MIMO V2V Communications Via Multiple Relays: Relay Selection Over Space-Time Correlated Channels

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***Abstract*—This paper presents an opportunistic relay selection policy related to the propagation characteristics of a multiple-input multiple-output (MIMO) vehicle-to-vehicle (V2V) multi-relay system, where the vehicle nodes are equipped with uniform linear multi-element antenna arrays. As Channel State Information (CSI) overhead is introduced by the relay selection process, reactive relay selection techniques over space-time correlated MIMO channels are presented based on the CSI of the links between the relays and the destination. Since the correlation of MIMO subchannels strongly depends on the distribution of the effective scatterers, a three-dimensional (3-D) geometrical model for MIMO V2V relay channels is utilized. The results depict the throughput and the packet error rate (PER) performance for different scenarios.**

***Keywords*—Correlation; decode-and-forward relaying; multiple-input multiple-output (MIMO) channels; relay selection; vehicular communications; 3-D scattering.**

I. Introduction

Vehicle-to-vehicle (V2V) communications, which are an integral part of Intelligent Transportation Systems (ITS), are expected to improve convenience and safety of transportation, efficiently control road traffic, and provide mobile infotainment applications. Nevertheless, the transmission links of V2V systems are usually vulnerable to harsh multipath fading effects. Combining the features of cooperative diversity [1] with the benefits of multiple-input multiple-output (MIMO) technology [2] can potentially lead to robust and reliable signal transmission in difficult terrains and/or long distances with enhanced channel capacity. Leveraging MIMO technology in V2V scenarios seems practically attractive, since multiple antennas can be easily mounted on large vehicle surfaces.

This paper investigates the performance of a MIMO V2V system in decode-and-forward (DF) multi-relay wireless networks, where one vehicle relay node is assigned to assist a source in forwarding its information to a destination [3]. A full-duplex (FD) operation mode is applied, which facilitates frequency reuse and enables data reception and transmission at the same time in a single frequency band. An opportunistic relay selection policy is performed, where only one relay is activated [4], [5] in order to improve the resource utilization and reduce the hardware complexity. In the DF relaying networks, there are two typical relay selection policies: reactive relay selection and proactive relay selection [6]. Since instantaneous channel state information (CSI) knowledge is required and multiple relays must be examined each time, the implementation complexity is increased in proactive relay selection scenarios leading to CSI overhead, especially in propagation scenarios with mobility properties, i.e., high vehicle velocity and rapid changing road topologies. Hence, a reactive relay selection policy is examined, where only the CSI of the links between the relays and the destination is required to perform distributed selection.

The proposed relay selection policy is directly related to the underlying radio channel [7], and the space-time correlation properties. Since the degree of correlation is a complicated function of the degree of scattering and the antenna inter-element spacing at the source, relay, and destination [8], the establishment of a particular geometry describing the location of the scattering objects is highly critical. It is assumed that the radio waves travel in both the horizontal and vertical plane. This assumption is realistic, especially in densely built-up urban areas, where the antenna arrays are usually located lower than the surrounding scatterers and the scattered waves propagate by diffraction from vertical structures, i.e., buildings, to the street level. In this paper, a modified version of the three-dimensional (3-D) model for MIMO V2V fading channels in relay-based networks in [9] is utilized, where the relay is equipped with both transmit and receive antennas. The results demonstrate the throughput and the Packet Error Rate (PER) performance for various fading conditions.

The rest of the paper is organized as follows. Section II presents the system model, while Section III outlines the applicability of the proposed system on ITS. Section IV details the system geometry and generates the MIMO channel matrix. Results are provided in Section V. Finally, conclusions are drawn in Section VI.

II. System Model

This paper considers an inter-vehicular communication system and frequency-flat MIMO channels. The source communicates with a destination through a set of M FD DF relays, while the direct link between source and destination is obstructed due to high attenuation. To aid our analysis, the subscripts S, D, and R are affiliated with the source, the destination, and the m-th selected relay, respectively. As shown in Fig. 1, the source and destination are equipped with one uniform linear array (ULA), whereas the relay is equipped with two ULAs; one for reception of the source's signal and one for transmission towards the destination. The antennas are omni-directional with low height and are numbered as $1 \le p \le p' \le L_S$, $1 \le q_R \le q'_R \le L_{RR}$, $1 \le q_T \le q'_T \le L_{RT}$, and $1 \le u \le u' \le L_D$, respectively, where L_S, L_{RR}, L_{RT}, and L_D are the antenna elements at the source, relay (reception), relay (transmission), and destination, respectively. It is considered that the multiple-antenna receivers use a Maximum Ratio Combining (MRC) diversity scheme. All the links exhibit block fading, which is considered constant during one time-slot and changes independently in the next time-slot. Additive white Gaussian noise (AWGN) at the receiver is assumed, where the noise N has zero mean and variance n, i.e., $N \sim \mathcal{CN}(O, n)$.

Due to DF relaying, the relays decode the received signal and then re-encode it for transmission to the destination. Thus, simultaneous reception and transmission take place resulting in loop-interference (LI) from the relay's output antenna to the relay's input antenna. However, depending on the vehicle size, the antennas at the relays can be isolated and perfect LI cancellation can be achieved. Additional LI cancellation and suppression techniques can be also applied to further mitigate LI effect. The source is considered saturated and has always data to transmit. Besides, the data rate is given in Bits-Per-Channel-Use (BPCU). In each time-slot, one relay is selected to establish communication between the source and the destination through FD transmissions.

Aiming at reducing the amount of CSI overhead, a reactive relay selection policy is examined. In this case, the source power level is fixed, the signal is broadcasted towards all the relays, and the relay's transmission power levels are dynamically changed, i.e., power adaptation is performed. This procedure intends to achieve a specific quality of service (QoS) level mapped to a signal-to-noise ratio (SNR) value based on the CSI of the R-D link, which is fed back to the source in order to perform the relay selection procedure. Then, power expenditure can be significantly reduced and network service provision is assured for extended time periods.

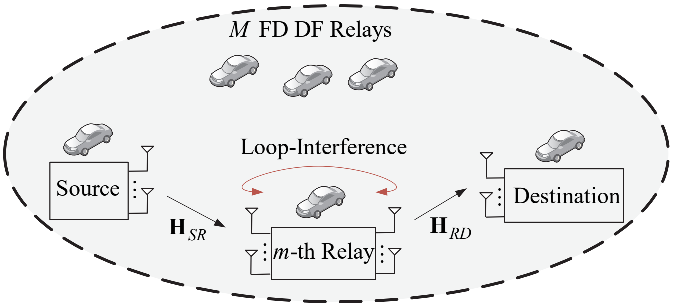

Fig. 1. Simple representation of a MIMO V2V multi-relay communication system, where one FD DF relay is selected.

To denote whether or not the destination has successfully received the source's packet, Acknowledgement/Negative-Acknowledgement (ACK/NACK) messages are sent by the destination, which in turn triggers a contention procedure, towards the source through the selected relay. Providing that a node fulfills the selection requirements, it can always deliver the packet to the destination. Otherwise, no candidates are available for relaying, and hence the source retransmits the data itself. At the start of each time-slot the relays should exchange signaling with the destination by sending pilot sequences. The latter estimates the CSI and notifies the relays on this CSI. The selection takes place among the relays which decoded the source's signal. The set of these relays is denoted as $U = \{R_m : SNR_{RD} \ge SNR_0\}$, where SNR_{RD} is the SNR in the R-D link and SNR_0 is an instantaneous SNR value at the receiver. The best relay is denoted by b_R and is chosen as follows [7]

$$b_R = \arg\min_{m \in U} \left(P_{R_m}\right) = \arg\min_{m \in U} \left(\frac{nSNR_0}{g_{R_m D}}\right), \quad (1)$$

where P_{R_m} is the m-th relay's transmission power and $g_{R_m D}$ is the channel power in the R-D link.

III. Application of the V2V Relaying Scheme on ITS

In this section, the application of the proposed system model and the relaying scheme on ITS G5 standard [10] is investigated. The physical and media access control (MAC) layer of ITS G5 is based on the most popular relevant standard, the IEEE 802.11p [11], with 10 MHz signal bandwidth. It is assumed that a safety critical ITS application is used, e.g., Cooperative Adaptive Cruise Control, which means that the ITS G5 Control Channel (CCH) is used.

In ITS applications, the vehicles will transmit data using random access, i.e., the IEEE 802.11p. For safety critical applications, all vehicles have the obligation to state their presence and inform other vehicles for status changes periodically. For typical applications, the minimum transmission frequency of ITS messages is 10 to 25 Hz. In the investigated system, 25 Hz minimum transmission frequency is assumed, which means that all vehicles participating in the network should broadcast at least one data packet every 40 msec. For the considered system, this means that every 40 msec a given vehicle will receive data from all the vehicles in the network.

The size of each ITS message is typically less than 1kByte for reduced latency and they are transmitted using orthogonal frequency division multiplexing (OFDM). These signals can be used to extract CSI for all the links with the adjacent nodes. However, in most cases, the nodes will exchange signals more frequently with much higher rate and therefore CSI is updated much more often.

Relays are assumed to have FD capabilities. This means that each relay is able to directly retransmit the received message from the source without the need to content for access in the medium. Moreover, possible throughput performance degradation due to the retransmission procedure is significantly reduced.

IV. A 3-D Model for MIMO V2V Relay Channels

This section proposes a modified version the 3-D geometrical model for MIMO V2V relay channels in [9] and considers that the m-th relay is equipped with one transmit and one receive ULA. Fig. 2 demonstrates this model for a 2x2x2 channel. One observes that the source, the m-th relay, and the destination are moving with speeds v_S, v_R, and v_D, respectively, in the directions determined by the angles γ_S, γ_R, and γ_D, respectively. The antenna inter-element spacing at the source, relay (reception), relay (transmission), and destination is denoted by δ_S, δ_{RR}, δ_{RT}, and δ_D, respectively, whereas the angles θ_S, θ_{RR}, θ_{RT}, and θ_D represent the orientation of the corresponding antenna arrays, relative to the x-axis. Moreover, the angles ψ_S, ψ_{RR}, ψ_{RT}, and ψ_D describe the elevation angle of the elements p, q_R, q_T, and u, respectively, relative to the x-y plane.

As shown in Fig. 2, the scattering objects in the vicinity of the vehicle nodes lie on the surface of three cylinders, which reflect the influence of three heterogeneous scattering environments. It is assumed that $M \to \infty$ scatterers denoted by $S_S^{(m)}$ $\left(m = 1, 2, ..., M\right)$ are situated around the source, on the surface of a cylinder of radius R_S. Similarly, $S_R^{(k)}$ $\left(k = 1, 2, ..., K\right)$ and $S_R^{(l)}$ $\left(l = 1, 2, ..., L\right)$ scatterers in the vicinity of the relay with $K = L \to \infty$ and $S_R^{(k)} = S_R^{(l)}$ for $k = l$ lie on a surface of a cylinder of radius R_R, while $N \to \infty$ scatterers denoted by $S_D^{(n)}$ $\left(n = 1, 2, ..., N\right)$ are situated at the destination, on the surface of a cylinder of radius R_D. Only double-bounce non-line-of-sight (NLoS) propagation conditions are considered, which are dominant in urban macrocells propagation environments [12]. The angles $a_S^{(m)}$ and $\beta_S^{(m)}$ denote the azimuth angle of departure (AAoD) and the elevation angle of departure (EAoD), respectively, of the wave transmitted from the source and impinged on $S_S^{(m)}$, while $a_{SR}^{(k)}$ and $\beta_{SR}^{(k)}$ are the azimuth angle of arrival (AAoA) and the elevation angle of arrival (EAoA), respectively, of the wave scattered from $S_R^{(k)}$ and received at the relay. Besides, $a_{RD}^{(l)}$ and $\beta_{RD}^{(l)}$ denote the AAoD and the EAoD, respectively, of the wave transmitted from the relay and impinged on $S_R^{(l)}$, while $a_D^{(n)}$ and $\beta_D^{(n)}$ are the AAoA and the EAoA, respectively, of the wave scattered from $S_D^{(n)}$ and received at the destination. Due to the heterogeneity of the propagation environments and the double-bounce scattering, the angles of departure are independent from the angles of arrival, while the azimuth and elevation angles are also independent [13].

A. Generation of the MIMO Channel Matrix

The effective MIMO channel transfer matrix describing the relay channel is expressed as

$$\mathbf{H} = \mathbf{H}_{RD}\mathbf{H}_{SR} \in \mathbb{C}^{L_D \times L_S}, \quad (2)$$

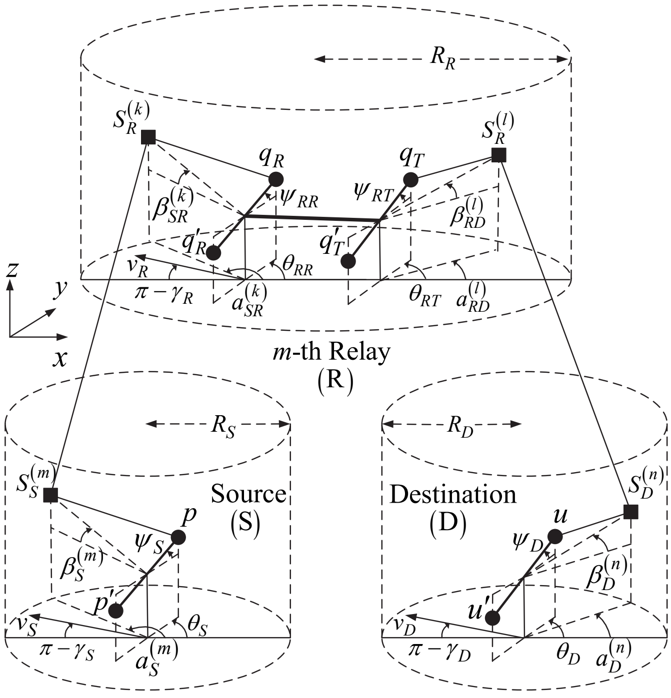

Fig. 2. The three-cylinder model for a 2x2x2 MIMO V2V relay channel, where the m-th FD DF relay equipped with one transmit and one receive ULA is selected.

where $\mathbf{H}_{SR} \in \mathbb{C}^{L_R \times L_S}$ is the MIMO channel transfer matrix for the S-R link and $\mathbf{H}_{RD} \in \mathbb{C}^{L_D \times L_R}$ is the MIMO channel transfer matrix for the R-D link. Considering a 2x2 MIMO channel, $\mathbf{H}_{SR}$ can be derived as follows [14]

$$\mathbf{H}_{SR} = \mathbf{R}_{SR}^{1/2}\mathbf{H}_w\mathbf{R}_S^{T/2}, \quad (3)$$

where $\mathbf{R}_S$ and $\mathbf{R}_{SR}$ are the 2x2 source and 2x2 relay (S-R link) correlation matrices, respectively, $\mathbf{H}_w$ is a 2x2 stochastic matrix with independent and identically distributed zero-mean complex Gaussian entries, $\left(\cdot\right)^{1/2}$ denotes the matrix square root operation, and $\left(\cdot\right)^T$ denotes the transpose operation.

Since the number of the scatterers in the vicinity of the source is infinite, the discrete AAoD $a_S^{(m)}$ and the discrete EAoD $\beta_S^{(m)}$ can be replaced with continuous random variables α_S and β_S, respectively, with a joint probability density function (pdf). The aforementioned random variables are mutually independent. Hence, the joint pdf can be decomposed to a product of two separate pdfs. The von Mises pdf [15] is used to characterize the AAoD α_S and is defined as

$$f\left(a_S\right) = \frac{\exp\left[k_S \cos\left(a_S - \mu_S\right)\right]}{2\pi I_0\left(k_S\right)}, \ -\pi \le a_S \le \pi, \quad (4)$$

where $I_0\left(\cdot\right)$ is the zeroth-order modified Bessel function of the first kind, $\mu_S \in \left[-\pi, \pi\right]$ is the mean angle at which the scatterers in the vicinity of the source are distributed in the

x-y plane, and $k_S \geq 0$ controls the spread around the mean. Setting $k_S = 0$, i.e., $f(a_S) = 1/2\pi$, incurs isotropic scattering. As k_S increases, the scattering becomes increasingly non-isotropic. The Parson's pdf [16] is used to characterize the EAoD β_S and is defined as

$$f(\beta_S) = \begin{cases} \frac{\pi}{4|\beta_{S_m}|}\cos\left(\frac{\pi}{2}\frac{\beta_S}{\beta_{S_m}}\right), & |\beta_S| < |\beta_{S_m}| \leq \frac{\pi}{2}, \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

where β_{S_m} is the maximum value of β_S.

Using (4) and (5) and carrying out extensive calculations, one can derive the source space-time correlation function (STCF) and then obtain the elements of the source correlation matrix $\mathbf{R}_S$ as follows [9], [17]

$$R^S_{p,p'}(\delta_T, \tau) = \int_{-\beta_{S_m}}^{\beta_{S_m}} \pi \cos\left(\frac{\pi}{2}\frac{\beta_S}{\beta_{S_m}}\right) \frac{I_0\left(\sqrt{x_S^2 + y_S^2}\cos\beta_S\right)}{4|\beta_{S_m}| I_0(k_S)}$$
$$\times \exp\left(j2\pi(p'-p)\delta_S \sin\psi_S \sin\beta_S / \lambda\right) d\beta_S, \quad (6)$$

where

$$x_S = j2\pi(p'-p)\delta_S \cos\theta_S \cos\psi_S / \lambda$$
$$- j2\pi\tau f_{S,\max} \cos\gamma_S + k_S \cos\mu_S / \cos\beta_S, \quad (7)$$

$$y_S = j2\pi(p'-p)\delta_S \sin\theta_S \cos\psi_S / \lambda$$
$$- j2\pi\tau f_{S,\max} \sin\gamma_S + k_S \sin\mu_S / \cos\beta_S, \quad (8)$$

$f_{S,\max} = v_S / \lambda$ is the maximum Doppler shift associated with the source, and λ is the carrier wavelength. Note that the source STCF in (6)-(8) is accurate only over a time duration that is much smaller than $\min\{R_S / v_S\}$.

Since a pair of source and relay (S-R link) correlation matrices is required to derive $\mathbf{H}_{SR}$, one can similarly define the relay (S-R link) STCF $R^{SR}_{q_R, q'_R}(\delta_{RR}, \tau)$ from (6)-(8) by replacing the indices and then construct the relay (S-R link) correlation matrix $\mathbf{R}_{SR}$. By following a similar procedure to that used to generate $\mathbf{H}_{SR}$, $\mathbf{H}_{RD}$ can be also generated. Then, using (2), the channel transfer matrix $\mathbf{H}$ describing the overall MIMO relay channel can be obtained.

V. Results

This section presents results regarding the performance evaluation of the proposed reactive relay selection technique. The evaluation was performed using a developed ITS G5 simulator. The simulator includes a complete implementation of the ITS G5 PHY and MAC layers. Six nodes were assumed, where nodes 1 and 2 are unable to communicate directly with each other. The relaying mechanism was introduced in the ITS G5 standard in order to establish connectivity between nodes 1 and 2. Nodes 5 and 6 have FD DF relaying capability and therefore can be used as relays, while nodes 3 and 4 are conventional single-antenna transceivers. Moreover, nodes 1, 2, 5, and 6 use two antennas. In transmitting mode, nodes 1 and 2 equally share the available power at both antennas. In receiving mode, an MRC algorithm is applied in order to fully exploit the diversity gain. It is noted that no standard modification is necessary in order to embed the MRC operation in an ITS G5 system.

The relaying mechanism was implemented in the ITS G5 standard with the following modifications: Nodes 1 and 2 use the Address 4 field of the MAC header in order to request relaying and indicate the preferred relaying node. Therefore, if the Address 4 is empty then conventional transmission occurs. Otherwise, the node indicated in the specific address will act as a relay. Transmission is performed in the ITS G5 Control Channel (10 MHz bandwidth), where 48 of the 64 ITS G5 OFDM subcarriers were used. The transmitted packet was generated randomly with an average size of 1kbyte. The average SNR at the receiver varied from 10 to 20 dB. The carrier frequency was 5.9 GHz. Communication is performed with the ITS G5 basic rate (BPSK ½ Coding). The values of the model parameters used to generate the MIMO channel matrix are $\delta_S = \delta_{RR} = \delta_{RT} = \delta_D = \lambda$, $\theta_S = \theta_{RR} = \theta_{RT} = \theta_D = 90^o$, $\psi_S = \psi_{RR} = \psi_{RT} = \psi_D = 45^o$, $\mu_S = \mu_D = 0^\circ$, $\mu_{SR} = \mu_{RD} = \pi/6$, $\gamma_S = \gamma_D = 0^\circ$, $\gamma_R = \pi/4$, and $f_{S,\max} = f_{R,\max} = f_{D,\max} = 100$ Hz. The selected maximum Doppler frequency corresponds to an average speed of 24 km/h.

The simulation model evaluates the gains offered by the use of an MRC diversity receiver. Moreover, the outdated CSI effects are considered. Since the preferred relay station is defined in the Address 4 field of the previously transmitted packet, the outdated CSI may have significant impact on the system performance, when no significant temporal correlation exists. Performance was evaluated for different distributions of the effective scattering objects, i.e., different degree of local scattering in the azimuth domain (parameter $k = k_S = k_{SR} = k_{RD} = k_D$) and different maximum value of the multipath elevation angles (parameter $\beta_{\max} = \beta_{S\max} = \beta_{SR\max} = \beta_{RD\max} = \beta_{D\max}$). Note that large k and small $\beta_{\max}$ values indicate that the local scatterers are concentrated in specific angles at azimuth and elevation planes correspondingly. On the contrary, small k and large $\beta_{\max}$ values indicate that the local scatterers are distributed in a much larger range of azimuth and elevation angles. Then, the wireless radio channel rapidly changes and the Doppler effects become more significant.

Fig. 3 presents the achieved net throughput between nodes 1 and 2 with DF relaying and MRC reception. To evaluate the diversity and relaying gain, the performance of conventional single-antenna point-to-point transmission between nodes 3 and 4 is also presented. In Fig. 4, the results of PER for the ITS G5 network are also demonstrated. Packet losses may occur either due to poor channel conditions or due to collisions in the random access scheme. More specifically, in high SNR packet loss occurs mostly due to packet collisions and thus the gain of the diversity technique is decreased. The results show that a) there are significant gains from the use of the MRC diversity receiver in the link performance and b) the performance degrades, when the scatterers are distributed in a large range of azimuth and/or elevation angles. These results also justify the inclusion of the third dimension of the geometrical channel model.

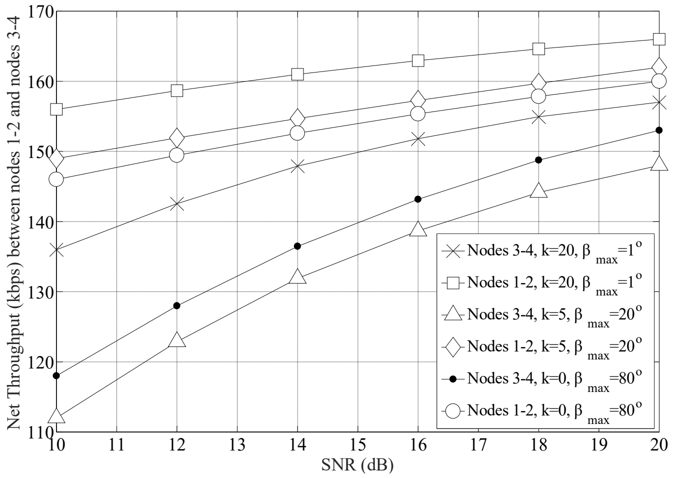

Fig. 3. Network throughput versus SNR for a) nodes 1 and 2 with relaying and MRC reception and b) nodes 3 and 4 with single-antenna point-to-point links for different degree of local scattering and different maximum multipath elevation angles.

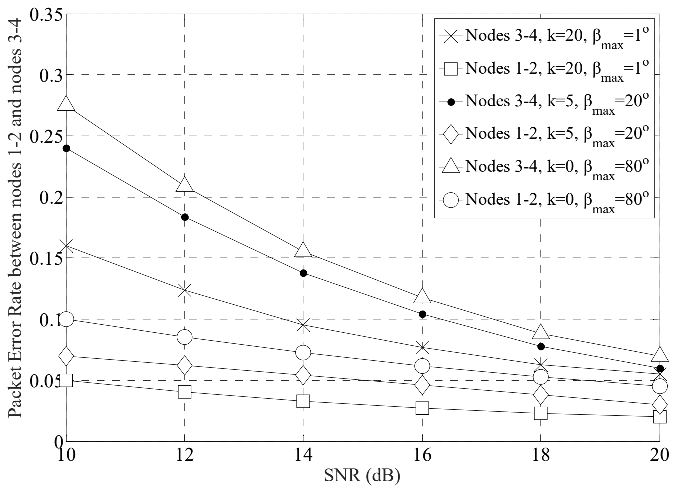

Fig. 4. PER versus SNR for the traffic between a) nodes 1 and 2 with relaying and MRC reception and b) nodes 3 and 4 with single-antenna point-to-point links for different degree of local scattering and different maximum multipath elevation angles.

VI. CONCLUSIONS

In this paper, an inter-vehicular MIMO wireless network, where a source and a destination communicate via multiple relays, has been studied. A reactive relay selection policy over space-time correlated MIMO relay channels has been applied based on instantaneous CSI knowledge, which selects the relay requiring the minimum power expenditure to forward the source's signal towards the destination. To compute the space-time correlation, a 3-D channel model for MIMO V2V relay channels, where the selected FD DF relay is equipped with one transmit and one receive ULA, has been proposed. Finally, the network throughput and PER performance for an ITS G5 network has been evaluated for various scattering conditions.

ACKNOWLEDGMENT

This research has received funding from the European Union's Horizon 2020 research and innovation programme under "ROADART" Grant Agreement No 636565.

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