

# Relay Selection in V2V Communications Based on 3-D Geometrical Channel Modeling

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**Abstract**—In this paper, an opportunistic relay selection policy related to the propagation characteristics for a vehicle-to-vehicle (V2V) relay-based system is presented, where a source communicates with a destination through multiple vehicle relay nodes. As Channel State Information (CSI) overhead is introduced by the relay selection process, reactive relaying is exploiting based on instantaneous CSI knowledge. To accurately characterize the corresponding wireless fading channel, a three-dimensional (3-D) model for V2V relay-based channels is initially constructed. From this model, a statistical sum-of-sinusoids (SoS) based simulation model is also developed, under 3-D non-isotropic scattering. The simulation results depict the throughput and the Packet Error Rate (PER) performance of the proposed relay selection scheme for different scattering conditions.

**Index Terms**—Decode-and-forward relaying, full-duplex relay, relay selection, vehicular communications, 3-D scattering.

## I. INTRODUCTION

With the advent of 5th generation (5G) wireless communication networks, vehicle-to-vehicle (V2V) systems, which are an integral part of Intelligent Transportation Systems (ITS), e.g., IEEE 802.11p standard [1], intend to improve convenience and safety of transportation, efficiently control road traffic, and provide mobile infotainment applications. Since multi-link propagation, which involves communication links between multiple spatially distributed nodes, has emerged for next generation wireless systems, exploiting relaying techniques leads to robust and reliable signal transmission in difficult terrains and/or long distances without using high power levels at the transmit side [2].

This paper investigates the performance of a V2V system in decode-and-forward (DF) multi-relay wireless networks, where multiple vehicle relay nodes, are assigned to assist a source in forwarding its information to a destination. 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 by allowing a certain amount of loop-interference (LI) due to signal leakage from the relays' transmission to their own reception. The residual LI can be minimized by adaptively control the power of the system [3], [4]. Since the performance of wireless relay networks can be significantly improved by selection of relays [5], [6] with respect to specific metrics, a relay selection policy is implemented, which is directly related to the propagation

characteristics [7]. Since signal impairments are mainly caused by the environment near the vehicle nodes, the establishment of a particular geometry describing the specific location of the scattering objects is highly critical and allows for an accurate characterization of the underlying fading channel. In this paper, a three-dimensional (3-D) geometry-based model for single-input single-output (SISO) V2V fading channels in relay-based networks is initially constructed, which is a simplified version of the multiple-input multiple-output (MIMO) channel model described in [8]. It is the first time that relay selection is performed through the use of a 3-D channel in inter-vehicular communications. The proposed model assumes that the radio waves travel in both the horizontal and the 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. To generate channel realizations for a finite number of scatterers, this paper adopts the sum-of-sinusoids (SoS) principle [9] and proposes a geometry-based statistical simulation channel model, under the framework of the 3-D scattering model.

In this paper, opportunistic relay selection is performed, where only one relay is activated [10], in order to improve the resource utilization and reduce the hardware complexity. The relay selection is based on the minimization of the transmission power, i.e., the selected FD DF relay requires the minimum sum of powers in the source-destination (S-D), source-relay (S-R), and relay-destination (R-D) links. Aiming at reducing the amount of channel state information (CSI) overhead, a reactive relay selection policy is examined, instead of a proactive relay selection policy. Since the power of the selected relay is adapted, CSI is required only in the R-D link, whereas in the S-R link, the source always transmits with a fixed power level. The proposed relay selection policy is examined in terms of the throughput and the Packet Error Rate (PER) performance for various fading conditions.

The remainder 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 develops a statistical simulation channel model, whereas Section V provides simulation results. Finally, conclusions are drawn in Section VI.

## II. SYSTEM MODEL

This paper considers an inter-vehicular communication system and frequency-flat channels. 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) channels are assumed, where the noise  $N$  has zero mean and variance  $n$ , i.e.,  $N \sim \mathcal{CN}(0, n)$ .

The source communicates with a destination through a set of  $M$  FD DF relays. To aid our analysis, the subscripts  $S$ ,  $D$ , and  $R$  are affiliated with the source, the destination, and the  $m$ -th selected relay, respectively. Then, the S-R-D system can be separated into the S-R and R-D subsystems. As shown in Fig. 1, the direct link between source and destination is obstructed due to high attenuation in the propagation medium. The source and destination are equipped with single antennas, whereas the relay nodes are equipped with two antennas; one for reception of the source's signal and one for transmission towards the destination. This configuration is practically attractive, since the antennas can be easily mounted on large vehicle surfaces.

Due to DF relaying, the relays decode the received signal and then re-encode it for transmission to the destination. Hence, simultaneous reception and transmission take place resulting in 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 equal to Bits-Per-Channel-Use (BPCU).

In each time-slot, one relay is selected to establish S-R-D communication through FD transmissions. Since instantaneous CSI knowledge is required and  $M$  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 special mobility properties, i.e., high vehicle velocity and rapid changing road topologies. To reduce the amount of CSI overhead, the reactive policy is proposed, where the source power level is fixed and the signal is broadcasted towards all the relays. The relay's transmission power levels are dynamically changed and power adaptation is performed. Hence, only the CSI of the R-D link is required for the distributed relay selection. In particular, 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 sub-channel, 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.

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.

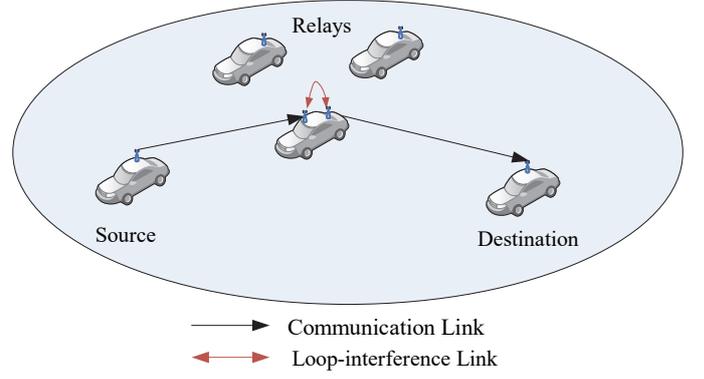


Fig. 1. Simple representation of a V2V multi-relay communication system, where one FD DF relay is selected.

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  $U = \{R_m : SNR_{RD} \geq SNR_0\}$ , 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 [7]

$$b_R = \arg \min_{m \in U} (P_{R_m}) = \arg \min_{m \in U} \left( \frac{n SNR_0}{g_{R_m D}} \right), \quad (1)$$

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 RELAYING SCHEME ON ITS

In this section, the application of the proposed system model and the relaying scheme on ITS G5 standard [11] 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 [1] with 10 MHz signal bandwidth. Moreover, 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 safety critical applications, the vehicles periodically broadcast safety messages in order to inform all the other vehicles in their proximity for status changes. Generally, the transmission frequency of messages in such applications is 10 to 25 Hz. Assuming 25 Hz frequency, time slots are defined with duration of 40 msec. Given the fact that IEEE 802.11p is a random access protocol, every 40 msec, all vehicles will contend for the medium and attempt broadcast transmission of their safety messages. This procedure has the following impact on our system model:

a) Every 40 msec a given vehicle is receiving signals from all adjacent vehicles. Therefore, it can use these signals as probes in order to estimate and update necessary CSI. However, in an active network messages between nodes will be exchanged with a much higher rate.

b) Due to the FD capability of the relay and with use of resources provided by the IEEE 802.11 MAC layer, the relay is able to directly retransmit the message towards the

destination without the obligation to gain access to the medium through contention.

c) Due to the fact that source and destination are not able to sense each others transmissions, collisions are highly possible. However, due to the FD setup of the relays, the collision will have no impact. The relay will be able to successfully decode both signals, and forward both messages as soon as the initial packets reception is concluded.

Typically, the size of each safety message as a Physical Layer orthogonal frequency-division multiplexing (OFDM) frame is less than 1kByte. Extra information regarding the relaying operation of the system may be embedded into the message.

#### IV. A 3-D MODEL FOR V2V RELAY FADING CHANNELS

This section describes a 3-D model for V2V relay-based channels, where the vehicle nodes are equipped with antennas with low height. It is assumed that the scattering objects in the vicinity of these nodes lie on the surface of three cylinders, which reflect the influence of three heterogeneous scattering environments. As shown in Fig. 2, the relay is positioned at an angle  $\omega_S$  with respect to the source, while the location of the relay seen from the destination is described by the angle  $\omega_D$ . In addition,  $O_S(O_R, O_D)$  denote the antennas at the source (relay, destination), while  $\tilde{O}_S(\tilde{O}_R, \tilde{O}_D)$  is the projection of  $O_S(O_R, O_D)$  to the  $x$ - $y$  plane. The source, the relay, and the destination are moving with speeds  $v_S$ ,  $v_R$ , and  $v_D$ , respectively, in the directions determined by the angles  $\gamma_S$ ,  $\gamma_R$ , and  $\gamma_D$ , respectively.

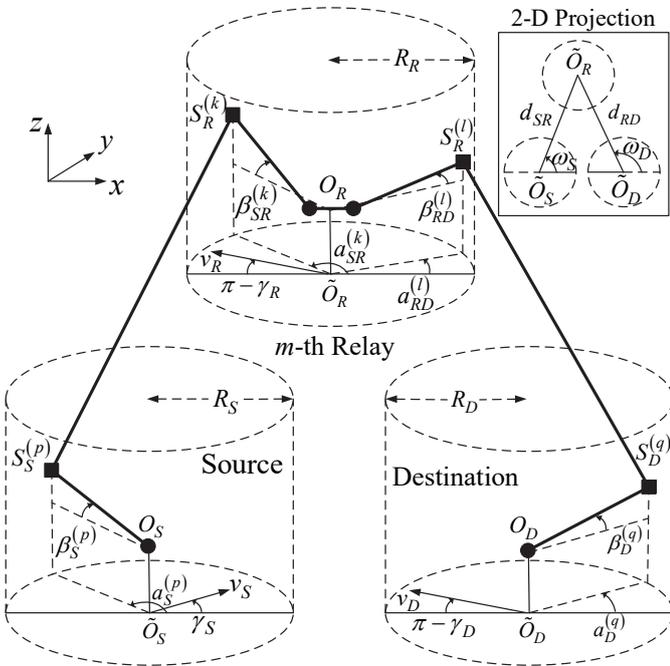


Fig. 2. The three-cylinder scattering model for a V2V relay fading channel.

The proposed model considers only double-bounce non-line-of-sight (NLoS) propagation conditions, which are dominant in urban macrocells environments [12]. It is assumed that  $P$  scatterers denoted by  $S_S^{(p)}$  ( $p=1,2,\dots,P$ ) are situated around the source, on the surface of a cylinder of radius  $R_S$ . Similarly,  $S_R^{(k)}$  ( $k=1,2,\dots,K$ ) and  $S_R^{(l)}$  ( $l=1,2,\dots,L$ ) scatterers in the vicinity of the relay with  $S_R^{(k)} = S_R^{(l)}$  for  $k=l$  lie on a surface of a cylinder of radius  $R_R$ , while  $Q$  scatterers denoted by  $S_D^{(q)}$  ( $q=1,2,\dots,Q$ ) are situated at the destination, on the surface of a cylinder of radius  $R_D$ . The angles  $a_S^{(p)}$  and  $\beta_S^{(p)}$  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 the scatterer  $S_S^{(p)}$ , 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  $a_D^{(q)}$  and  $\beta_D^{(q)}$  are the AAoA and the EAoA, respectively, of the wave scattered from  $S_D^{(q)}$  and received at the destination. The aforementioned angles are random variables. Due to the heterogeneity of the scattering 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.

#### A. A statistical Simulation Model for V2V Relay Channels

Based on the proposed 3-D scattering model, this section develops a statistical (Monte Carlo) simulation model with a finite number of scatterers. This model reflects actual channel realizations, since the scatterers are placed at different positions sights for each simulation trial.

The received complex faded envelope of the transmission link from the source antenna to the destination antenna via the  $m$ -th relay antenna is given by

$$h_{SRD}(t) = h_{SR}(t)h_{RD}(t), \quad (2)$$

where  $h_{SR}(t)$  is the received complex faded envelope for the link from the source antenna to the  $m$ -th relay antenna and  $h_{RD}(t)$  is the received complex faded envelope for the link from the  $m$ -th relay antenna to the destination relay antenna.

Using the results in [13] and considering that the source and the  $m$ -th relay are equipped with single antennas,  $h_{SR}(t)$  can be obtained as follows

$$h_{SR}(t) \approx (P_A P_E K_A K_E)^{-1/2} \sum_{p_A, p_E=1}^{P_A, P_E} \sum_{k_A, k_E=1}^{K_A, K_E} A_{SR} \times \exp(j\varphi_{p_A, p_E, k_A, k_E}) \exp[j2\pi t(f_S + f_{SR})], \quad (3)$$

where  $P_A P_E = P$ ,  $K_A K_E = K$ ,

$$A_{SR} \approx \exp \left\{ -j2\pi \left[ R_S / \cos \beta_S^{(p_E)} + R_R / \cos \beta_{SR}^{(k_E)} + d_{SR} \right. \right. \\ \left. \left. - R_S \cos \left( a_S^{(p_A)} - \omega_S \right) - R_R \cos \left( a_{SR}^{(k_A)} - \omega_S \right) \right] / \lambda \right\}, \\ f_S = f_{S,\max} \cos \left( a_S^{(p_A)} - \gamma_S \right) \cos \beta_S^{(p_E)}, \\ f_{SR} = f_{R,\max} \cos \left( a_{SR}^{(k_A)} - \gamma_R \right) \cos \beta_{SR}^{(k_E)}, \quad (4)$$

$f_{S,\max} = v_S / \lambda$  and  $f_{R,\max} = v_R / \lambda$  are the maximum Doppler shifts associated with source and relay, respectively,  $\lambda$  is the carrier wavelength,  $d_{SR}$  denotes the distance between the source antenna and the  $m$ -th relay antenna, and the indices A and E are associated with the multipath azimuth and elevation angles, respectively. The phases  $\varphi_{m_A, m_E, k_A, k_E}$  are variables uniformly distributed in the interval  $[0, 2\pi]$  and independent from the angles of arrival (departure).

Based on [13], we generate the AAoD  $a_S^{(p_A)}$  and the EAoD  $\beta_S^{(p_E)}$  as follows

$$a_S^{(p_A)} = F^{-1} \left( (p_A + \delta_S - 1) / P_A \right), \quad (5)$$

$$\beta_S^{(p_E)} = \frac{2\beta_{S,\max}}{\pi} \arcsin \left( \frac{2(p_E + \zeta_S - 1)}{P_E} - 1 \right) \quad (6)$$

for  $m_A = 1, \dots, M_A$  and  $m_E = 1, \dots, M_E$ , where  $\delta_S$  and  $\zeta_S$  are independent random variables uniformly distributed in the interval  $[0, 1)$ . Moreover, the function  $F^{-1}(\cdot)$  denotes the inverse function of the von Mises cumulative distribution function (cdf) and can be numerically evaluated [14] by defining the mean angle  $\mu_S \in [-\pi, \pi]$  at which the scatterers in the vicinity of the source are distributed in the  $x$ - $y$  plane, and the parameter  $k_S \geq 0$  (degree of scattering), which controls the spread around the mean. Setting  $k_S = 0$  incurs isotropic scattering, while the scattering becomes increasingly non-isotropic by increasing  $k_S$ . In addition,  $\beta_{S,\max}$  is the maximum value of  $\beta_S^{(p_E)}$ , usually less than  $20^\circ$ , value typical for V2V communications, i.e., cars driving through streets [15]. Note that one can generate the other random variables related with the azimuth angle of arrival (departure) and elevation angle of arrival (departure) using (5) and (6), respectively.

Similarly, considering that the  $m$ -th relay and the destination are equipped with single antennas,  $h_{RD}(t)$  can be defined from (3)-(4) by replacing the indices as follows

$$h_{RD}(t) = (L_A L_E Q_A Q_E)^{-1/2} \sum_{l_A, l_E=1}^{L_A, L_E} \sum_{q_A, q_E=1}^{Q_A, Q_E} A_{RD} \\ \times \exp \left( j\varphi_{l_A, l_E, q_A, q_E} \right) \exp \left[ j2\pi t (f_{RD} + f_D) \right], \quad (7)$$

where  $L_A L_E = L$ ,  $Q_A Q_E = Q$ ,

$$A_{RD} \approx \exp \left\{ -j2\pi \left[ R_D / \cos \beta_D^{(q_E)} + R_R / \cos \beta_{RD}^{(l_E)} + d_{RD} \right. \right. \\ \left. \left. - R_D \cos \left( a_D^{(q_A)} - \omega_D \right) - R_R \cos \left( a_{RD}^{(l_A)} - \omega_D \right) \right] / \lambda \right\}, \\ f_D = f_{D,\max} \cos \left( a_D^{(q_A)} - \gamma_D \right) \cos \beta_D^{(q_E)}, \\ f_{RD} = f_{R,\max} \cos \left( a_{RD}^{(l_A)} - \gamma_R \right) \cos \beta_{RD}^{(l_E)}, \quad (8)$$

$f_{D,\max} = v_D / \lambda$  is the maximum Doppler shift associated with the destination, and  $d_{RD}$  denotes the distance between the  $m$ -th relay antenna and the destination antenna. The phases  $\varphi_{l_A, l_E, q_A, q_E}$  are variables uniformly distributed in the interval  $[0, 2\pi]$  and independent from the other random variables.

To generate the received complex faded envelope in (2), an average procedure and the generation of multiple random variables are required.

## V. RESULTS

This section presents results regarding the performance evaluation of the proposed reactive relay selection technique. In particular, the throughput and the PER are investigated assuming an ITS G5 transmission scheme. In addition,  $M = 2$  FD DF relays are assumed. A complete ITS G5 PHY and MAC simulator was developed. The evaluated network consists of 6 nodes. Nodes 1 and 2 have no direct connectivity and therefore, a relay is necessary for communication. Nodes 4 and 5 are FD DF relays, while the two remaining nodes are conventional transceivers. The Address 4 field of the MAC header, which is not used in ITS G5, is properly filled to indicate the need for relaying for every packet transmitted by Nodes 1 and 2. All messages are sent through the ITS G5 Control Channel at 5.9 GHz with 10 MHz bandwidth. The basic rate (BPSK  $\frac{1}{2}$  Coding) was used. All Nodes are mobile with average speed 24 km/h. The values of the model parameters used are  $R_S = R_R = R_D = 50$  m,  $d_{SR} = d_{RD} = 1$  km,  $\omega_S = \omega_D = \pi/4$ ,  $\mu_S = \mu_D = 0^\circ$ ,  $\mu_{SR} = \mu_{RD} = \pi/6$ ,  $\gamma_S = \gamma_D = 0^\circ$ ,  $\gamma_R = \pi/4$ , and  $f_{S,\max} = f_{R,\max} = f_{D,\max} = 100$  Hz. The simulation was performed for  $P_A = K_A = L_A = Q_A = 20$ ,  $P_E = K_E = L_E = Q_E = 3$ , and 50 simulation trials.

The simulation results examine the effect of the use of outdated CSI in the relay selection scheme for different distribution of the effective scattering objects, i.e., different degree of local scattering in the azimuth domain (parameter  $k = k_S = k_{SR} = k_{RD} = k_D$ ) at the vehicle nodes and different maximum value of the multipath elevation angles (parameter  $\beta_{\max} = \beta_{S\max} = \beta_{SR\max} = \beta_{RD\max} = \beta_{D\max}$ ). Since the multipath elevation angles are expected to be high in dense-urban areas, where the scatterers are usually dense and tall, values for the maximum multipath elevation angles up to  $80^\circ$  are considered. During simulation, each node transmitted information with an average rate of two packets per msec. Thus, relay selection is performed according to (1) based on the estimated SNR from the previous measurement. Performance of relay selection assuming perfect CSI is also provided as reference. Results for

the achieved network throughput between Nodes 1 and 2 are presented in Fig. 3. In Fig. 4, the results of PER for the ITS G5 network and particularly for the link between nodes 1 and 2 are demonstrated. Packet losses may occur either due to poor channel conditions or due to collisions since a random access scheme is used.

The results show that the effects of outdated CSI in the degradation of performance increases as a) the degree of local scattering decreases and as b) the maximum multipath elevation angles increase. The aforementioned behavior is expected, since the wireless radio channel changes more rapidly, when the scatterers are distributed in a much larger range of azimuth and elevation angles. As the source, the  $m$ -th relay, and the destination move among the effective scatterers in their vicinity, the Doppler effects become more significant and the regions of stationarity becomes smaller. These results also justify the inclusion of the third dimension of the proposed channel model.

## VI. CONCLUSIONS

In this paper, a network where a source and a destination communicate via multiple relays has been studied. In order to achieve realistic propagation behavior, 3-D channel characterization combined with statistical simulation modeling have been used and various scattering conditions have been investigated. Moreover, a reactive relay selection policy 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. Finally, the network throughput and PER performance for an ITS G5 network has been evaluated.

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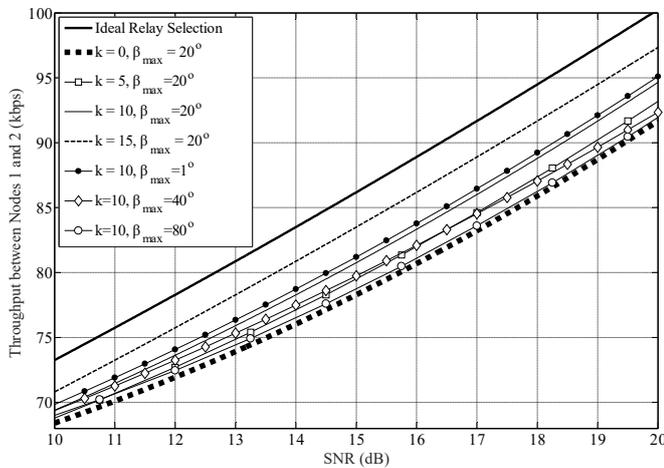


Fig. 3. Network throughput versus SNR between Nodes 1 and 2 for different degree of local scattering at the vehicle nodes and different maximum multipath elevation angles.

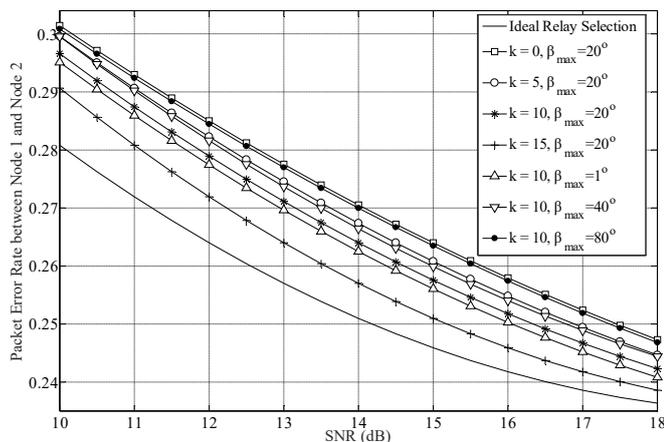


Fig. 4. PER versus SNR for the traffic between Nodes 1 and 2 for different degree of local scattering at the vehicle nodes and different maximum multipath elevation angles.