Performance Improvement in Cellular V2X (CV2X) by Using Massive MIMO Jacobi Detector

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***Abstract*—Cellular Vehicle-to-Everything (CV2X) has recently piqued the interest of both industry and academia. CV2X extends communication coverage by using the cellular infrastructure as a standard for vehicular communication. CV2X also enables the communication between vehicles and pedestrians, vehicles and the cellular network, along with vehicle to vehicle communication. The CV2X standard's expectations are gradually rising as the number of vehicles, cell phone users, smart devices connected to vehicles, and other factors increase. A more efficient CV2X framework is needed to fulfill these expectations. We focused on the PHY layer of the CV2X standard and proposed a model featuring Massive MIMO Jacobi Detection algorithm. Our experimental results suggest that our proposed model is able to improve reliability by reducing the bit error rate compared to the existing PHY layer framework. In addition, our proposed model can increase the throughput up to 3 times and reduce the computational complexity up to 93.2% compared to the existing signal detection and equalization algorithm.**

Index Terms*—*CV2X, SC-FDM, MIMO, Turbo coding, throughput, bit error rate, Massive MIMO, Jacobi Detector

I. Introduction

Information is exchanged between vehicles, between vehicles and infrastructure, and pedestrians using vehicular communication. This information will allow both vehicles and pedestrians to accurately assess their surroundings to predict any imminent adverse situation and take appropriate action after being in an adverse situation. A better communication framework is always welcome in this regard. A better communication framework can be defined by having a better bit error rate and throughput. There are two communication frameworks available for vehicular communication which are Cellular V2X (CV2X) and Dedicated Short Range Communication (DSRC). Both frameworks have different structures and are not interoperable. [1] DSRC covers two types of communication scenarios which are Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). CV2X covers two more communication scenarios along with V2V and V2I which are Vehicle-to-Network (V2N) and Vehicle-to-Pedestrian (V2P). V2V communication can be used to transfer safety information like collision avoidance warnings. V2I communication can be used to transfer traffic signal information, intersection warning message, and so on. V2N communication can be used to transfer real-time traffic/routing information, cloud service information, and so on. V2P communication can be used to transfer information like safety alerts to pedestrians, bicyclists, and so on. Ensuring passenger and traffic safety are the prime targets of vehicular communication [2]. Statistics from The U.S Department of Transportation (DOT) suggested that 82% of all road crashes in the United States can be addressed if an efficient vehicular communication framework is implemented [3]. Communication hindrances like unfavorable weather conditions, various mobility patterns, different traffic scenarios, varying speed of vehicles, adverse road conditions, and so on produce noise which can affect the transmitting signals severely [4].

Researchers have been trying to improve the performance of DSRC and CV2X in recent years by evaluating different techniques and methods. A system level simulator [5] and a test bed [6] were designed to simulate the CV2X communication scenarios and assess the quality of service more accurately. [7] An LTE based vehicular communication scenario was evaluated in an OMNET++ simulated environment for multimedia transmission. A model for vehicular communication is proposed in [8] to evaluate CV2X under different propagation scenarios. A model was proposed in [9] to support Mobile Edge Computing (MEC) for performance improvement. [10] Multiple Input Multiple Output (MIMO) is a technology that can improve energy and spectral efficiency by employing multiple antennas at both the transmitter and the receiver sides. [11] Two types of MIMO are more beneficial for improving communication performance which are Transmit Diversity and Spatial Multiplexing. A more robust vehicular communication structure was proposed in [12] which includes Orthogonal Space-Time Block Codes (OSTBC) enabled MIMO technique. A PHY layer including MIMO was proposed to conduct communication in V2I in the DSRC standard to improve throughput and bit error rate with the help of Software Defined Radio (SDR) [13]. Spatial Multiplexing MIMO and 5G NR were used on top of DSRC to improve vehicular communication performance [14], [15]. An improvement in throughput for non-safety services and improvement in reliability for safety services was done in

[16] using the selective MIMO technique. [17] Low Density Parity Check (LDPC) code was also employed in the DSRC standard as well for throughput improvement.

There are two major ways to improve vehicular communication performance which are using more transmit antennas and receive antennas and using a better channel coding mechanism. CV2X already uses MIMO technology along with linear signal detection and equalization algorithms like Zero Forcing (ZF) or Minimum Mean Squared Error (MMSE). MIMO is a key technology in the context of wireless communication due to its high spectral efficiency and high reliability. Massive MIMO is a concept that takes the MIMO idea to the next level by utilizing much more antennas compared to the simple MIMO technique [20], [21]. It includes a large number of receiving antennas compared to a small number of transmitting antennas. The existing signal detection and equalization techniques work fine for simple MIMO scenarios like a small number of antennas at the transmitter and receiver side but become computationally expensive with the increased number of antennas [22]. The computational complexity of these algorithms is very high when even eight antennas are used. Jacobi Detector (JD) is an iterative signal detection and equalization algorithm which has the ability to perform better than ZF or MMSE algorithm with reduced computational complexity in a Massive MIMO scenario. To make the JD algorithm work at its full capacity, the number of receiving antennas must be way larger than the number of transmitting antennas. This type of scenario is a perfect example of V2I communication where multiple vehicles can establish a connection with the base station simultaneously. A sample Massive MIMO Scenario in CV2X is displayed in Fig. 1. We proposed a modified PHY layer for the CV2X standard to employ the JD algorithm and assessed the performance and compared the performance with the MMSE method.

The remaining portions of the paper are designed as follows: Section II demonstrates V2X communication in detail. It shows the block diagram of the PHY layer of CV2X and the allocated spectrum for CV2X communication in the 5.9 GHz band. Section III presents how the JD algorithm can be employed in the CV2X standard. Then, section IV contains the experimental details and the metrics to evaluate the results from the simulation. After that, section V displays the experimental results and comparative analysis of the results. Finally, the paper is concluded in section VI which mentions reasonable future plans for this work.

II. V2X Communication

Federal Communication Commission (FCC) determines vehicular communication protocols and standards in the United States. FCC approved DSRC in 1992 for physical (PHY) layer specification. IEEE 802.11 family adopted DSRC in the IEEE 802.11p standard in 2004. In 2021, FCC adopted CV2X to define a new PHY layer specification for vehicular communication. [1] CV2X leverages the framework of the cellular communication PHY layer to define the

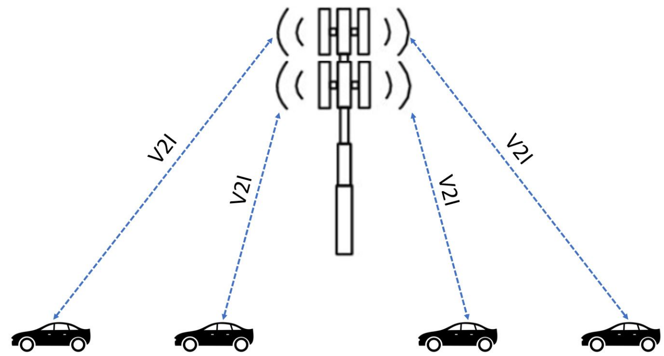

Fig. 1. Massive MIMO Scenario in CV2X.

PHY layer of vehicular communication and uses the cellular infrastructure for data transmission.

A. PHY Layer in CV2X Communication

The block diagram of the PHY layer structure of the CV2X standard is presented in Fig. 2. According to this figure, the PHY layer gets the bit streams of the information generated by the application layer after processing through the other layers. In the PHY layer, the information data goes through several steps to be prepared for transmission. The steps on the transmitter side include FEC (Forward Error Correction) Coding (channel coding), Signal Modulation, SC-FDM (Single Carrier Frequency Division Multiplexing) Modulation, and MIMO Transmitter. The information bits are converted to codeword bits in the FEC Coding step based on the coding method and coding rate. The codeword bits are modulated in the signal Modulation step based on a specified modulation scheme. The SC-FDM Modulation step prepares the modulated symbols to be resistant to multipath fading and inter-symbol interference. The MIMO Transmitter step aligns the SC-FDM Modulated symbols to the appropriate transmit antenna ports for multi-antenna communication. On the receiver side, the same steps are followed in reverse order to reconstruct the transmitted information. [18], [19] The SC-FDM specifications of the CV2X standard is presented in Table I.

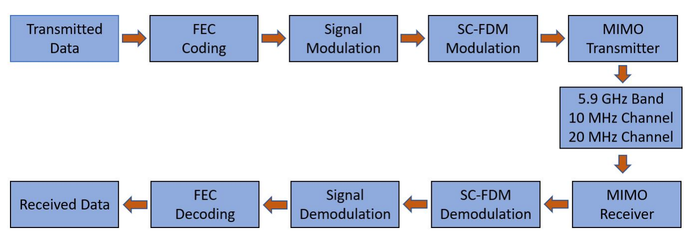

Fig. 2. Block Diagram of the PHY layer of CV2X.

B. Radio Channel Details for Vehicular Communication

There are two PHY layer standards available for Vehicle-to-Everything (V2X) communication which are CV2X and IEEE 802.11p (Dedicated Short Range Communication).

TABLE I
SC-FDM CHARACTERISTICS OF CV2X

Parameter	Value
Number of Subcarriers	12
Subcarrier Frequency Spacing	15 KHz
Number of Symbols per Subcarrier	14
Guard Interval (GI)	4.68 μsec
Symbol Interval (including GI)	71.35 μsec

FCC specified 75 MHz spectrum in the 5.9 GHz band for wireless communication. The spectrum division is presented in Fig. 3. The lower 45 MHz spectrum is kept for unlicensed use and the higher 30 MHz is kept for V2X communication. The higher 30 MHz spectrum is divided into two bandwidths which are 10 MHz and 20 MHz. FCC allocated both the bandwidths for Cellular V2X use but IEEE 802.11p can only use 10 MHz bandwidth. Doppler effect and Multipath fading are the prime signal interfering factors during data transmission for a given bandwidth. Doppler effect is characterized as a distortion in the signal due to the relative motion of the transmitter and the receiver. Multipath fading is characterized as an interference in the signal when the signal is either reflected, diffracted, or scattered by objects on the way to the receiver. We built a MIMO channel model using the existing Matlab object which had rayleigh fading distribution and a certain doppler shift value. We specified the rayleigh fading distribution parameters by using random path delay, path gain, and sampling frequency. Channel specific values of delay spread and sampling frequency were used to calculate the path delays. We specified the doppler shift value in such a way that the communication can reflect a high mobility scenario. We also used the regular Additive White Gaussian Noise (AWGN) channel model to have randomized channel noise in the signal.

III. JACOBI DETECTOR (JD) IN V2X COMMUNICATION

Jacobi Detector (JD) is a signal detection and equalization algorithm which is used in massive MIMO scenarios when a large number of transmitting antennas (as large as 16) and receiving antennas (as large as 44) are considered. The computational complexity of this method is lower compared to Zero Forcing or Minimum Mean Squared Error due to having an iterative working mechanism. [23] The estimated signal using this method is shown in Eqn. 1.

$$\hat{x}^{(n)} = D^{-1}(\hat{x}_{MF} + (D - A)\hat{x}^{(n-1)}) \tag{1}$$

Here, D is the diagonal matrix of A. The estimation of A is shown in Eqn. 2.

$$A = (H^H H) + NI \tag{2}$$

Here, H is the estimated channel matrix, N is the noise variance and I is the identity matrix of size equal to the number of transmitting antennas. The approximation of the initial signal estimation and estimation of $\hat{x}_{MF}$ are shown in Eqn. 3 and 4 respectively.

$$\hat{x}^{(0)} = D^{-1}\hat{x}_{MF} \tag{3}$$

$$\hat{x}_{MF} = H^H y \tag{4}$$

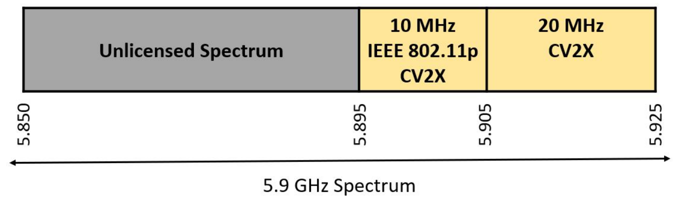

Fig. 3. 5.9 GHz spectrum division in United States.

We incorporated the Jacobi Detector (JD) technique in the MIMO receiver block along with the MMSE method. Then we tested the performance of the JD method in comparison with the MMSE method. Based on the discussion above, we prepared a modified PHY layer of the CV2X standard.

IV. EXPERIMENTAL DESCRIPTION

MIMO is a technique that can improve the throughput of the communication link by transmitting a large amount of data by using multiple transmit and receive antennas. In addition, having a large number of antennas can improve performance even further. That's why we employed the JD method in the CV2X PHY layer which is displayed as a block diagram in Fig. 4. We used 2x2 (two transmitting antennas and two receiving antennas) and 4x4 (four transmitting antennas and four receiving antennas) antenna configurations to evaluate the MMSE method. Also, we evaluated JD for four variations of antenna configuration which are shown in Table II.

According to our proposed model presented in Fig. 4 we used the turbo coding scheme in the FEC Coding and FEC Decoding blocks. In addition, the QPSK modulation technique was used in the Signal Modulation and Signal Demodulation blocks. We configured the parameters of SC-FDM Modulation and SC-FDM Demodulation blocks based on the CV2X specifications. In the MIMO Receiver block, we used both Minimum Mean Squared Error (MMSE) and Jacobi Detector (JD) as the signal detection and equalization method. We implemented functionalities for all the blocks presented in the proposed model in the Matlab environment and ran the simulation as a complete package. We recorded the simulation results and presented them in the next section. The experimental parameter values are shown in Table III.

We evaluated our proposed model based on two metrics which are given below.

a) Bit Error Rate (BER): BER is defined by the number of error bits that are received per unit time. It is calculated by the ratio of the number of error bits at the receiver divided by the total number of bits transmitted during the simulation time.

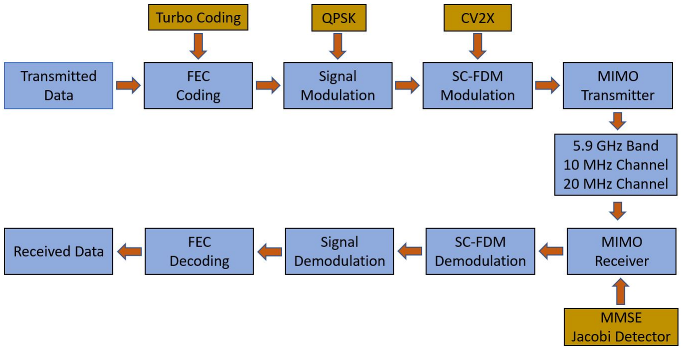

Fig. 4. Block diagram of the proposed model.

TABLE II
ANTENNA CONFIGURATION FOR MIMO AND MASSIVE MIMO IN CV2X

MIMO Configuration	Number of Transmit Antenna	Number of Receive Antenna
Conventional MIMO with MMSE	2	2
	4	4
Massive MIMO with Jacobi Detector	2	2
	2	4
	4	8
	8	20
	16	44

b) Throughput: Throughput is defined by the total number of frames successfully received, divided by the total time over which the transmission is being held. Throughput is expressed in Mbps, which refers to channel capacity as well. In our experiments, we used 1 ms as a transfer time for each frame to calculate throughput.

V. EXPERIMENTAL RESULT AND ANALYSIS

We designed our Matlab simulation according to the proposed model shown in the experimental description section. We ran our simulation for both conventional MIMO with MMSE and massive MIMO with the JD method. We stored throughput and BER values from the simulation and presented a comparative analysis below.

A. Bit Error Rate (BER) Analysis

Fig. 5 and 6 display the BER comparison of MMSE and JD method in CV2X framework at 10 MHz and 20 MHz channels respectively. In both the figures, the black line and brown line represent BER using the MMSE method for 2x2 and 4x4 antenna configurations respectively. Also, the red line, blue line, cyan line, and magenta line represent BER using the JD method for 2x2, 4x8, 8x20, and 16x44 antenna configurations respectively. From Fig. 5 and 6, it is observed that the BER performance of JD method is equal to or better than MMSE method. The reason for that is, having a large number of receiving antennas compared to a small number of transmitting antennas helps the JD method to detect and equalize the transmitted signal more efficiently than the MMSE method.

TABLE III
EXPERIMENTAL PARAMETERS

Parameter	Value
Channel Model	Rayleigh Fading
Modulation Type	QPSK
Channel Bandwidth	10 MHz & 20 MHz
Doppler Shift	300Hz
SNR Range	0 - 30 dB
CRC Code	24 bit CRC Checksum
Coding Scheme	Turbo Code
Coding Rate	1/3
Maximum Number of Bits Processed	2e5
Number of Iterations for JD Method	3

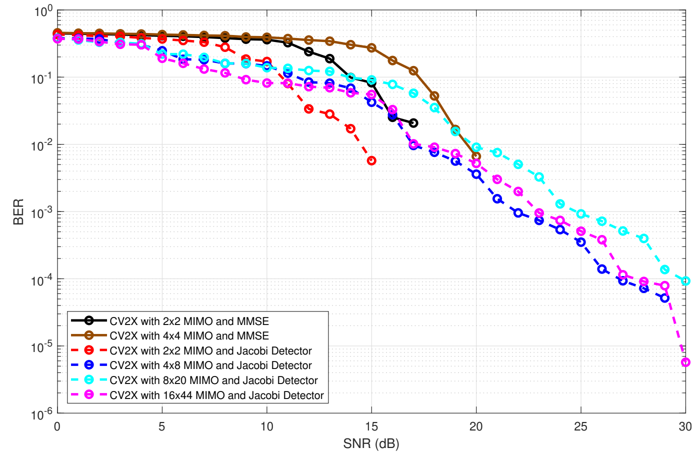

Fig. 5. BER comparison between MMSE and JD method at 10 MHz channel.

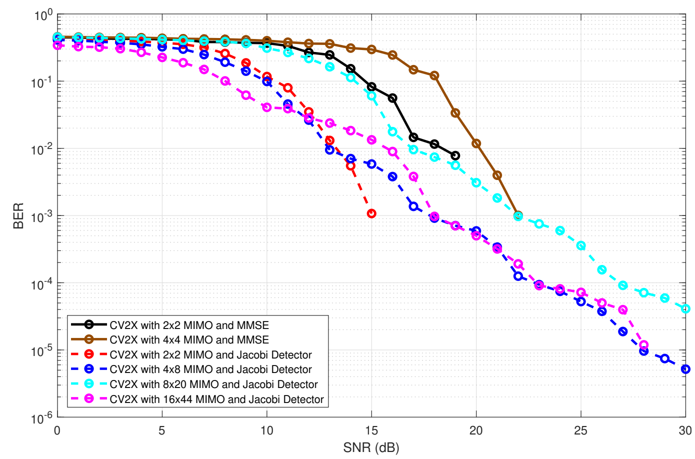

Fig. 6. BER comparison between MMSE and JD method at 20 MHz channel.

B. Throughput Analysis

Fig. 7 and 8 display the throughput comparison of MMSE method and JD method in CV2X framework at 10 MHz and 20 MHz channels respectively. In both the figures, the black line and brown line represent throughput using the MMSE method for 2x2 and 4x4 antenna configurations respectively. Also, the red line, blue line, cyan line, and magenta line represent throughput using the JD method for 2x2, 4x8, 8x20,

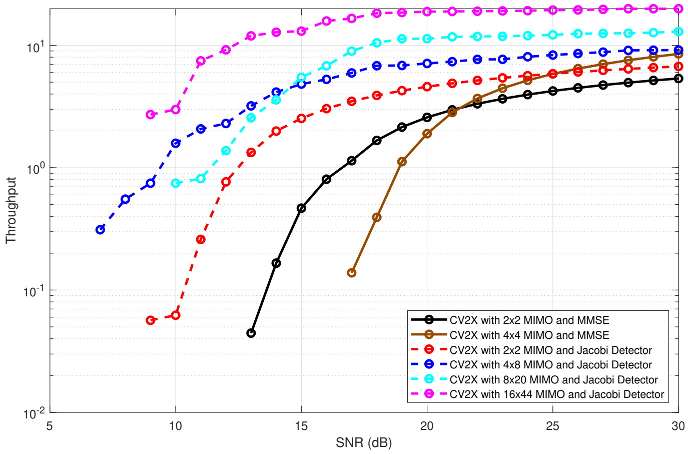

Fig. 7. Throughput comparison between MMSE and JD method at 10 MHz channel.

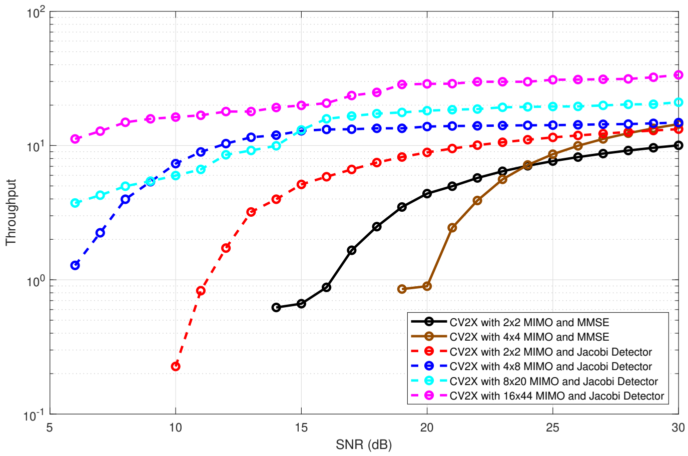

Fig. 8. Throughput comparison between MMSE and JD method at 20 MHz channel.

and 16x44 antenna configurations respectively. From Fig. 7 and 8, it is observed that the performance of the JD method is similar to MMSE method for 2x2 antenna configuration but significantly better than the MMSE method for 4x8, 8x20, and 16x44 antenna configurations. Also, the performance of the JD method keeps increasing with the increase of the number of transmitting and receiving antennas. The reason for that is more signal information can be sent through the channels using a large number of antennas. Also, the BER of the JD method is lower than the MMSE method, which also impacts the throughput as well.

The final throughput using the MMSE method and JD method at both 10 MHz and 20 MHz at the end of the simulation is presented in Table IV and Table V respectively. From Table IV and V, it is evident that the throughput of the 2x2 antenna configuration and 4x4 antenna configuration with the MMSE method is quite similar in comparison with the throughput of the 2x2 antenna configuration with the JD method. The throughput of the 4x8 antenna configuration with the JD method is a little over 1.7 times and 1.1 times better compared to the 2x2 antenna configuration and 4x4 antenna configuration with the MMSE method respectively at both 10 MHz and 20 MHz channels. In addition, The throughput of the 8x20 antenna configuration with the JD method is 2 times and 1.2 times better compared to the 2x2 antenna configuration and 4x4 antenna configuration with the MMSE method respectively at both 10 MHz and 20 MHz channels. Moreover, The throughput of the 16x44 antenna configuration with the JD method is 3 times and almost 2 times better compared to the 2x2 antenna configuration and 4x4 antenna configuration with the MMSE method respectively at both 10 MHz and 20 MHz channels.

C. Complexity Analysis

The MMSE algorithm is a linear signal detection and equalization algorithm. So, the complexity of this algorithm largely depends on the number receive antenna. [10], [20] On the other hand, the JD algorithm is an iterative signal detection and equalization algorithm. So, the complexity of the JD algorithm largely depends on the number of iterations it is taking throughout the process. We used big $\mathcal{O}$ notation to represent the computational complexity. Big $\mathcal{O}$ notation is used to define the computational complexity of any algorithm in a worst case scenario. The computational complexity of the MMSE method is computed in the order of $\mathcal{O}(MN^2)$ where M is the number of receive antenna and N is the number of transmit antenna. [21], [22] On the other hand, the computational complexity of the JD method is computed in the order of $\mathcal{O}(kN^2)$ where k is the number of iterations and N is the number of transmit antenna. We used 3 as a number of iterations for the JD algorithm. The computational complexity of both the MMSE and JD algorithms for all the antenna configurations are presented in Table VI. From Table VI, it is observed that the complexity of JD for 2x2 antenna configuration is not better than MMSE but the complexity of JD starts to reduce when the number of antennas is increased. Hence, The complexity of JD is reduced by 65.5%, 81.3%, and 93.2% compared to MMSE when 4x8, 8x20, and 16x44 antenna configurations are used respectively.

TABLE IV
THROUGHPUT COMPARISON AT 10 MHZ CHANNEL

MIMO Configuration	Antenna Configuration	Throughput in Mbps
Conventional MIMO with MMSE	2x2	5.49
	4x4	8.59
Massive MIMO with Jacobi Detector	2x2	6.96
	4x8	10.19
	8x20	13.29
	16x44	16.47

VI. CONCLUSION

Jacobi Detector (JD) algorithm provides efficient performance when a large number of receiving antennas are used compared to a small number of transmitting antennas. With the iterative computation power, the JD algorithm can reduce

TABLE V
THROUGHPUT COMPARISON AT 20 MHZ CHANNEL

MIMO Configuration	Antenna Configuration	Throughput in Mbps
Conventional MIMO with MMSE	2x2	9.63
	4x4	15.76
Massive MIMO with Jacobi Detector	2x2	13.09
	4x8	16.76
	8x16	19.56
	16x44	28.90

TABLE VI
COMPLEXITY COMPARISON BETWEEN THE MMSE AND JD METHOD

MIMO Configuration	Antenna Configuration	Complexity of MMSE	Complexity of TD
Conventional MIMO with MMSE	2x2	8	12
	4x4	64	48
Massive MIMO with Jacobi Detector	2x2	8	12
	4x8	128	48
	8x16	1024	192
	16x44	11264	768

the computational complexity significantly on the receiver side. In addition, the JD algorithm can increase the reliability of the communication link by reducing the bit error rate when a higher number of antenna configurations is used. Moreover, a large number of antennas can improve the throughput accordingly using the JD method compared to the MMSE method. So, A modification in the PHY layer of the CV2X standard is proposed to accommodate the JD method instead of the MMSE method. This kind of improved performance will be required in near future as vehicle users and cellular consumers are going to be using the same cellular framework. Our experimental results corroborate that, the JD method in the CV2X framework can improve communication performance greatly. Moreover, we are trying to explore other Massive MIMO optimization algorithms like Gauss Seidel and Neumann Series algorithms in the context of vehicular communication. Our future work includes checking the compatibility and performance of the Gauss Seidel and Neumann Series algorithms in the CV2X framework.

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