

Performance Evaluation of Adaptive Beamforming in 5G-V2X Networks

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Abstract—Vehicles are the third fastest growing connected device type after smart phones and tablets. Also, automotive industry is interested to get more vehicles connected to the internet to improve traffic safety and efficiency. This creates a need for Vehicle-to-Everything (V2X) communications. In this work, the possibility of exploiting beamforming in LTE-V2X is considered. Singular value decomposition (SVD) receiver and precoder is implemented in an LTE-A system level simulator and the performance on multi-lane highway scenario is simulated and analyzed in downlink Vehicle-to-Infrastructure (V2I) scenario. The performance is compared to the conventional maximum-ratio combining (MRC) and LTE codebook precoded minimum mean square error (MMSE) receivers. In addition, the switched-beam beamforming is imitated by modified antenna patterns with 7 and 15 narrow beams. The results show that the SVD receiver provides gain compared to the conventional MRC and MMSE receivers in ideal scenario. Furthermore, with modified antenna patterns, the performance was enhanced when compared to the default antenna pattern.

Index Terms—LTE-V2X, vehicle, reliability, system level simulations, 5G.

I. INTRODUCTION

With the help of Vehicle-to-Everything (V2X) communication, vehicles and drivers are able to sense the surrounding vehicles and get information from the infrastructure [1], [2]. The goal is to improve traffic management and travel safety with the help of wireless communications. For example, vehicles can be informed about accidents and get guidance on speed and route for optimizing the traffic flow and in that way minimize traffic congestion. V2X communication also creates new commercial opportunities to vehicle and communication industries.

The 3GPP has listed over twenty different use cases, which contain cases such as emergency stop, queue warning and road safety warnings [3]. The automotive domain is interested especially in the following V2X use cases [4]:

- Automated driving.

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- Road safety and traffic efficiency services.
- Digitalization of transport and logistics.
- Intelligent navigation.
- Information society on the road.

Several wireless standards have been researched and proposed to V2X communications: WLAN, Bluetooth and cellular networks [1], [4], [5]. However, none of them is able to satisfy all the requirements of safety services in terms of latency and availability. At the moment, IEEE 802.11p based standards (DSRC and WAVE) and cellular based (LTE-A and future 5G) standards are the most promising standards for V2X communications. Recent studies have preferred using LTE as the V2X technology [6], [7], mainly because LTE cellular network infrastructure already exists [8].

In this paper, the V2X communications is simulated with a Matlab-based system level LTE-A simulator and it is extension of [11]. The simulator is used to simulate V2I communications from an road side unit (RSU) to a vehicle, i.e., the downlink in the highway scenario. In this work, we only consider the LTE-Uu interface and not the LTE-PC5 interface. Because it is expected that different carrier frequency is used for V2V communication. We utilize the two most used receiver types MRC and MMSE with LTE codebook precoding and compare them in ideal case to SVD beamforming. Furthermore, we evaluate the performance when channel-quality indicator (CQI)-delay is considered and analyze the performance when different antenna patterns are used. This paper is organized as follows. The system and link models are defined in Sections II and III, respectively. Section IV provides the performance evaluation of the vehicular network. Finally, Section V concludes the paper.

II. SYSTEM MODEL

A network with single user single-input multiple-output (SU-SIMO) and with single user multiple-input multiple-output (SU-MIMO) transmission schemes using orthogonal frequency-division multiple access (OFDMA) is considered. Let \mathcal{B} be a set of RSUs where RSU b has N_t transmit antennas (Tx), which serves a set of vehicles \mathcal{V}_b , where vehicle v has

N_r receive antennas (Rx). The frequency domain consists of a set of subcarriers \mathcal{S} .

In the SU-SIMO transmission scheme the signal vector received from the RSU b by the vehicle $v \in \mathcal{V}_b$ over the subcarrier $s \in \mathcal{S}$ can be written as

$$\mathbf{y}_{b,v}^s = \mathbf{h}_{b,v}^s \mathbf{x}_{b,v}^s + \sum_{i \in \mathcal{B} \setminus b} \mathbf{h}_{i,v}^s \mathbf{x}_{i,v}^s + \mathbf{n}_{b,v}^s, \quad (1)$$

where $\mathbf{x}_{b,v}^s \in \mathbb{C}^{N_t}$ is the transmitted signal from the desired RSU b to vehicle v over subcarrier s , $\mathbf{h}_{b,v}^s \in \mathbb{C}^{N_r \times N_t}$ is the channel vector from the desired RSU b to the v th vehicle over the s th subcarrier, $\mathbf{x}_{i,v}^s \in \mathbb{C}^{N_t}$ is the transmitted signal from the i th interfering RSU at subcarrier s , $\mathbf{h}_{i,v}^s$ is the channel vector from the i th interfering RSU to the v th vehicle at subcarrier s , and $\mathbf{n}_{b,v}^s \sim \mathcal{CN}(0, N_0 \mathbf{I}_{N_r})$ denotes the additive white Gaussian noise with zero mean.

We analyze the performance of the network considering two types of receivers: maximum ratio combining (MRC) and linear minimum mean square error (LMMSE). Furthermore, singular value decomposition (SVD) precoding is used to benchmark other precoding methods. The MRC weight vector $\mathbf{w}_{b,v}^s \in \mathbb{C}^{N_r \times N_t}$ is given by

$$\mathbf{w}_{b,v}^s = (\mathbf{h}_{b,v}^s)^*, \quad (2)$$

where $(\cdot)^*$ denotes the conjugate transpose.

When LMMSE and $N_t = 2$ used, LTE specific precoder providing the best performance has been applied in transmission. In the SU-MIMO transmission scheme, the received signal vector from RSU b by the vehicle v over the subcarrier s is given by

$$\mathbf{y}_{b,v}^s = \mathbf{H}_{b,v}^s \mathbf{x}_{b,v}^s + \sum_{i \in \mathcal{B} \setminus b} \mathbf{H}_{i,v}^s \mathbf{x}_{i,v}^s + \mathbf{n}_{b,v}^s, \quad (3)$$

where $\mathbf{H}_{b,v}^s \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix from desired RSU b to the v th vehicle over the s th subcarrier, and $\mathbf{H}_{i,v}^s$ is the channel matrix from the i th interfering RSU to the v th vehicle at subcarrier s .

For the LMMSE filter, the weight matrix $\mathbf{W}_{b,v}^s \in \mathbb{C}^{N_r \times N_t}$ of the LMMSE receiver is given by

$$\mathbf{W}_{b,v}^s = \arg \min_{\mathbf{W}_{b,v}^s} E[\|\hat{\mathbf{x}}_{b,v}^s - \mathbf{W}_{b,v}^s \mathbf{y}_{b,v}^s\|^2], \quad (4)$$

where $\hat{\mathbf{x}}_{b,v}^s = (\mathbf{W}_{b,v}^s)^H \mathbf{y}_{b,v}^s$ is the vector of estimated received data. Therefore, the weight matrix can be written as [9]

$$\mathbf{W}_{b,v}^s = (\mathbf{H}_{b,v}^s (\mathbf{H}_{b,v}^s)^H + \mathbf{R}_{b,v}^s)^{-1} \mathbf{H}_{b,v}^s, \quad (5)$$

where $\mathbf{R}_{b,v}^s$ is the inter-cell interference plus noise covariance matrix and it is assumed to be known at the receiver.

This idea of using SVD to precode the transmission is only theoretical, as it requires the perfect channel information. Generally, the precoding matrix will not perfectly match the channel matrix as there is always some residual interference between multiplexed signals. SVD is not considered to be a viable precoding scheme due to substantial feedback and complexity of singular value decomposition. However, SVD can be used to benchmark the systems performance.

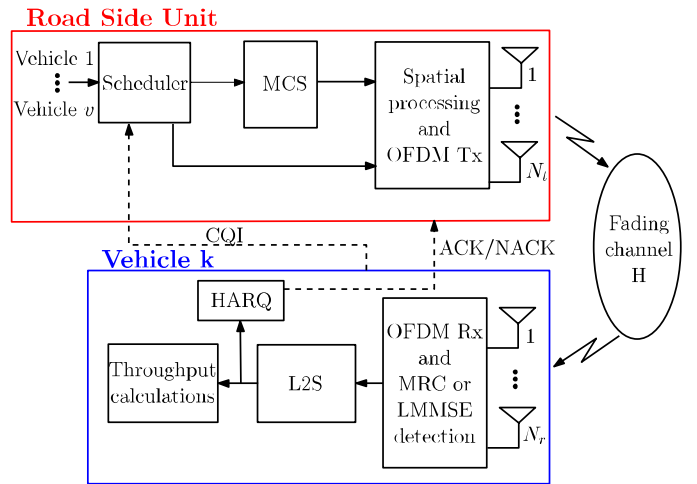


Fig. 1. Link model of the used system level simulator.

III. LINK MODEL

Fig. 1 shows the simulator's link model [10], [11]. The RSU side starts with the scheduler, which is responsible of the resource allocation for the vehicles. The simulator uses a proportional fair (PF) scheduler, which exploits short-term channel variations and maintains the long-term average user data rate. The vehicle transmits the channel-quality indicator (CQI) that the scheduler utilizes and performs the resource allocation. The simulator estimates the CQI from the received signal and the calculated signal-to-interference-plus-noise ratio (SINR) for every physical resource block (PRB).

Next, the modulation and coding scheme (MCS) is selected for the vehicles. It uses the CQI information to estimate the suitable MCS level for each scheduled user. The last step on the RSU is the transmitter side spatial and Orthogonal Frequency-Division Multiplexing (OFDM) processing. The cyclic prefix is assumed to be longer than the multipath delay spread, thus inter-symbol-interference (ISI) is not considered in these simulations.

The vehicle, i.e., the receiver side link-to-system (L2S) mapping is done with the Mutual Information Effective SINR Mapping (MIESM). Using MIESM, computational overhead can be reduced, but the results are still sufficiently accurate [12]. The L2S interface calculates the SINR and maps it to the corresponding average mutual information. The average Frame Error Probability (FEP) is estimated based on this MIESM value with the help of the predefined Frame Error Rate (FER) curve. The FER value detects the successful and failed frames and the hybrid automatic repeat request (HARQ) is used to control the retransmissions. HARQ sends an acknowledgement (ACK) or a negative acknowledgment (NACK) to the transmitter (RSU) to report whether the transmission was successful or not.

IV. SYSTEM LEVEL PERFORMANCE RESULTS

System level simulations are particularly useful for studying network related issues, such as resource allocation, interfer-

TABLE I
3GPP SPECIFICATIONS FOR A HIGHWAY SCENARIO

Parameter	Value
Number of lanes	3 in each direction, 6 in total
Lane width	4 m
Simulation area size	highway length longer than 2000 m
Vehicle speed	140 km/h

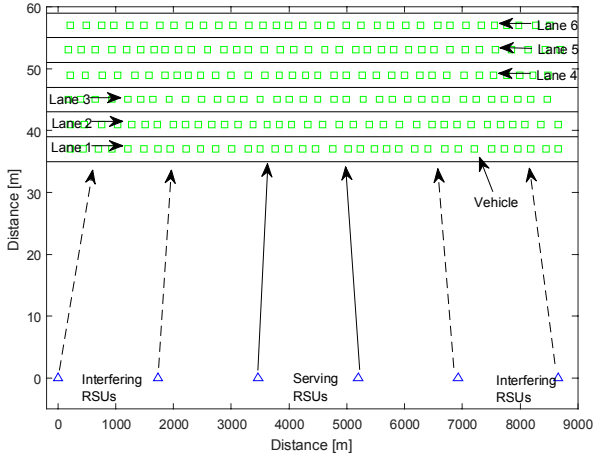


Fig. 2. The layout of the highway model used in the simulations.

ence management and mobility management. 5G related system level simulations are also necessary in the future because we can not only rely on analytical analysis. Furthermore, when the simulation platform follows the standardization it can provide reliable results on the expected performance.

In this work, LTE-A system level simulator is used to model a highway RSU network, which is used to serve vehicles at high speed. The 3GPP has specified parameters for V2X highway simulations, which can be found in Table I [3].

The highway model used in the simulations is presented in Fig. 2. The RSUs are located along the road, 35 m from the highway. Each RSU serves multiple vehicles (green squares), but a vehicle is connected only to a single RSU. The vehicles on lanes 1 to 3 are moving right and vehicles on lanes 4 to 6 are moving left. All six RSUs are modeled but the performance is measured only from the middle RSUs 3 and 4. This explains why four of the RSUs are marked to be interfering. In the simulations inter-vehicular distance is 116 m - about 90 vehicles are served by one base station.

The used system bandwidth is 10 MHz, which results into 50 PRBs. Each RSU serves multiple vehicles and one vehicle is connected to a single RSU. Generally, V2X traffic is periodically sent. However, for this work we have mapped 1600 byte package to be sent with a time interval of 100 ms to be equivalent to a constant transmission with a target rate of 128 kb/s per vehicle. The used receiver types are maximum-ratio combining (MRC), minimum mean square error (MMSE) and SVD receivers. All the main simulation parameters are

shown in Table II.

TABLE II
SIMULATION PARAMETERS AND ASSUMPTIONS

Parameter	Assumption
Duplex mode	FDD
System bandwidth	10 MHz
Number of PRBs	50
Antenna configuration	$1 \times 2, 2 \times 2, 4 \times 2$
Distance between RSUs	1732 m
Receivers	MRC, MMSE, SVD
HARQ	Chase combining
Transmission power	46 dBm
Feedback CQI period	6 ms
Feedback CQI delay	2 ms
Channel estimation	Ideal
Traffic model	Continuous constant rate transmission
Scheduler	Proportional fair
Target rate	128 kb/s

A. Performance Analysis of LTE codebook and SVD precoding

In the first scenario Rayleigh channel model is used to analyze the performance in ideal case. The first receiver MRC does not have any precoding and it just combines signals from every channel together in the receiver. In the second receiver, the precoding was made with the LTE codebook-based precoding and MMSE-receiver was utilized, which minimizes the mean square error of the signals. The third type of the simulated precoding and reception combination was built upon SVD, which is the theoretically best precoding method. The system performance is analyzed from the receiver SINR value and the results are presented as a Cumulative Distribution Function (CDF) of the SINR. Especially, the performance of the cell edge vehicles (5% from the CDF figure) and the performance of the median SINR vehicles (50% of the CDF figure) is analyzed.

The receiver SINR CDF-plot is shown in Fig. 3. The results are following the theory: the SVD receiver type is the best, as the precoder is picked to match perfectly the channel as there is no delay at the CQI. Also, when adding more transmit antennas, the transmit diversity gives some gain and the 4×2 SVD gives better performance than 2×2 SVD. The transmit diversity gain in this scenario was 2.3 dB, but in high SNR region (over 35 dB) the curves began to overlap. The third best performance was achieved with the LTE codebook precoded MMSE receiver. The performance was 4.5 dB lower than with 4×2 SVD and 2.2 dB lower than with 2×2 SVD. The MRC receiver had the worst performance and it was 10.4 dB lower than with 4×2 SVD.

The SINR performance of 5% probability (cell-edge vehicles) and with 50% probability (median SINR vehicles) is presented in Table III. With SVD, the cell-edge vehicles are getting enormous gain (10 dB) with the SVD receiver, when comparing to the MRC receiver. The MRC receiver is not able to suppress the interference from other communications, whereas MMSE is able to suppress the interference more

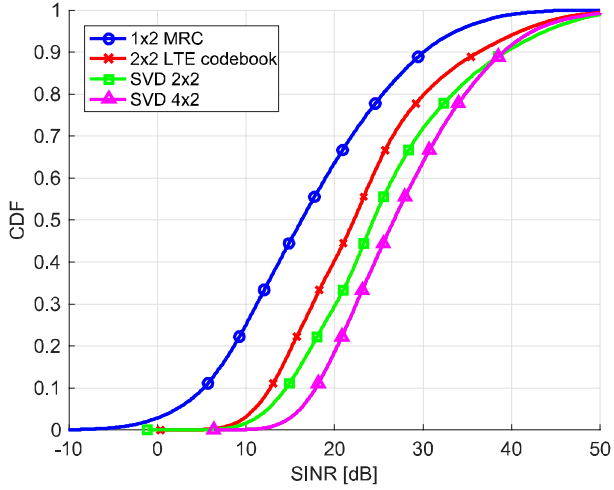


Fig. 3. Receiver SINR comparison of the LTE codebook and SVD without delay and with the inter-vehicle distance 116 m.

TABLE III

THE SINR PERFORMANCE OF DIFFERENT CDF PROBABILITIES WITH THE INTER-VEHICLE DISTANCE OF 116 METERS

Probability	MRC	LTE codebook	2×2 SVD	4×2 SVD
50%	16.3 dB	22.2 dB	24.4 dB	26.7 dB
5%	2.1 dB	10.9 dB	12.4 dB	16.1 dB

effectively. The MMSE had 8.8 dB better performance than the MRC. [13]

In the previous result, the simulations were made without delay in the CQI information. In that case, the base station can pick the best possible precoder for the transmission as it knows the channel conditions. Next, we analyze the impact of CQI delay to the SINR performance. The CDF-plot of the receiver SINR is presented in Fig. 4. As expected, the 2×2 SVD without delay has the best performance, because the precoding can be done perfectly. However, when 4 ms of delay is added, the performance is decreased by 3 dB. In this situation, the optimal precoder is not selected and the interference is not canceled perfectly. The LTE codebook precoded MMSE without delay has a similar performance as the SVD receiver with delay.

B. Performance evaluation with switched-beam beamforming

The simulations with the modified antenna patterns were performed with the LTE codebook precoding and the MMSE receiver. The antenna configuration was 2 transmitter and 2 receiver antennas. In this scenario the simulations utilize WINNER II channel model implementation and parametrization [14]. In the previous section, the base station was only 35 meters away from the road. To achieve more precise angle tracking, the base stations were moved to 135 meters away from the roadside.

Fig. 5 illustrates the CDF-plot of SINR with the previously presented three different antenna beam patterns: default [15],

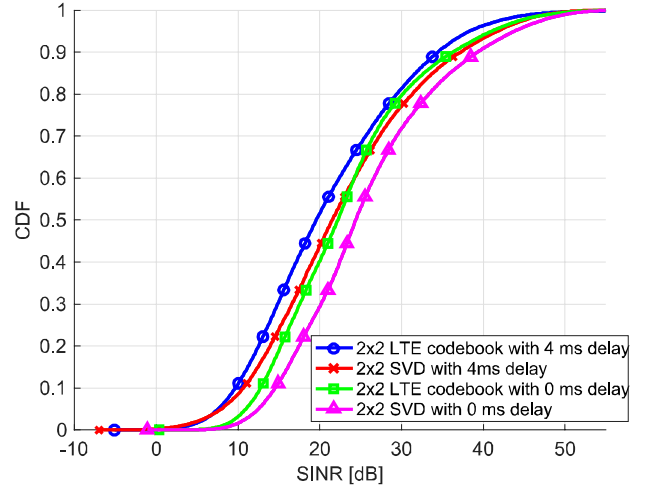


Fig. 4. Receiver SINR comparison of the LTE codebook and SVD without and with delay and with the inter-vehicle distance 116 m.

TABLE IV

THE SINR PERFORMANCE WITH DIFFERENT BEAM PATTERNS WHEN THE BASE STATIONS ARE 135 METERS FROM THE ROADSIDE

Probability	Default	7 beams	15 beams
50%	26.0 dB	29.5 dB	35.9 dB
5%	8.7 dB	12.2 dB	21.1 dB

7 beams and 15 beams. As expected, the wide default antenna pattern had the lowest performance. With the 7 beams antenna pattern the performance was enhanced by 3.8 dB in lower SINR values and about the same performance was achieved in the higher SINR region than with the default pattern. With the very narrow 15 beams, the performance was remarkably better - 10 dB higher than with the default pattern. The performance gains are coming from the narrower overall pattern. The interference from the vehicles communicating with other base stations can be decreased as the antenna pattern is covering only the served users. The antenna patterns were designed to cover only that part and so the interference is minimized. Also, the narrower beams would have higher gain, so the higher gains with the modified patterns also enhanced the performance.

The cell-edge and median SINR vehicles SINR performance is presented in Table IV. Median SINR vehicles will have 3.5 dB increase in the SINR when comparing the 7 beams antenna pattern to the default one. With 15 beams antenna pattern, the performance is 9.9 dB higher than with the default pattern. When considering the cell-edge vehicles, the performance is even better, which can be explained with the comparison of the antenna patterns. When the angle is 80 degrees from the base station, the default antenna pattern gain is -15 dB. Whereas the 15 beams antenna pattern gain is -5 dB. This increased gain to the served vehicle combined with increased interference suppression results in improvement in the SINR values.

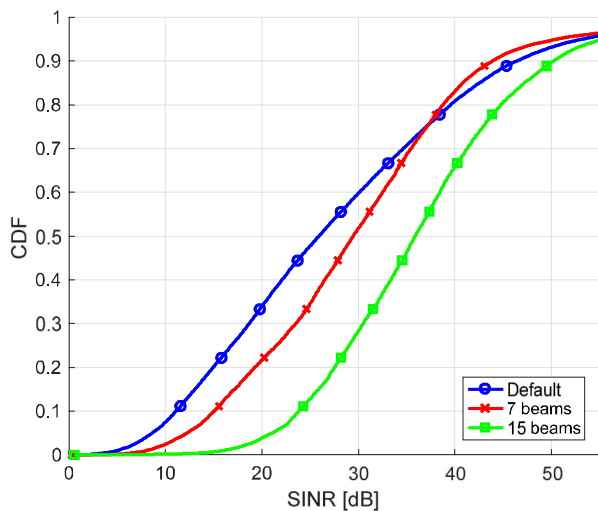


Fig. 5. CDF of SINR with different antenna patterns with the inter-vehicle distances 116 meters. The base station is 135 meters from the road.

V. CONCLUSION

We have investigated how to utilize beamformers in mobile and dense V2X networks. The target was to improve the overall performance in the whole V2X network and also in the cell-edge vehicles. The simulator used 3GPP specified parameters for V2X highway simulations. The results were in line with the theory and SVD precoding and reception had better performance than MMSE receiver with LTE codebook precoding and MRC receiver. Switched-beam beamforming was imitated by modifying the default antenna pattern to have multiple narrow beams. Two different antenna patterns, with 7 and 15 beams, were designed and implemented to the simulator. The simulation results showed that the SINR performance with the modified antenna patterns was better than with the default antenna pattern. Further development and study for the antenna patterns and beamforming in V2X is needed to evaluate the possibilities of beamforming in vehicular communications. The V2X scenario has very dynamic

network topology and it poses challenges to design the optimal beamformers.

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