Performance Analysis of Variant MIMO Systems Over 3-D Vehicular to Vehicular Channel

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ABSTRACT This article analyzes the performance of variant multiple–input multiple–output (MIMO) systems over three-dimensional (3D) vehicular to vehicular (V2V) wireless communication channel. In particular, quadrature spatial modulation (QSM), spatial multiplexing (SMX) and spatial modulation (SM) MIMO techniques are considered. A unified framework to analyze the average bit error rate (BER) for all considered MIMO techniques is developed while considering the 3D geometry dependent stochastic V2V channel model and substantiated through Monte Carlo simulation results. Reported results corroborate the accuracy of the derived formulas and the impact of different system and channel parameters is studied. Specifically, the encroachment of Doppler effect, channel estimation errors, 3D features and vehicle traffic density (VTD) on the BER performance of all systems are examined and discussed. It is revealed that QSM system achieves substantial gains as compared to its counterpart SM and SMX schemes. Gains of up to 2–4 dB in signal-to-noise-ratio are reported for different scenarios.

INDEX TERMS Spatial modulation (SM), quadrature spatial modulation (QSM), spatial multiplexing (SMX), multiple–input multiple–output (MIMO), vehicle-to-vehicle (V2V), vehicle traffic density (VTD), three-dimensional channel model (3D-channel), performance analysis.

I. INTRODUCTION

Future wireless networks are supposed to enable connectivity for vehicle to vehicle (V2V) and vehicle to infrastructure wireless communication with high-bandwidth, low latency and high reliability. Moving vehicles constitute a broad range of transport and traffic-related sensors and the market is undergoing key technological transformation [1]. Among the many considered technologies for fifth generation (5G) and beyond standards, massive multiple input multiple output (MIMO) plays substantial role to improve system capacity and throughput. Yet, high vehicle speeds may alter massive MIMO operation due to outdated channel information and Doppler spread. Hence, novel algorithms that are robust to these imperfections should be designed taking the advantages of vehicle characteristics [2].

Among the many existing MIMO techniques in literature, spatial multiplexing (SMX), spatial modulation (SM) and quadrature spatial modulation (QSM) system promise several assets with diverse appealing benefits [3]–[6]. SMX achieves the maximum possible data rate by transmitting simultaneous independent data streams from the existing multiple transmit antennas. However, each transmit antenna should be driven by an RF-chain and sophisticated algorithms are required to resolve interference at the receiver side, which increases complexity, cost, power consumption and degrades the performance. Alternatively, SM and QSM enable single RF-chain transmitter operation, which reduces power consumption and hardware cost while maintaining low error probability and receiver computational complexity [7]. Yet, they only promise logarithmic data rate enhancement with the number of transmit antennas and not linearly as in SMX. As such, they attracted significant research interests and wide range of applications where proposed with their implementations [8, and references therein].

V2V communication, on the other hand, witnessed immense market growth lately driven by the development of autonomous vehicles while aiming to bring safer transportation and improved traffic flow with the support of roadside infrastructure. Therefore, wireless communication
among vehicles attracted considerable research interests and several algorithms were developed [9]–[11].

Previous studies analyzed the performance of the considered MIMO techniques over variant fading channels and in the presence of channel impairments such as spatial correlation and imperfect channel estimation [3], [5], [12]. The impact of channel correlation on generalized QSM, QSM and SM over 2D V2V MIMO channel model is studied in [13]. Performance analysis of SM over 2D V2V channel model was examined in [14], where the influence of dissimilar propagation features, e.g., TX-Rx distance, maximum Doppler frequency, and antenna element spacing on the correlation properties of V2V channel and the related BER performance are investigated. Another study reported in [15] investigated the performance of SM over a 3D V2V MIMO channel and studied the impact of relevant related parameters.

Yet and to the best of the authors knowledge, no study addressed the performance of QSM and SMX MIMO systems over 3D V2V channel. Hence, this study contributes to existing theory by analyzing and comparing the performance of the three considered MIMO systems while considering the 3D geometry-based stochastic V2V MIMO channel model [16]. The adopted channel model works with the most effective and accurate methods for capturing all types of vehicular traffic density (VTD) through the channel [16], [17]. In particular, a unified closed-form analytical upper bound expression on the average bit error rate (BER) performance of the proposed techniques is developed and corroborated through Monte Carlo simulation results. Reported results reveal close match over wide range of system and channel parameters. Besides, the impact of variant channel impairments such as Doppler effect, channel estimation errors, and VTD on the overall performance is examined and discussed. As well, performance comparison among the considered MIMO techniques QSM, SMX, and SM, is presented and discussed. Conferred results reveal the superior advantages of QSM over other techniques and significant gains in signal-to-noise-ratio (SNR) are reported.

In summary and with reference to existing literature, the main contributions of this paper are three-folds:

1) Applying QSM MIMO system for V2V communication and comparing its performance with SM and SMX counterpart systems.
2) A novel unified framework to analyze the BER performance for all studied systems is derived while considering space-time correlation, spatial correlation and channel estimation errors.
3) Derived analytical formula is corroborated through Monte Carlo simulation results for wide range of system and channel parameters.

The rest of the paper is organized as follows. Section II presents the considered system and channel models. Performance analysis of the considered systems over 3D V2V MIMO channel model is presented in Section III. Analytical and Monte Carlo simulation results are discussed in Section IV and the paper is concluded in Section V.

II. SYSTEM AND CHANNEL MODELS

A. SYSTEM MODEL

This article acquires the most illustrious MIMO techniques including SMX, SM, and QSM. A brief revision on each of them is provided hereunder.

1) SPATIAL MULTIPLEXING (SMX)

SMX is a widely considered MIMO system that promises linear increase of the data rate with the number of transmit antennas. In SMX, incoming data bits are divided into \(N_t\) branches, with \(N_t\) denoting the number of transmit antennas, where each branch contains \(\log_2(M)\) bits, with \(M\) being the size of the considered phase shift keying (PSK)/quadrature amplitude modulation (QAM) constellation diagram. The bits in each branch are modulated and transmitted simultaneously from the \(N_t\) antennas. Hence, the spectral efficiency is \(\eta_{\text{SMX}} = N_t \log_2(M)\).

2) SPATIAL MODULATION (SM)

SM is a single stream MIMO transmission technique, where only one transmit antenna is active at a time. At each time instant, \(\eta_{\text{SM}} = \log_2(N_tM)\) bits are transmitted, where \(\log_2(M)\) bits modulate a complex symbol drawn from arbitrary PSK/QAM constellation diagram and \(\log_2(N_t)\) bits modulate one of the available transmit antennas \(\ell \in \{1 : N_t\}\) that will be used at this time to transmit the modulated symbol.

3) QUADRATURE SPATIAL MODULATION (QSM)

QSM MIMO system is an amendment to SM by enhancing the number of data bits transmitted over the spatial domain. This is attained by creating another orthogonal spatial constellation diagram that is used to transmit additional \(\log_2(N_t)\) bits. In particular, QSM transmits \(\eta_{\text{QSM}} = \log_2(N_t^2M)\) bits at each time instant and one or two transmit antennas can be activated. The complex data symbol that will be transmitted is modulated by \(\log_2(M)\) bits as in SM. However, the modulated symbol is decomposed to its in-phase and quadrature components and each component is transmitted from a transmit antenna that is determined by a sequence of \(\log_2(N_t)\) bits. Denoting the complex symbol by \(s = s\Re + s\Im\), \(s\Re\) will transmit \(s\Re\) whereas \(s\Im\), will transmit \(s\Im\), \(s\Re\) and \(s\Im\) \(\ell, \ell\ell, 2\) and \(\ell, \ell\ell, 2\) in \(\{1 : N_t\}\).

4) MAXIMUM LIKELIHOOD (ML) RECEIVER

For all considered MIMO systems, the \(N_r\)-dimensional transmit vector, \(s(t)\), is broadcasted over the \(N_r \times N_t\) MIMO channel matrix \(H(t, t)\), with \(N_r\) being the number of receive antennas and the received vector is formulated as [4],

\[
y(t) = \sqrt{E_s}H(t, t) \otimes s(t) + n(t),
\]

where \(E_s\) denotes the transmitted energy, \(\otimes\) being the convolution operator and \(n(t)\) is an \(N_t\)-dimensional complex...
additive white Gaussian noise (AWGN) vector with zero mean and $N_0$ power spectral density.

The channel entries are denoted by $h_{q,p}(t, r), \forall p = 1, \ldots, N$, and $q = 1, \ldots, N_p$ and represents the channel impulse response between the $p^{\text{th}}$ transmit and the $q^{\text{th}}$ receive antennas with $\tau$ denoting the time delay.

Let $h_{\ell,q}$ denotes the $\ell^{\text{th}}$ column of $H$, i.e., $h_{\ell,q} = [h_{1,\ell,q}, \ldots, h_{N,\ell,q}]^T$. The channel entries are assumed to be correlated and identically distributed complex Gaussian random variables with zero mean and $\sigma^2$ variance. Then, the received signal is rewritten as

$$y = (h_{\ell,q} s_{\ell} + jh_{\ell,q} s_{\ell}) + n, \forall (\ell,q) \in \{1,2,\ldots, N\}$$

(2)

Assuming the receiver has full channel state information, it applies an optimum ML decoder to retrieve the original data bits as

$$\hat{y}_{\ell,q} = \arg \min_{\ell_{\hat{q}}, \ell_{\hat{q}}, s_{\ell}, j_{\ell}} \left\| y - \sqrt{E_s} (h_{\ell_{\hat{q}},s_{\ell}} + jh_{\ell_{\hat{q}},s_{\ell}}) \right\|^2$$

$$= \arg \min_{\ell_{\hat{q}}, \ell_{\hat{q}}, s_{\ell}, j_{\ell}} \left\| z \right\|^2 - 2\Re\{y^H z\},$$

(3)

where $^H$ represents the Hermitian of a matrix or a vector, $\parallel \cdot \parallel$ denotes the norm operator and $z = \sqrt{E_s} (h_{\ell_{\hat{q}},s_{\ell}} + jh_{\ell_{\hat{q}},s_{\ell}})$. The antenna indices $\hat{\ell}_{\hat{q}}$ and $\hat{\ell}_{\hat{q}}$ along with the data symbols $s_{\ell}$ and $j_{\ell}$ are used to retrieve the original data bits using inverse mapping table to that used at the transmitter.

B. 3D V2V MIMO CHANNEL MODEL

A 3D V2V MIMO channel model is considered throughout this study, where the propagation model is assumed to have both non line of sight (NLoS) and line of sight (LoS) components. Furthermore, the NLoS components can be grouped into single bounced (SB) and double bounced (DB) rays. Hence, each channel element, $h_{q,p}(t)$, is formulated as [16]

$$h_{q,p}(t) = h_{q,p}^{\text{LoS}}(t) + \sum_{i=1}^{2} h_{q,p}^{\text{SB}}(t) + h_{q,p}^{\text{DB}}(t),$$

(4)

where $h_{q,p}^{\text{LoS}}(t)$, $h_{q,p}^{\text{SB}}(t)$ and $h_{q,p}^{\text{DB}}(t)$ respectively denote the LoS component, SB component, and DB component that are expressed as

$$h_{q,p}^{\text{LoS}}(t) = \sqrt{\frac{K}{K + 1}} e^{-2\pi f_c \tau_{qp}}$$

$$\times e^{2\pi f_{\text{max}}} \cos(\alpha_{T}^{\text{LoS}} - \gamma_T) \cos \beta_{T}^{\text{LoS}}$$

$$\times e^{2\pi f_{\text{max}}} \cos(\alpha_{R}^{\text{LoS}} - \gamma_R) \cos \beta_{R}^{\text{LoS}}$$

$$\times e^{2\pi f_{\text{max}}} \cos(\alpha_{P}^{\text{LoS}} - \gamma_P) \cos \beta_{P}^{\text{LoS}}$$

(5)

$$h_{q,p}^{\text{SB}}(t) = \frac{\eta_{\text{SB}}}{K + 1} \lim_{N \to \infty} \frac{1}{N_1} e^{i(\psi_{n_1} - 2\pi f_c \tau_{qp,n_1})}$$

$$\times e^{2\pi f_{\text{max}}} \cos(\alpha_{T}^{(n_1)} - \gamma_T) \cos \beta_{T}^{(n_1)}$$

$$\times e^{2\pi f_{\text{max}}} \cos(\alpha_{R}^{(n_1)} - \gamma_R) \cos \beta_{R}^{(n_1)}$$

$$\times e^{2\pi f_{\text{max}}} \cos(\alpha_{P}^{(n_1)} - \gamma_P) \cos \beta_{P}^{(n_1)}.$$ 

(6)

The 3D channel model considers the case of two vehicles driving towards each other with $v_{T/R}$ speed and $\gamma_{T/R}$ direction angle. Let the maximum Doppler frequencies for transmitter and receiver be $f_{\text{max}}$ and $f_{\text{max}}$, respectively. The LoS component has an azimuth angle-of-departure (AoD), $\beta_{T}^{\text{LoS}}$, azimuth angle-of-arrival (AoA), $\alpha_{T}^{\text{LoS}}$, elevation AoD, $\alpha_{R}^{\text{LoS}}$, and elevation AoA $\beta_{R}^{\text{LoS}}$. Considering the prespecified movement scenario in this study, it is fair to assume $\alpha_{T}^{\text{LoS}} \approx 0$, $\beta_{T}^{\text{LoS}} \approx 0$, and $\alpha_{R}^{\text{LoS}} \approx \pi$.

Similarly, the signals traveling from the scatterer, $n_1$, has the following angles $\alpha_{T}^{(n_1)}$, $\alpha_{R}^{(n_1)}$, $\beta_{T}^{(n_1)}$, and $\beta_{R}^{(n_1)}$, respectively denoting that azimuth AoD, azimuth AoA, elevation AoD, and elevation AoA. Also, the path delays between $Tx_{p} \rightarrow Rx_{q}, Txp \rightarrow s_{(n)} \rightarrow Rx_{q}$, and $Txp \rightarrow s_{(n)} \rightarrow s_{(n)} \rightarrow Rx_{q}$ are given by $\tau_{qp}, \tau_{qp,n_1}$, and $\tau_{qp,n_2}$.

In the considered 3D channel model, the SB rays are assumed to be comprised of three components, SB1 representing the reflection from the transmitter sphere, SB2 corresponding to the reflection from the receiver sphere, and SB3 being the reflections from the elliptic cylinder.

The power ratios contributed by the SB and DB rays to the total scattered power, $(1/K + 1)$, are denoted by $\eta_{\text{DB}}$ and $\eta_{\text{SB}}$, such that $\sum_{n=1}^{N} \eta_{\text{SB}} + \eta_{\text{DB}} = 1$. Finally, $\psi_{n_1}$ and $\psi_{n_2,n_3}$ represent the phases of the rays that are modeled as independent and identically distributed uniform random variables in the range of $[-\pi, \pi]$. It is also assumed that the rays in the DB reflections are uncorrelated, whereas the SB reflections are related geometrically. Besides, if $\beta_{T}^{\text{LoS}} = \beta_{T}^{\text{LoS}} = \beta_{T}^{(n_1)} = \beta_{R}^{(n_1)} = 0, \forall (1 = 1, 2, 3)$, the 3D channel model is reduced to a two dimensional (2D) model with two rings and one ellipse.

C. HIGH VTD AND LOW VTD SCENARIOS

In vehicular communication, two channel propagation characteristics can be defined based on the environment, number of vehicles and speed. Namely, high VTD and low VTD scenarios are defined and explained hereinafter [16], [18].

1) In high VTD area, dozens of vehicles exist per square kilometer that is much larger than a low VTD scenarios. As such, a busy urban road is classified as a high VTD environment whereas a highway is categorized as a low VTD.

2) In low VTD environment, the majority of scattered power is mainly due to stationary elements on the roadside, i.e., $\eta_{\text{SB3}} > \max(\eta_{\text{SB1}}, \eta_{\text{SB2}}) > \eta_{\text{DB}}$.

Yet, in high VTD scenario, double bounce
rays carry more power than single bounce rays as there are many moving objects in this scenario, i.e., \( \eta_{DB} > \max(\eta_{SB_{1}}, \eta_{SB_{2}}, \eta_{SB_{3}}) \).

3) Denoting the sphere model of the transmitter, the receiver and the elliptic–cylinder by \( k_{1}, k_{2}, \) and \( k_{3} \), respectively; the values of \( k_{1} \) and \( k_{2} \) in high VTD scenario is lower than that of low VTD, whereas \( k_{3} \) is nearly the same in both setups.

4) The Rician \( K \)-factor for a high VTD scenario is almost 1, while low VTD environment has a \( K \)-factor close to 10.

D. SPACE TIME CORRELATION FUNCTION (STCF)

Typical wireless communication channel suffers generally from space-time correlation defined as the correlation between the channel paths \( h_{qp}(t) \) and \( h_{\tilde{q}\tilde{p}} \) expressed as [16]

\[
\rho_{h_{qp}h_{\tilde{q}\tilde{p}}} (\tau) = E \left[ h_{qp}(t) h_{\tilde{q}\tilde{p}}^{*} (t - \tau) \right] (K + 1),
\]

(8)

where \( (\cdot)^{\dagger} \) denotes the complex conjugate operation and \( E[\cdot] \) is the statistical expectation operator. For the considered 3D V2V channel model, the STCF is calculated as [16]

\[
\rho_{h_{qp}h_{\tilde{q}\tilde{p}}} (\tau) = \rho_{h_{qp}h_{\tilde{q}\tilde{p}}}^{0} (\tau) + \sum_{i=1}^{I} \rho_{h_{\tilde{q}\tilde{p}}h_{\tilde{q}\tilde{p}}} (\tau) + \rho_{h_{qp}h_{\tilde{q}\tilde{p}}}^{DB} (\tau).
\]

(9)

The STCF is depicted in Fig. 1 for both low VTD and high VTD scenarios versus the normalized time separation, \( \tau \times f_{\text{max}} \), while varying the Doppler frequency, \( f_{\text{max}} \). As evident in the figure, high VTD scenarios demonstrate better performance. The correlation values are almost 100 times larger in low VTD as compared to high VTD, which degrades MIMO system performance.

III. AVERAGE BIT ERROR RATE OVER 3D V2V MIMO CHANNEL FADING

A General framework for the average BER of arbitrary MIMO systems over generalized fading channels and in the presence of spatial correlation and channel estimation errors is proposed in [3, Chapter 4, Section 4.2] and it will be considered here as well.

The received signal for the considered MIMO system in the presence of spatial correlation can be reformulated as

\[
y = \hat{H} s + n.
\]

(10)

where \( \hat{H} \) represents a correlated MIMO channel matrix that is expressed as

\[
\hat{H} = R_{Rx}^{\frac{1}{2}} H R_{Tx}^{\frac{1}{2}},
\]

(11)

with \( H \) being the predescribed V2V MIMO channel matrix, \( R_{Rx} \) and \( R_{Tx} \) respectively denote the receiver and the transmitter correlation matrices defined as

\[
R_{Tx} (p, \tilde{p}) = R_{Rx} (q, \tilde{q}) = \rho_{h_{qp}h_{\tilde{q}\tilde{p}}} (0),
\]

(12)

where \( \rho_{h_{qp}h_{\tilde{q}\tilde{p}}} (0) \) denotes the STCF of the 3D V2V channel model defined in (9) assuming perfect channel estimation, i.e., \( \tau = 0 \). The ML-optimum decoder can be expressed as

\[
\hat{s} = \arg \min_{s \in S} ||y - \hat{H} s||_{F}^{2}
\]

(13)

where \( S \) is a set containing all possible transmitted vectors for the considered MIMO technique.

In practical scenarios, acquiring perfect channel knowledge at the receiver is not possible due to the presence of AWGN and channel estimation errors (CSE) will be present. The received signal considering the estimated channel, \( \hat{H} \) is written as

\[
y = \hat{H} s + n.
\]

(14)

Assuming \( \hat{H} \) and \( H \) are jointly ergodic and stationary processes while the CSE, \( e \) is orthogonal to \( \hat{H} \) yields

\[
\hat{H} = H + e,
\]

(15)

where \( e \) being a matrix with similar dimension as that of \( H \) and entries are complex Gaussian random variables with zero mean and \( \sigma_{e}^{2} \) variance. The combined model in the presence of both CSE and spatial correlation can be obtained as

\[
\hat{H}_{e} = R_{Rx}^{\frac{1}{2}} H R_{Tx}^{\frac{1}{2}} + e.
\]

(16)

Now, the derivation of the average bit error rate for QSM-MIMO under the 3D V2V channel model can be obtained by computing the pairwise error probability (PEP), which is given by

\[
\Pr (s_{i} \rightarrow s | \hat{H}_{e}) = \Pr \left( \frac{1}{F} \sqrt{\frac{y - \hat{H}_{e} s_{i}}{\|y - \hat{H}_{e} s_{i}\|_{F}^{2}}} > \frac{1}{F} \sqrt{\frac{y - \hat{H}_{e} s}{\|y - \hat{H}_{e} s\|_{F}^{2}}} | \hat{H}_{e} \right),
\]

(17)
which after few mathematical manipulation gives

$$\Pr \left( s_t \rightarrow s | \bar{H}_e \right) = Q \left( \frac{\| \bar{H}_e \Psi_F \|^2}{2 \sigma_n^2} \right)$$

$$= \frac{1}{\pi} \int_0^{\pi/2} \exp \left( - \frac{\bar{Y} \| \bar{H}_e \Psi_F \|^2}{2 \sin^2 \theta} \right) d\theta$$

(18)

where $\Psi = (s_t - s)$ and the SNR is given by $\bar{Y} = 1/(2\sigma_n^2)$ assuming unity transmit power and $\sigma_n^2 = \sigma_s^2 + \| s \|^2$.

To evaluate the average PEP, the expectation of (18) is taken yielding

$$E \{ \Pr_{\text{error}} \} = \Pr (s_t \rightarrow s) = \frac{1}{\pi} \int_0^{\pi/2} M_\theta \left( - \frac{\bar{Y} \| \bar{H}_e \Psi_F \|^2}{2 \sin^2 \theta} \right) d\theta,$$  

(19)

where $M_\theta(\cdot)$ denotes the moment-generation function.

Following similar steps as discussed in [3], the average BER for variant MIMO systems over 3D V2V channel in the presence of spatial correlation and CSE is deduced as

$$AEBR \leq \frac{1}{2^n} \sum_{\ell, i, j} \left( \frac{\| \bar{Y} \|^2}{2n} \right)^{\ell_i / 2} \left( \frac{\| \bar{Y} \|^2}{2n} \right)^{\ell_i / 2}$$

$$\times \exp \left( - \frac{\bar{Y}}{2} \sum_{\ell, i, j} \left( \frac{\| \bar{Y} \|^2}{2n} \right)^{\ell_i / 2} \left( \frac{\| \bar{Y} \|^2}{2n} \right)^{\ell_i / 2} \right) u_h^H \left( I_{N_t} N_t + \frac{\bar{Y}}{2} L_h \right) u_h$$

$$\left( I_{N_t} N_t + \frac{\bar{Y}}{2} L_h \right) u_h,$$  

(20)

where $\Lambda = I_{N_t} \otimes \Psi_H$, $u_h = u_{h_1} R_x^{1/2} \times I_{N_t N_t}$, with $u_{h_1} = \sqrt{\frac{K}{K+1}}$ denoting the mean value of the Rician fading channel and $I_{N_t N_t}$ being a ones matrix with $N_t \times N_t$ dimension. Also, $L_h = \sigma_n^2 R_x$ denotes the covariance matrix of the considered channel, where $R_x = R_{k_x} \otimes R_{k_y}$ with $\otimes$ denoting the Kronecker product.

### IV. SIMULATION AND ANALYTICAL RESULTS

Monte Carlo simulation results are provided in this section to corroborate the accuracy of the derived formulas and investigate the impact of variant system and channel parameters on the overall performance of QSM over 3D V2V MIMO channel. Reported results reveal the verity of the obtained analysis, where close match between theoretical and simulation results is noticed at pragmatic SNR values and for different system setups. The considered simulation parameters are listed in Table 1.

The first results shown in Fig. 2 and Fig. 3 validate the accuracy of the derived ABER bound assuming perfect channel knowledge at the receiver, where analytical and simulation results for QSM, SM, and SMX MIMO systems are shown to match closely over wide range of SNR values and while considering different VTD scenarios for the 3D V2V MIMO channel. It is also obvious in the results that the performance over high VTD channel is much better than that of low VTD scenario. This is mainly because high VTD represents a rich scattering environment with low Rician $K$–factor, whereas high VTD channel contains a dominant LoS path with high $K$–factor. High $K$–factor induces higher correlations among channel paths and degrades MIMO systems performance as reported before for different channel conditions [5], [19]. Degradation of about 5 dB can be clearly seen in the figure at a BER of $10^{-4}$ when changing from high to low VTD scenario. The results in both figures reveal that QSM system outperforms both SM and SMX where a gain in SNR of about 4 dB can be clearly seen at a BER of $10^{-4}$ when compared to SMX and nearly 2 dB as compared to SM in Fig. 2. As well, the gain slightly increases for low VTD scenario in both figures reveal that QSM system outperforms both SM and SMX where a gain in SNR of about 4 dB can be clearly seen at a BER of $10^{-4}$ when compared to SMX and nearly 5 dB.

The next two figures, Fig. 4 and Fig. 5, illustrate similar comparison as in the previous figures but with $\eta = 8$ bits/s/Hz for all systems while assuming perfect channel state information (CSI). The target spectral efficiency is accomplished with

### TABLE 1. Considered system and channel parameters.

| Parameter                  | Value       |
|----------------------------|-------------|
| Carrier Frequency          | $f_c = 5.9$ MHz |
| Doppler Shift              | $f_{T_{max}} = f_{R_{max}} = 570$ Hz |
| TX–RX distance             | $d = 300$ m |
| Arrival angles             | $\gamma_T = \gamma_R = 0^\circ$ |
| Antenna Separation         | $\lambda/2$ m |
| Rician $K$–factor (Low VTD) | 3.786       |
| Rician $K$–factor (High VTD)| 0.756       |
| No. of simulated symbols   | $10^9$/SNR value |
FIGURE 3. Analytical and Monte Carlo simulation average BER results for QSM, SM, and SMX all achieving $\eta = 4$ bits/s/Hz spectral efficiency with $2 \times 4$ MIMO configuration and under low VTD scenario. QSM and SMX both use $M = 4$–QAM, while SM considers $8$–QAM modulation.

FIGURE 4. Analytical and Monte Carlo simulation average BER results for QSM, SM, and SMX all achieving $\eta = 8$ bits/s/Hz spectral efficiency with $4 \times 4$ MIMO configuration and under low VTD scenario. QSM uses $16$–QAM, SM applies $64$–QAM and SMX considers $4$–QAM modulation.

FIGURE 5. Analytical and Monte Carlo simulation average BER results for QSM, SM, and SMX all achieving $\eta = 8$ bits/s/Hz spectral efficiency with $4 \times 4$ MIMO configuration and under high VTD scenario. QSM uses $16$–QAM, SM applies $64$–QAM and SMX considers $4$–QAM modulation.

FIGURE 6. Impact of Doppler frequency on the average BER performance of a $2 \times 4$ QSM MIMO system with $4$–QAM modulation over 3-D V2V channel and under low and high VTD scenarios.

$4 \times 4$ MIMO configuration while using $16$–QAM for QSM, $64$–QAM for SM and $4$–QAM for SMX. Similar observations as in the previous figures can be concluded here as well. All MIMO systems perform better in high VTD scenario, Fig. 5, as compared to low VTD environment, Fig. 4, and a gain of nearly 1 dB can be seen. This is again due to the high scattering nature of high VTD environment, which simplifies the receiver task of resolving different channel paths and leads to better performance. Besides, QSM still demonstrates the best performance even with this higher configuration and outperforms both SMX and SM for the two considered environment.

The impact of varying the Doppler frequency is studied and results are shown in Fig. 6. For the sake of brevity, only QSM results are shown and similar behavior is noticed for the other two systems. A $2 \times 4$ MIMO configuration is considered with $4$–QAM modulation while applying both VTD scenarios. It is observed that a low Doppler frequency results in better performance. For instance, using $f_{\text{max}} = 190$ Hz is shown to outperform $f_{\text{max}} = 570$ Hz by nearly 1 dB for both low and high VTD environments. However, the impact of Doppler frequency is shown to be fringy, which promotes the use of QSM for high speed V2V communication. For example, results demonstrate that increasing the speed from 35 km/hour to 105 km/hour degrades the performance by no more than 1 dB in SNR at a BER of $10^{-4}$.

The effect of increasing the number of transmitter antennas is illustrated in Fig. 7 and Fig. 8, where and $8 \times 4$ MIMO configuration is considered for QSM and SMX systems. QSM uses $4$–QAM modulation whereas SMX applies BPSK to attain the spectral efficiency of 8 bits/s/Hz. Please note that SM would require the use of $32$–QAM to reach the target
spectral efficiency and it will provide the worst performance among other techniques. Hence and for the sake of better illustration, SM results are omitted in both figures. Again and for this configuration as well, QSM outperforms SM by nearly 3 dB and high VTD provides better results than low VTD scenario.

The next set of results, Fig. 9 and Fig. 10, study the impact of CSE on the ABER performance of all considered MIMO schemes under different VTD scenarios. A $2 \times 4$ MIMO configuration is considered for all systems to achieve a spectral efficiency of 4 bits/s/Hz while assuming $\sigma_r = 1/\sigma_n$. Imperfect channel knowledge at the receiver clearly impacts the overall system performance of all systems and degrades the performance.

The results demonstrate that the channel estimation error significantly degrades the performance of the all considered MIMO systems by 2-3 dB. Again, it is obvious in the results that the performance over high VTD channel is better than that of low VTD scenario even in the presence of imperfect CSI. The negative impact of CSE on all systems is evident in the last set of results depicted in Fig. 11, which compares the performance assuming perfect and imperfect channel knowledge assuming $2 \times 4$ configurations for all systems and under low VTD scenario. Roughly, around 2–3 dB performance degradation can be noticed for the different systems. QSM still reveals the best performance among all other studied techniques.

V. CONCLUSIONS

The performance of SMX, QSM and SM MIMO systems over a 3D V2V wireless communication channel is studied and
analyzed in this article while considering spatial correlation and channel estimation errors. It is disclosed that QSM is a viable scheme for V2V communication as it significantly outperforms SMX and SM techniques. It is also shown that MIMO systems perform better with high VTD scenario as compared to low VTD environment, which promotes MIMO for dense V2V communication premises. It is also reported that increasing the vehicle speed degrades the performance marginally for QSM system and less than 1 dB performance degradation is noticed. The derived unified analytical bound for the considered systems is shown to be accurate over wide range of system and channel parameters. Future works will consider different V2V communication scenarios and design proper communication scheme for each one to optimize the performance.

ACKNOWLEDGMENT

The authors acknowledge that this research work was completed as part of the thesis requirements for the degree of M.Sc. in electrical engineering during the studies of Mr. Anas Alashqar at Princess Sumaya University for Technology. Also, the authors acknowledge the support of Prof. Cheng-Xiang Wang who provided us with the Matlab codes for the V2V 3-D channel model that were used in this study.

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