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Performance Analysis of Full-Duplex Cooperative Communication in Vehicular Ad-Hoc Networks

Samuel Baraldi Mafra * **Evelio M. G. Fernandez** *
Richard Demo Souza **

* *Federal University of Paraná, Curitiba, Brazil, (e-mails: mafrasamuel@gmail.com, evelio@ufpr.br)*
** *Federal University of Technology - Paraná, Curitiba, Brazil, (e-mail: richard@utfpr.edu.br)*

Abstract: This paper evaluates the use of full-duplex nodes to increase the performance of a vehicular ad hoc network (VANET) composed of one transmitter, multiple full-duplex relays and one destination, where the best relay is selected to assist communication. With the use of full-duplex communication, it is possible to obtain a better use of the radio resources, eliminating the multiplexing loss of half duplex systems. We consider Nakagami-m fading, aimed at analyzing the schemes in scenarios with line-of-sight and where the channel condition is critical, for instance a sub-Rayleigh channel, which are typical propagation scenarios to model vehicular networks. Furthermore, the analysis includes the self-interference at the relay node. Results presented in terms of outage probability shown that the full-duplex scheme is suitable for improving communication over vehicular channels.

Keywords: Vehicular Communication, Full-Duplex, Relay Selection Scheme

1. INTRODUCTION

In recent years, works with applications of communication among vehicles have attracted the interest of the industry and academia. Vehicular communication enable the vehicles to share different information about traffic jam, weather and accident prevention. Vehicular ad-hoc networks (VANETs) are composed of roadside units (RSUs) fixed near roads and self-organizing vehicles. The vehicles can communicate with others vehicles forming a vehicle to vehicle communication (V2V) or with an RSU forming a vehicle to infrastructure communication (V2I) (Al-Sultan et al. (2014)).

Cooperative communication was proposed in (Laneman et al. (2004); Nosratinia et al. (2004)) with the objective of improving the link reliability and energy efficiency of communication systems. The idea behind this strategy is to make use of one or more nodes (called relays) in order to emulate a physical antenna array. As a consequence, the same benefits obtained in multiple-input multiple-output systems can also be achieved with the use of single-antenna nodes through the distributed transmission and processing of the information. In (Laneman et al. (2004)), the cooperative decode-and-forward (DF) protocol and its selective (SDF) and incremental (IDF) variants are introduced. In the SDF protocol the message is forwarded only if its decoding at the relay was successful. While, in the IDF protocol, the message also needs to be correctly decoded by the relay; but the forwarding occurs only when requested by the destination. In cooperative systems, the relay can operate on either half-duplex (HD) or full-duplex (FD) modes (Laneman et al. (2004); Kramer et al. (2005)). Specifically, in half-duplex mode, the relay transmits and receives in orthogonal channels, whereas in full-duplex mode the transmission and reception are performed at the same time and at the same frequency band. Owing to this fact, half-duplex relays require the use of additional system resources, while full-duplex relays arise as a viable option to alleviate this problem. However, although ideal full-duplex relaying can achieve higher capacity than half-duplex relaying (Kramer et al. (2005)), its use introduces self-interference that is inherent to the full-duplex approach. Nevertheless, the works in (Riihonen et al. (2009); Kwon et al. (2010); Alves et al. (2012)) showed that full-duplex relays can still achieve high performance, even in the presence of strong interference levels. When multiple relays are available, relay selection schemes become attractive solutions to reduce complexity and to increase the throughput (Bletsas et al. (2005)). In (Khafagy et al. (2015a)), relay selection schemes are proposed for a full-duplex DF cooperative network, where the selected relay transmits the message even if it has not been correctly decoded. The results show that the performance improves with the increment in the number of relays.

Recent works evaluate the use of full-duplex communication in cooperative networks. In Kim et al. (2012), the authors evaluate a cognitive scenario with a full-duplex relay subject to self-interference. A full-duplex dual-hop (DH) relaying scheme is proposed, in which the self-interference at the relay was taken into account and the direct link is seen as interference at the secondary destination. In (Khafagy et al. (2013)), the authors evaluate the outage

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probability of a full-duplex cooperative network, where the signal of the direct link is exploited at the secondary destination and the relay employs the Selective-Decode-and-Forward (SDF) protocol. In (Khafagy et al. (2015b)), the authors evaluate the protocols proposed in (Khafagy et al. (2013)), for a scenario subject to Nakagami-m fading. The proposed protocols have better performance in terms of outage probability than half-duplex and others full-duplex protocols. In (Mafra et al. (2015)), the authors propose a new full-duplex relaying scheme for a cooperative cognitive underlay network, where the direct link can be seen as useful information at the secondary destination rather than interference. Furthermore, the authors propose an optimal power allocation (OPA) scheme. The results show that the proposed scheme under the OPA policy has the best performance among all schemes investigated in that work.

Motivated by the important benefits acquired with cooperative diversity techniques, recent works have analyzed the performance of cooperative vehicular networks (Pan et al. (2012); Zhang et al. (2012); Rayel et al. (2013)). In (Pan et al. (2012)), a cooperative scheme is evaluated for a cognitive VANET and an optimization problem aimed at maximizing the throughput of the network is proposed. The results show that the proposed scheme has a better performance than schemes with only one transmission mode (direct transmission or cooperative communication). In (Zhang et al. (2012)), the uplink and downlink connectivity probability are evaluated for a multi-hop infrastructured vehicular network. With the proposed model, the engineers can design the vehicular network according to traffic density and user requirements. In (Rayel et al. (2013)), a non-binary network coding scheme is evaluated for a VANET, where the vehicles have different information to send to a common destination. Moreover, the users are provided with multiple antennas. The combination of network coding and multiple antennas improves the performance in comparison with others schemes in the literature.

Differently from all previous works in vehicular networks, in this paper we consider a vehicular cooperative network with multiple relays operating in full-duplex mode, where the best relay is selected. In particular, this paper evaluates, in a vehicular network, the full duplex joint decoding (FDJD) scheme initially proposed in (Khafagy et al. (2013)) and further adapted for a cognitive network in (Mafra et al. (2015)). In this scheme the destination applies joint decoding with the signals received from the relay and from the source such that the direct link can be seen as useful information rather than interference at the destination. The scheme termed as vehicular full-duplex joint-decoding (VJD) relaying, is compared with the vehicular full-duplex dual-hop (VDH) scheme, which is based on the scheme proposed in (Kim et al. (2012)) for a cognitive network, as well as with the standard vehicular half-duplex joint-decoding (VHD) relaying and non-cooperative schemes. Considering Nakagami-m fading, three different scenarios are evaluated in the simulations, the first scenario considers that the conditions of direct link are critical, as could be the case of buildings and other obstacles blocking the communication between source and destination. In the second scenario, the conditions of the channels are not critical, but there is no line-of-sight between users. Finally, the third scenario considers some line-of-sight in the links between source-relay and relay-destination. Our results demonstrate that the VJD scheme can considerably outperform the VDH method for the whole signal-to-noise ratio (SNR) range. Moreover, our results show that the VJD method performs better than the VHD and non cooperative schemes in terms of outage probability even in the presence of self-interference.

The rest of this paper is organized as follows. In Section 2, the system model is introduced. In Section 3, an analytical performance analysis of the vehicular schemes is carried out in terms of outage probability. In Section 4, representative numerical plots are shown and insightful discussions are provided. Finally, Section 5 concludes the paper.

2. SYSTEM MODEL

Consider a vehicular ad-hoc network composed of one source, N relay nodes denoted as $r(l)$, $l \in \Phi = \{1, 2, \ldots, N\}$ and one destination as depicted in Fig. 1, in which the relay selected by the scheme sch is denoted as $r(l^{\text{sch}})$, with sch $\in \{\text{VHD}, \text{VDH}, \text{VJD}\}$.

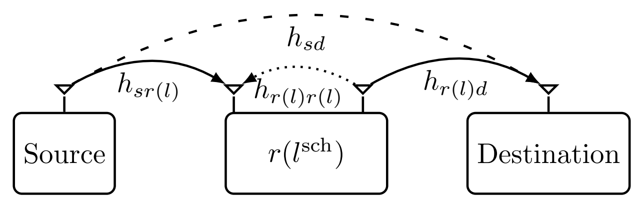

Fig. 1. System model: a vehicular cooperative network with a selected relay $r(l^{\text{sch}})$.

We also consider that the N relays are in a cluster, so that they are assumed to be at approximately the same spatial location.

The channel between any transmitter i and receiver j is denoted by h_{ij} and follows a Nakagami-m distribution (Nakagami (1960)) with fading parameter m_{ij} and average power λ_{ij}. In our notation $i \in \{s, r(l)\}$ and $j \in \{r(l), d\}$ where s is the source, $r(l)$ the l-th relay and d the destination. Moreover, through this model the severity of the fading can be adjusted by the parameter m. The Nakagami-m distribution is a general approach that includes the Rayleigh distribution as a special case (when $m_{ij} = 1$). In accordance to the channel characterization presented in (Cheng et al. (2007)) for mobile vehicle-to-vehicle communications, we consider values of $m_{ij} = 0.5$, $m_{ij} = 1$ and $m_{ij} = 2$ for characterizing sub-Rayleigh, non line-of-sight (NLOS) and some line-of-sight (LOS) scenarios, respectively.

The average power is defined as $\lambda_{ij} = \frac{1}{(d_{ij})^{\alpha}}$, where d_{ij} is the normalized distance between transmitter i and receiver j with respect to the distance between source and destination (d_{sd}) which is assumed equal to one and α is the path-loss exponent.

The received signals at the relay $r(l)$ and at the destination can be expressed, respectively, as

$$y_{r(l)} = \sqrt{P_s}\, h_{sr(l)}\, x_s + \sqrt{P_{r(l)}} h_{r(l)r(l)}\, x_{r(l)} + n_{r(l)}, \quad (1)$$

$$y_d = \sqrt{P_{r(l)}}\, h_{r(l)d}\, x_{r(l)} + \sqrt{P_s}\, h_{sd}\, x_s + n_d, \quad (2)$$

where P_i is the transmit power of node i, x_i is the message sent by node i, $h_{r(l)r(l)}$ denotes the fading coefficient of the self-interference at the full-duplex relay and $n_j \sim \mathcal{CN}(0, \sigma_n^2)$ stands for the additive white Gaussian noise at node j with variance $\sigma_n^2 = N_0$, where N_0 is the one-sided noise power spectral density, as we assume a unitary bandwidth. Note that the self-interference may represent the residual interference after the application of some interference cancellation technique at the relay (Kwon et al. (2010); Duarte et al. (2012)). We recall that the self-interference is dominated by the scattering component once the line-of-sight component is considerably reduced by antenna isolation Kwon et al. (2010), which leads to in general very small values of $\lambda_{r(l)r(l)}$ (Alves et al. (2012)).

3. OUTAGE ANALYSIS

In this section, we present the outage probability analysis for the full-duplex VJD relaying, full-duplex VDH and VHD joint decoding schemes. As defined in (Goldsmith (2005)), the outage probability is the probability of a failure in the communication between nodes i and j. Therefore, an outage can be defined as the event that the mutual information, $\mathcal{I}_{ij}$, is lower than the attempted transmission rate $\mathcal{R}$. Thus, assuming unitary bandwidth and Gaussian inputs, the outage probability of the i-j link is given by (see Laneman et al. (2004))

$$\mathcal{O}_{ij} = \Pr\left[\mathcal{I}_{ij} < \mathcal{R}\right] = \Pr\left[\log_2\left(1 + \frac{|h_{ij}|^2 P_i}{N_0}\right) < \mathcal{R}\right], \quad (3)$$

where $\Pr[\theta]$ is the probability of event θ.

In this article, we consider a proactive relay selection scheme (see Bletsas et al. (2005)), where the selected relay is chosen before the transmission by doing

$$l^{\mathrm{sch}} = \arg\max_{l \in \Phi} \left(\min\left(\mathcal{I}_{sr(l)}, \mathcal{I}_{r(l)d}\right)\right). \quad (4)$$

As in Khafagy et al. (2015a), we consider that the full channel state information is available at the transmitters.

3.1 Vehicular Full-Duplex Joint Decoding (VJD)

The vehicular cooperative communication scheme (VJD) relies on the help of a FD relay such that the direct link is seen as useful information instead of interference at the destination. Thus, when the source-relay link is in outage, the message can still be successfully received through the direct link. First, the source broadcasts its message to relay and destination. Then, after a processing delay, during the multiple access phase, the relay forwards the received message to the destination. As we consider a SDF protocol, if the source-relay link is in outage, the relay remains silent, otherwise it forwards the message to the destination.

Fig. 2 depicts such encoding/decoding strategy where the frame is split into L blocks. Notice that x_s denotes the message sent by the source, while $x_{r(l)}$ is the re-encoded message at the relay. There is a delay between source and relay transmissions, which we assume to be of one block in this work. After receiving the last block, the destination applies backward decoding scheme (see (Willems and van der Meulen (1985); Zeng et al. (1989)) for more details) to jointly decodes the signals received from source and relay (Kramer et al. (2005); Alves et al. (2014, 2013); Khafagy et al. (2013); Mafra et al. (2015)). The backward decoding is an iterative process, whose purpose is to combine the transmissions from source and relay, using advanced detection techniques and the acquired knowledge from previously received frames (Khafagy et al. (2013); Mafra et al. (2015)).

The mutual information for the links between the source and relay and between source and destination can be written as

$$\mathcal{I}_{sr(l)}^{VJD} = \log_2\left(1 + \frac{\left|h_{sr(l)}\right|^2 P_s}{\left|h_{r(l)r(l)}\right|^2 P_{r(l)} + N_0}\right), \quad (5)$$

$$\mathcal{I}_{sd}^{VJD} = \log_2\left(1 + \frac{P_s\left|h_{sd}\right|^2}{N_0}\right), \quad (6)$$

respectively, while the mutual information for the link between the relay and the destination is given by

$$\mathcal{I}_{r(l)d}^{VJD} = \log_2\left(1 + \frac{P_s\left|h_{sd}\right|^2 + P_{r(l)}\left|h_{r(l)d}\right|^2}{N_0}\right). \quad (7)$$

Note that in (7), the signals coming from the transmitter and the selected relay are seen as useful information at the destination. Moreover, also note that the self-interference at the selected relay is taken into account in (5).

As in the VJD scheme, the destination can receive the message by the direct link or with the help of the relay node. The equivalent mutual information is given by the maximum between the mutual information of the direct link and the mutual information of the cooperative link. Thus, the overall outage probability of the VJD scheme with N relays becomes

$$\mathcal{O}_{VJD} = \Pr\left[\max\left(\mathcal{I}_{sd}^{VJD}, \max_{l\in\Phi}\left(\min\left(\mathcal{I}_{sr(l)}^{VJD}, \mathcal{I}_{r(l)d}^{VJD}\right)\right)\right) < \mathcal{R}\right]. \quad (8)$$

For the particular case of $N = 1$ relay, the outage probability of the VJD scheme is given by:

$$\mathcal{O}_{VJD} = \mathcal{O}_{sd}^{VJD}\mathcal{O}_{sr(l)}^{VJD} + \left(1 - \mathcal{O}_{sr(l)}^{VJD}\right)\mathcal{O}_{r(l)d}^{VJD}. \quad (9)$$

3.2 Vehicular Full-Duplex Dual Hop (VDH)

In the vehicular full-duplex dual-hop (VDH) scheme which is based on the scheme proposed for a cognitive network in (Kim et al. (2012)), differently from the VJD scheme, the direct link s-d is seen as interference at the destination. Thus, the mutual information of the s-r link is written as in (5), while the mutual information of the r-d link is now defined as

$$\mathcal{I}_{r(l)d}^{VDH} = \log_2\left(1 + \frac{\left|h_{r(l)d}\right|^2 P_{r(l)}}{\left|h_{sd}\right|^2 P_s + N_0}\right). \quad (10)$$

Note that, as previously stated, the source transmission is seen as interference in (10). The overall outage probability can be written as

$$\mathcal{O}_{VDH} = \Pr\left[\max_{l\in\Phi}\left(\min\left(\mathcal{I}_{sr(l)}^{VDH}, \mathcal{I}_{r(l)d}^{VDH}\right)\right) < \mathcal{R}\right]. \quad (11)$$

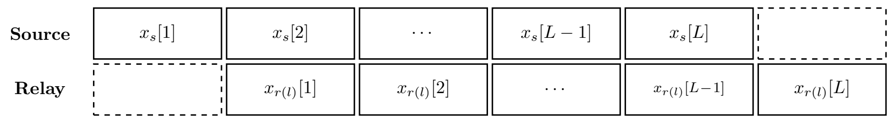

Fig. 2. Full-duplex relaying encoding. The message is split into L blocks, note that the delay between messages from the relay and the source is of one block.

For the particular case of $N = 1$ relay, the outage probability of the VDH scheme is given by

$$\mathcal{O}_{VDH} = \mathcal{O}^{VDH}_{sr(l)} + \mathcal{O}^{VDH}_{r(l)d} - \mathcal{O}^{VDH}_{sr(l)}\mathcal{O}^{VDH}_{r(l)d}. \tag{12}$$

3.3 Vehicular Half-Duplex Joint Decoding (VHD)

In the vehicular half-duplex scheme, the transmission occurs in two time slots. In the first time slot, the source broadcasts its message to the selected relay and to the destination, while in the second time slot the relay retransmits the source message if correctly decoded and if requested by the destination. It is noteworthy that we assume the incremental decode-and-forward (IDF) protocol introduced in (Laneman et al. (2004)), in which the relay only acts if requested by the destination and if the source message was decoded free of error. Note that the IDF protocol was chosen as it performs better than the fixed and selective decode-and-forward protocols. Thus, at the destination both messages are combined and jointly decoded. Based on the above discussion, and making the appropriate substitutions, the mutual information of the *s-r(l)* and *s-d* links can be both written as

$$\mathcal{I}^{VHD}_{sk} = \frac{1}{2}\log_2\left(1 + \frac{P_s\,|h_{sk}|^2}{N_0}\right), \tag{13}$$

with $k \in \{r(l), d\}$.

As the messages from the source and the relay are jointly decoded at the destination, the mutual information of the *r-d* link is

$$\mathcal{I}^{VHD}_{r(l)d} = \frac{1}{2}\log_2\left(1 + \frac{P_s\,|h_{sd}|^2 + P_{r(l)}\,\left|h_{r(l)d}\right|^2}{N_0}\right). \tag{14}$$

Similarly to the VJD scheme, the overall outage probability of the VHD scheme can be finally defined as

$$\mathcal{O}_{VHD} = \Pr\left[\max\left(\mathcal{I}^{VHD}_{sd}, \max_{l\in\Phi}\left(\min\left(\mathcal{I}^{VHD}_{sr(l)}, \mathcal{I}^{VHD}_{r(l)d}\right)\right)\right) < \mathcal{R}\right]. \tag{15}$$

For the particular case of $N = 1$ relay, the outage probability of the VHD scheme is given by

$$\mathcal{O}_{VHD} = \mathcal{O}^{VHD}_{sd}\mathcal{O}^{VHD}_{sr(l)} + \left(1 - \mathcal{O}^{VHD}_{sr(l)}\right)\mathcal{O}^{VHD}_{r(l)d}. \tag{16}$$

4. NUMERICAL RESULTS AND DISCUSSIONS

This section presents some numerical results in order to investigate the performance of full-duplex cooperative vehicular network using joint decoding at the destination. Moreover, the performance of the VJD scheme is compared to the full-duplex VDH, half-duplex VHD and non cooperative schemes. Monte Carlo simulations have been carried out to compare the different schemes in terms of outage probability. In the plots, we assume the path loss model $d_{ij}^{-\alpha}$ with $\alpha = 4$, the transmit powers of source and the selected relay are equal ($P_s = P_{r(l)} = P$) and $N_0 = 1$. We consider three different scenarios of vehicular networks regarding the severity parameter of the channels:

- Case 1: Sub-Rayleigh channel for the link source-destination ($m_{sd} = 0.5$) and Rayleigh channels for the others links ($m_{sr(l)} = 1$, $m_{r(l)r(l)} = 1$ and $m_{r(l)d} = 1$);
- Case 2: Rayleigh channels for all links, ($m_{sd} = 1$, $m_{sr(l)} = 1$, $m_{r(l)r(l)} = 1$ and $m_{r(l)d} = 1$);
- Case 3: Links between source-relay and relay-destination with some line of sight ($m_{sr(l)} = 2$, $m_{r(l)d} = 2$) and Rayleigh channels for the others links, ($m_{sd} = 1$, $m_{r(l)r(l)} = 1$).

The first scenario considers that the conditions of the direct link are critical; in this case buildings and other obstacles block the communication between source and destination. In the second scenario, the condition of the channels is not critical, but there is no line-of-sight between users. Finally, the third scenario considers some line-of-sight in the links between source-relay and relay-destination.

Fig. 3 presents the outage probability as a function of the transmit power P. We consider a scenario with one relay node, where $d_{sr(l)} = d_{r(l)d} = 1/2$, $d_{sd} = 1$, $\lambda_{r(l)r(l)} = 10^{-4}$, $\mathcal{R} = 3$ bits per channel use (bpcu) and the severity channel parameters given by the Case 1.

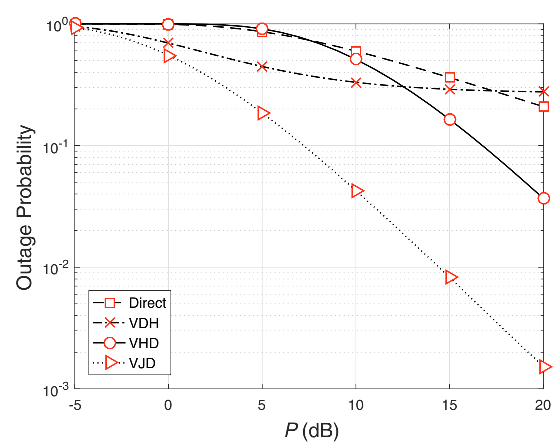

Fig. 3. Outage probability for the different schemes as a function of transmit power P.

From the figure, it can be seen that VJD has the better performance among the schemes in terms of outage probability. For $P = 10$ dB, the VJD scheme has an outage probability of 4×10^{-2}, while for the direct transmission and VHD schemes, the outage probability are equal to 0.6 and 0.5, respectively. Furthermore, the outage probability of the full-duplex VDH method saturates for large values of P, because of the effects of the self-interference and of the interference of the direct link.

Fig. 4 presents the outage probability as a function of the attempted transmission rate $\mathcal{R}$, with the severity channel parameters given by the Case 1. We consider a scenario with a one relay node, where $d_{sr(l)} = d_{r(l)d} = 1/2$, $d_{sd} = 1$, $\lambda_{r(l)r(l)} = 10^{-4}$ and $P = 10$ dB.

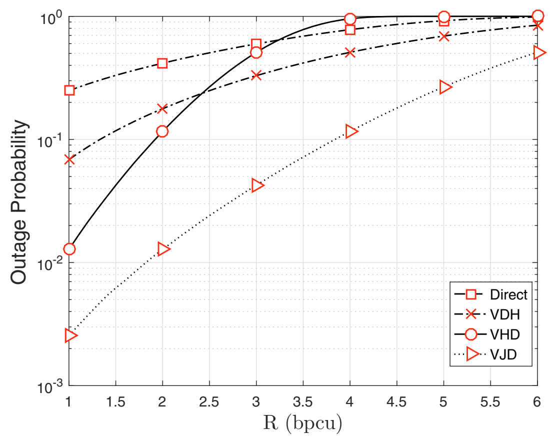

Fig. 4. Outage probability for the different schemes as a function of attempted transmission rate $\mathcal{R}$.

From the figure, it can be noted that for low values of $\mathcal{R}$, the VHD scheme has better performance than the VDH scheme because of the performance floor caused by the self interference at the full-duplex relay and by the interference of the direct link for high values of P. The VJD scheme has the best performance amongst all schemes for the whole $\mathcal{R}$ range, thus this scheme can operate at a greater rate given an outage probability threshold in comparison to the other schemes. For instance, when the outage probability threshold is equal to 4×10^{-2}, the maximum attempted rates are $\mathcal{R} = 3$ bpcu and $\mathcal{R} = 1.5$ bpcu for the VJD and VHD schemes, respectively.

Fig. 5 shows the outage probability for the VJD scheme as a function of the transmit power P.

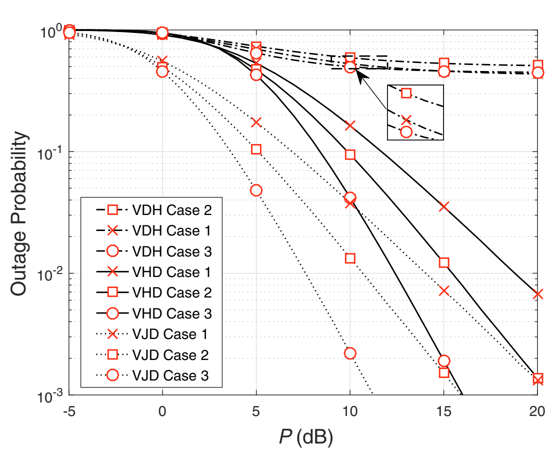

Fig. 5. Outage probability for the different schemes as a function of transmit power P varying the severity channel parameters.

In this figure the performance of the schemes is compared for the three different cases. We assume a scenario with one relay node, where $d_{sr(l)} = d_{r(l)d} = d_{sd} = 1$ and $\lambda_{r(l)r(l)} = 10^{-4}$. It can be observed that for the VDH scheme, the outage probability of Case 1 is better than that of Case 2, because in this method, the direct link is seen as interference, thus the performance increase when the interference link has a worse channel. Moreover, the performance of all schemes improves when the links source-relay and relay-destination have some line of sight (Case 3). Finally, for the particular value of $P = 10$ dB, an outage probability of 4×10^{-2} is obtained when the condition of the source-destination channel is critical in the VJD scheme, while a LOS scenario is necessary for the VHD scheme.

In Fig. 6, we analyze the performance of the VJD scheme by varying the number of relay nodes, with the severity channel parameters given by the Case 1. We also consider that the cluster of relays is centered in a straight line between s and d ($d_{sr(l)} = d_{r(l)d} = 1/2$), $d_{sd} = 1$, $\lambda_{r(l)r(l)} = 10^{-4}$ and $\mathcal{R} = 3$ bpcu. It can be seen that the

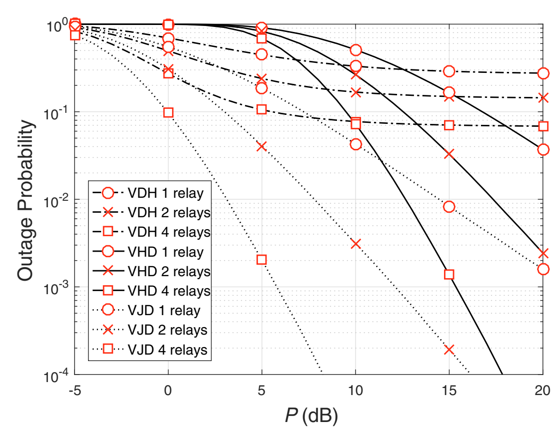

Fig. 6. Outage probability for the different schemes as a function of transmit power P varying the number of relay nodes.

performance of all schemes improves with the increment in the number of relay nodes. With four relays, an outage probability of 2×10^{-3} is obtained with $P = 5$ dB for the VJD method, while for the VHD scheme, the same probability is obtained with $P = 14$ dB. Finally, an outage probability of 3×10^{-2} is obtained with only one relay in the VJD scheme, while four relays are necessary for the VHD scheme.

5. CONCLUSIONS

In this paper the use of full-duplex nodes is evaluated with the objective of increasing the performance of a vehicular ad hoc network. Moreover, a selection relay scheme for the full-duplex vehicular ad-hoc network is proposed. Assuming Nakagami-m fading, we evaluated three different scenarios of vehicular networks in terms of outage probability. The VJD method performs better than the VHD and non cooperative schemes in terms of outage probability, even in the presence of self-interference. Furthermore, the VJD scheme can achieve the same value of outage probability with lower transmit power and with small number of relays when compared with the VHD scheme, even when a sub-Raylegh channel is considered.

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