHz Vehicle-to-Vehicle Channels", IEEE Transactions on Vehicular Technology, 2018, 67(3), 1855-1866. https://doi.org/10.1109/tvt.2017.2764267.

[32] Waliullah, G. M., Bala, D., Hena, M. A., Abdullah, M. I., & Hossain, M. A. (2020). Performance Analysis of Zero Forcing and MMSE Equalizer on MIMO System in Wireless Channel. Journal of Network and Information Security, 8(1&2), 19-25. http://publishingindia.com/JNIS/69/performance-analysis-of-zero-forcing-and-mmse-equalizer-on-mimo-system-in-wireless-channel/888/6127/.

[33] Riadi, A., Boulouird, M., & Hassani, M. M. R. (2021). ZF and MMSE detectors performances of a massive MIMO system combined with OFDM and M-QAM modulation. Wireless Personal Communications, 116(4), 3261-3276. https://doi.org/10.1007/s11277-020-07848-4.

[34] Jiang, Y., Varanasi, M. K., & Li, J. (2011). Performance analysis of ZF and MMSE equalizers for MIMO systems: An in-depth study of the high SNR regime. IEEE Transactions on Information Theory, 57(4), 2008-2026. https://doi.org/10.1109/tit.2011.2112070.

[35] Elbahhar, F., Rivenq-Menhaj, A., & Rouvaen, J. M. ," Multi-User Ultra-Wide Band Communication System Based on Modified Gegenbauer and Hermite Functions", Wireless Personal Communications, 2005, 34(3), 255-277. https://doi.org/10.1007/s11277-005-3922-2.

[36] Hu, W., & Zheng, G. (2005, April). Orthogonal Hermite pulses used for UWB M-ary communication. In International Conference on Information Technology: Coding and Computing (ITCC'05)-Volume II (Vol. 1, pp. 97-101). IEEE. https://ieeexplore.ieee.org/abstract/document/1428444/.

[37] Menon, M. D., Rodrigues, J., & Gudino, L. J. (2020, July). Synthesis of UWB Pulse Shaper for Efficient Pulse Propagation in Human Tissue. In 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP) (pp. 1-5). IEEE, https://ieeexplore.ieee.org/document/9249543.

[38] Fan, Y., Feng, Y., Liu, L., Dong, S., Su, Z., Qiu, J., & Lin, X. (2022). Measurements and characterization for the vehicle-to-infrastructure channel in urban and highway scenarios at 5.92 GHz. China Communications, 19(4), 28-43. https://doi.org/10.23919/JCC.2022.04.003

[39] Yu, J., Jiang, F., Luo, Y., & Kong, W. (2022). Improved model-free adaptive predictive control-based cooperative driving control for connected and automated vehicles subject to time-varying communication delays and packet losses at signal-free intersections. IET Intelligent Transport Systems. https://doi.org/10.1049/itr2.12222