Cross-Layer Design Based Transmit Antenna Selection for Vehicular Ad-hoc Networks

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Abstract. The wide range of applications in Vehicular Ad-hoc NETworks (VANETs) make vehicles connected all along the trip. For reasons of security or leisure, the connected vehicles ask frequently to establish connection in the network. Due to the high request for access to the channel, some vehicles could be temporarily blocked from sending or receiving data. In this paper, we are interested in minimizing the vehicles blocking effect and in improving the throughput in VANET by implementing a cross-layer design (PHY/MAC) based on transmit antenna selection jointly with a dedicated MAC protocol. We show a significant performance improvement of the throughput in the network.

Keywords: Cross-layer design, multiple-input multiple-output (MIMO), ZF-BLAST detector, transmit antenna selection, Vehicular Ad hoc NETworks (VANETs), throughput.

1 Introduction

In recent years, Vehicular Ad-hoc NETwork (VANET) is an emerging field of research for its importance in daily life. The researchers focused on a number of applications such as security to ensure a safe trip for the driver and passengers in the vehicle as well as entertainment to make the trip more enjoyable [1]. However, it is necessary, for better reliability that these various applications do not interfere with each other. Consequently, many users could be temporarily blocked under the medium access control (MAC) layer to avoid interference and collision.

Cross-layer approaches are a suitable solution to achieve better performance in vehicular environment [2]. Several cross-layer designs (PHY/MAC) have been proposed for VANETs [3–6], where one or several parameters of the physical layer are adapted to improve the output of the MAC layer and/or vice versa. In [3], authors proposed a cross-layer design based on modulation rate adaptation

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for vehicular networks in urban and downtown environments. In [4], a bit rate adaptation protocol that is responsive to rapidly varying channel conditions is proposed. Caizzone et al. proposed in [5] a mechanism that increases or decreases the transmission power based on the number of neighbors. In [6], Rawat et al. proposed another mechanism that focuses on adapting the transmit power based on the network density and the time during which a sender must wait to avoid a collision before reattempting to access the channel (contention window size).

On another point, multiple-input multiple-output (MIMO) systems have been proposed in VANETs to provide reliable transmission using space-time coding or spatial multiplexing techniques [7]. In particular, many algorithms of antenna selections have been proposed in the literature to improve the performance of VANETs [8,9]. In [8], authors proposed an antenna selection approach in vehicle-to-road (V2R) communications, where the road side uses all available antennas but the vehicle side chooses a subset of available antennas such that the link capacity becomes maximized. In [9], an antenna selection procedure for vehicle to vehicle communication systems in highways is proposed to achieve better capacity performance.

The cross-layer (PHY/MAC) approach has been associated with antenna selection in [10] with the aim to maximize the network throughput under the Automatic Repeat Request reQuest (ARQ) protocol as well as to solve the node blocking problem associated with the IEEE 802.11 MAC protocol. In this paper, we adapt the idea proposed in [10] to the VANETs environment, where vehicle-to-vehicle (V2V) data transmissions are carried out over time-varying channels due to vehicles mobility. We show, through simulations, that a significant improvement of the network throughput can be achieved compared to the case of no antenna selection and the conventional MAC protocol.

This paper is organized as follows. In Section 2, a cross-layer design based on transmit antenna selection as well as the proposed MAC protocol for V2V communications are introduced. The VANET simulation environment and the performance analysis of the proposed design are given in Section 3. Finally, some conclusions are drawn in Section 4.

Some notations are used in the following: matrices are represented as bold uppercase, vectors as bold lowercase and complex scalars as italic lowercase,$(.)^H$ is the conjugate transpose (Hermitian), $Q(.)$ is the complementary error function under Gaussian statistic, $r_{i,j}$ is the $(i,j)^{th}$ entry of the matrix $\mathbf{R}$, $q(.)$ is the modulation dependent quantizing function.

2 Cross-Layer Design and MAC Protocol for V2V Communications

In this Section, we first present a cross-layer design based on transmit antenna selection that maximizes the throughput by selecting the optimum subset of transmit antennas for each transmitter (Section 2.1). This cross-layer scheme is then jointly proposed with a MAC protocol that minimizes the transmission blocking effect inherent to the frequent request for connection in the network

(Section 2.2). The adaptation of the cross-layer scheme and the MAC protocol to the context of V2V communications in VANETs where the channel changes over time due to the vehicles mobility, is presented in Section 2.3.

2.1 Transmit Antenna Selection Approach

We consider spatial multiplexing (V-BLAST) over MIMO time-varying flat-fading channel with N_T transmit and N_R receive antennas ($N_R \geqslant N_T$). The ℓ^{th} received MIMO symbol is expressed by:

$$\mathbf{y}[\ell] = \mathbf{H}[\ell]\,\mathbf{\Pi}[\ell]\,\mathbf{x}[\ell]+\mathbf{n}[\ell], \tag{1}$$

where ℓ is the symbol time index, $\mathbf{y}[\ell] \in \mathbb{C}^{N_R \times 1}$ is the received signal vector, $\mathbf{H}[\ell] \in \mathbb{C}^{N_R \times N_T}$ is channel matrix, $\mathbf{x}[\ell] \in \mathbb{C}^{N_T \times 1}$ is the transmitted signal vector with $E[\mathbf{x}^H \mathbf{x}] = P_t$, $\mathbf{\Pi}[\ell] \in \mathbb{R}^{N_T \times N_T}$ is a permutation matrix corresponding to the detection ordering [11] and $\mathbf{n}[\ell] \sim \mathcal{CN}(0, \sigma^2 I_{N_R})$ is the circularly symmetric complex Gaussian noise vector. In order to simplify the presentation, the time index ℓ is removed in the following equations.

We assume the Zero-forcing decoding scheme at the receiver [12] through QR decomposition, and that the channel matrix is perfectly known at the receiver. The greedy QR-decomposition of the channel matrix is written as $\mathbf{H\Pi} = \mathbf{QR}$ where $\mathbf{Q} \in \mathbb{C}^{N_R \times N_T}$ is a unitary matrix and $\mathbf{R} \in \mathbb{C}^{N_T \times N_T}$ is an upper triangular matrix. The received signal is first multiplied by $\mathbf{Q}^H$, yielding $\tilde{\mathbf{y}} = \mathbf{Q}^H \mathbf{y} = \mathbf{Rx}+\tilde{\mathbf{n}}$. Hence, the i^{th} element of $\tilde{\mathbf{y}}$ is given by:

$$\tilde{y}_i = r_{i,i}\, x_i + \sum_{j=i+1}^{N_T} r_{i,j}\, x_j + \tilde{n}_i, \qquad i = 1, 2, ..., N_R. \tag{2}$$

The interference nulling and cancellation is done as follows: first, the symbol from the last antenna is detected and quantized to the nearest transmitted symbol $\hat{x}_{N_T} = q(\frac{\tilde{y}_{N_T}}{r_{N_T,N_T}})$. Then, the contribution of $\hat{x}_{N_T}$ is removed from $\tilde{\mathbf{y}}$ before the detection of x_{N_T-1} and so on. So we get:

$$\hat{x}_i = q\,(\frac{\tilde{y}_i - \sum_{j=i+1}^{N_T} r_{i,j}\, \hat{x}_j}{r_{i,i}}), \qquad i = 1, 2, ..., N_T - 1. \tag{3}$$

Considering packets of L MIMO symbols and the BPSK modulation scheme, as well as ignoring error propagation in the cancellation process, the packet error rate is:

$$PER = 1 - [\prod_{i=1}^{N_T} (1 - SER_i)]^{L/N_T}, \tag{4}$$

where SER_i and γ_i are the symbol error rate and the instantaneous signal-to-noise ratio at the i^{th} received antenna given by (5) and (6), respectively.

$$SER_i = Q(\sqrt{2\,\gamma_i}), \qquad i = 1, 2, ..., N_T. \tag{5}$$

$$\gamma_i = \frac{r_{i,i}^2 \, P_t}{N_T \, \sigma^2}, \qquad i = 1, 2, ..., N_T. \tag{6}$$

For all possible subsets of $K \leq N_T$ transmit antennas, $K \in \{1, 2, ..., N_T\}$, the associated throughput, which is given by (7) and (8) for the Go-Back-N protocol with a window size W and the Selective-Repeat protocol [13] respectively, is first evaluated by the receiver based on the knowledge of $\mathbf{H}$. Then, the receiver informs the transmitter about the antennas subset which provides the highest throughput (for this purpose, we assume an error-free feedback channel).

$$\eta(GBN) = K \times (1 - PER)/[1 + (W - 1) \times PER], \tag{7}$$

$$\eta(SR) = K \times (1 - PER). \tag{8}$$

2.2 MAC Protocol

In this section, we provide a quick presentation of the MAC protocol originally proposed in [10], adapted to our V2V context. This protocol aims at reducing the blocking effect which appears in IEEE 802.11p MAC protocol when two (or more) transmitters want to transmit simultaneously while being in the same transmission range: simultaneous transmissions have to be forbidden in order to prevent the vehicles from interfering with each other.

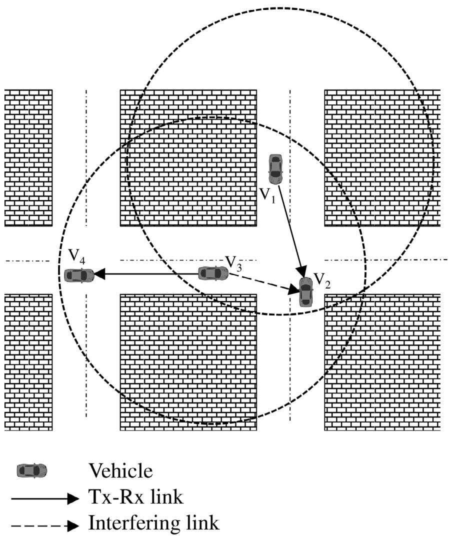

Fig. 1. An example of a four vehicles topology

We consider a typical V2V network topology as depicted in Fig. 1, where the vehicles V_1 and V_3 want to transmit data to the vehicles V_2 and V_4 respectively. Circles around V_1 and V_3 represent their radio range. Supposing that V_1 is the first to access the channel, it sends a transmission request to V_2. When V_2 receives the transmission request, it calculates the throughput over different subsets of transmit antennas and saves this information in a sorted list AS[1] with the identity of the corresponding antennas (this list is created for each transmission request and updated only by the receiver). Then, V_2 sends its AS list to V_1 which informs all neighboring vehicles (i.e., V_2 and V_3 in this case) about the identification of the antennas chosen for transmission, noting that when a transmitter receives an AS list from its neighbors, it transmits the list to its receiver. The antenna selection process is also repeated between V_3 and V_4. At this stage, the handshake between the vehicles V_1, V_3 and V_2, V_4, respectively is finished.

As seen in the scenario, V_3 is a potential interferer to V_2, which would result in a blocking effect under the classical 802.11 MAC layer. In order to avoid this effect, the MAC protocol in this paper leverages the interference cancellation ZF-BLAST procedure described in Section 2.1. However, to make the interference cancellation possible, the sum of the number of transmit antennas selected by each receiver should not exceed the number of receive antennas N_R. We will refer to this assumption as the *Antenna quantity restriction hypothesis*. In order to ensure this hypothesis, V_2 checks whether the number of selected antennas by itself and by the neighboring vehicle V_4 does not exceed N_R. If the hypothesis is not satisfied, V_2 selects another antennas combination from its AS list by taking into account the AS lists of the neighboring vehicles (i.e. V_4). When the *Antenna quantity restriction hypothesis* is reached, V_2 apprises V_1 of the final list of transmit antennas chosen for the transmission between them. Finally, V_1 updates its AS list and informs its neighboring vehicles.

At this time, all vehicles are ready to transmit their data through the adequate subsets of transmit antennas. Each transmitting vehicle starts transmitting its data and each receiving vehicle extracts the desired packet using the ZF-BLAST detector. Note that when packets do not reach the receiver they are re-transmitted using the GBN protocol or the SR protocol, otherwise a reception confirmation acknowledgment is sent to the transmitter.

2.3 Cross-Layer Design Steps in V2V Communications

In this section, we explain how the technique developed in section 2.1 and 2.2 can be adapted to a V2V communication context where the channel changes over time. Note that we limit ourselves to single-hop V2V communications. The time-varying character of the channel is expressed by the maximum Doppler shift, which is proportional to the vehicles speed. It is given by $f_{\mathcal{D}} = \frac{\mathcal{V}_r}{\lambda}$, where $\mathcal{V}_r$ is the relative velocity between the transmitter and the receiver and $\lambda = \frac{c}{f}$ is the wavelength, where c is the speed of light and f is the wave's frequency. Note that the channel remains stationary for a coherence time $T_c \approx \frac{1}{f_{\mathcal{D}}}$ [14].

[1] Antenna Selection.

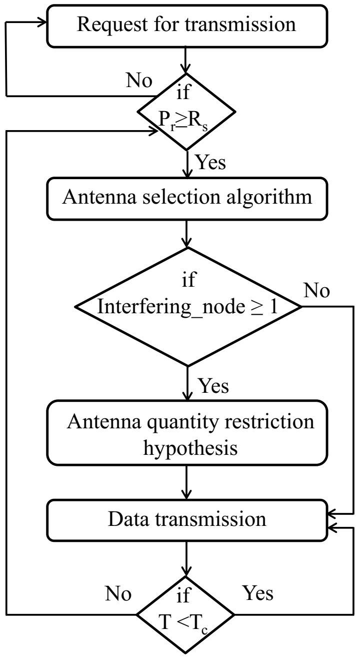

Fig. 2. Organizational structure of the cross-layer design

The different stages of the proposed cross-layer scheme are depicted in Fig. 2. To explain how the algorithm works, let us denote (V_T, V_R) a pair of transmitting and receiving vehicles. When V_T requests to establish a connection with V_R, then if V_R is not in V_T's transmission range, the power at the reception is not sufficient to receive the request for packet transmission. In this case, if V_T does not receive any response from V_R, it considers that the connection between them is impossible and it seeks for another potential receiver. However, if V_T and V_R are within the same radio range, V_R applies the antenna selection approach and ensures that the *Antenna quantity restriction hypothesis* is verified, knowing that V_R can find its neighbors which also ask to transmit data, from the AS lists received (from V_T and its neighbors). When V_R chooses its final list AS, it forwards it to V_T and its neighbors.

Finally, V_T is ready to transmit data during a coherence period T_c. After that, the receiver V_R should look for a new subset of transmit antennas according to a new channel estimation. Furthermore, V_R must verify whether it is still in V_T's radio range; if yes, it selects a new antennas subset; if not, the transmission between V_T and V_R is stopped (note that after each T_c the distance between the transmitter and the receiver does not change significantly).

3 Performance Analysis of the Cross-Layer Design

3.1 Simulation Environment

In order to evaluate the performance of the proposed approach in a VANET environment, we consider 20 vehicles which are randomly distributed in a $100m \times 100m$ area (i.g. downtown) and which drive at a constant speed (40 km/h) in predictable roads as shown in Fig. 3. In addition, we assume that all the vehicles have the same transmit power P_t and the same receiver sensitivity R_s. The signal propagation follows a path-loss model given by :

$$P_L = \frac{(4\pi)^2 d^\alpha}{\lambda^2}, \tag{9}$$

where d is the distance between the transmitter and the receiver and α is the path loss exponent. The average received power can be expressed as:

$$P_r = P_t + G_t + G_r - 10\log_{10}(P_L), \tag{10}$$

where G_t and G_r are the antenna gains of the transmitting and receiving antennas, respectively. The radio range, R, depends on the environment between the transmitter and receiver, as well as the receiver sensitivity R_s. It is defined as the distance at which $P_r = R_s$, that is:

$$R = \left(\frac{P_t\, G_t\, G_r\, \lambda^2}{(4\pi)^2 R_s}\right)^{1/\alpha}. \tag{11}$$

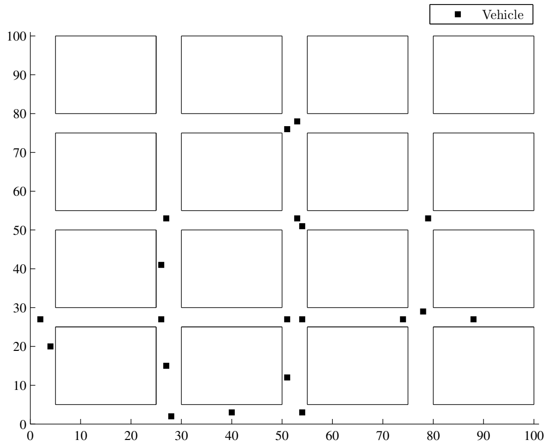

Fig. 3. Vehicle mobility scenario

We assumed that all vehicles in the simulated area will emit or receive information over Rayleigh fading channels during a simulation time T_s, as long as the power at the reception is sufficient to properly receive data. During T_s, some vehicles may leave the simulated area. In this case, we suppose that the transmission between the receiver and the transmitter is stopped.

In [10], authors neglect the interference radiated at a distance greater than R from the transmitter (for such a distance the cross-layer scheme is not realized). The focus of this work is more realistic since we also evaluate the effect of the interference form vehicles outside the radio range. The instantaneous signal-to-interference-plus-noise ratio (SINR) is expressed by:

$$\xi_i = \frac{r_{i,i}^2 \, P_{r_i}}{\sum_{j=1}^{N} P_{ij} + \sigma^2}, \qquad (12)$$

where P_{r_i} is the received power at the i^{th} antenna and N is the number of interfering vehicles outside the radio range of i and P_{ij} is the strength of the received interference from j to i.

3.2 Simulation Results

We studied the network performance in terms of throughput vs. input signal-to-noise ratio P_t/σ^2. The simulation parameters used in this paper are shown in Table 1. The simulation is run 30 times with each time a new random topology realization, and the throughput is averaged over the number of simulation and the number of V2V-links. Fig. 4 shows the average throughput per single-link (V2V) according to the proposed approach. In order to evaluate the results, we also plot the throughput for SR without antenna selection using the classical IEEE 802.11p MAC protocol. The throughput given without antenna selection is lower than those given by the cross-layer scheme for SR and GBN. We can also note that the throughput for SR is slightly higher than for GBN due to the frequent packet error when employing GBN.

At low SNRs the antenna selection approach tends to choose the minimum number of transmit antennas. However, at high SNRs, the optimal subset consists in all available transmit antennas. But to satisfy the *Antenna quantity restriction hypothesis* and allow more nearby transmissions, vehicles are forced to use a less than optimal number of antennas. This fact reduces the throughput of a single-link (V2V), but increases the average throughput of the network by giving the opportunity to other vehicles to communicate.

It should be noted that various factor affect the overall throughput of the network including the number of antennas N_T, the radio range area and the network density. The latter is due to the *Antenna quantity restriction hypothesis* which limit the maximum number of simultaneously transmitting vehicles within the same radio range to be N_R. The proposed cross-layer scheme associated with MAC protocol solves partially the problem, and is more efficient in low density networks. Nevertheless, the proposed protocol remains more efficient than the conventional IEEE 802.11p MAC protocol also in dense networks.

Table 1. Simulation Parameters

Frequency	f	5.9 GHz
Simulation Time	T_s	50 s
Number of Simulations		30
Number of Nodes		20
Transmitter Power	P_t	30 dBm
Receiver Sensitivity	R_s	-90 dBm
Transmitting Antennas Gain	G_t	0 dBi
Receiving Antennas Gain	G_r	0 dBi
Path Loss Exponent	α	3
Area		10 km^2
Velocity	$\mathcal{V}$	40 km/h
Symbol Duration		8 μs
Frame Length	L	180 BPSK symbols
Coherence Time	T_c	20 ms
Network Configuration		Single hop
ARQ Protocol		GBN or SR
Go-Back-N window size	W	4

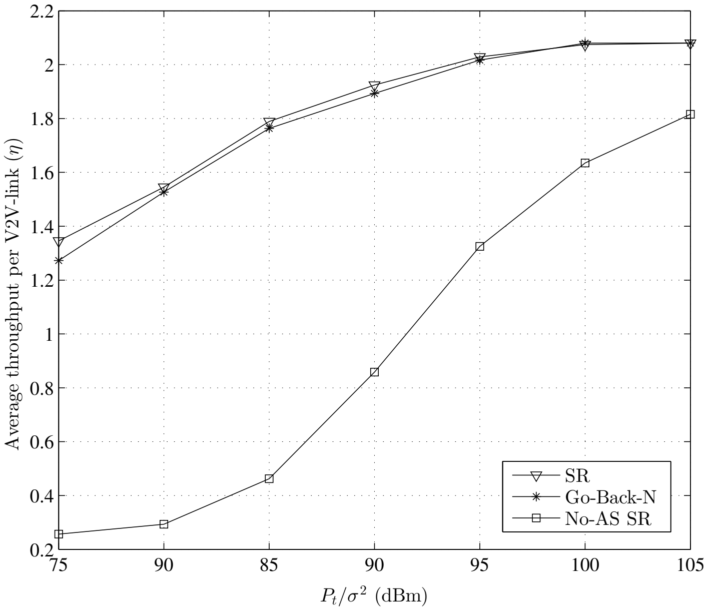

Fig. 4. Throughput performance in 4×4 - MIMO Rayleigh fading channel, ignoring interference

The results of Fig. 4 do not consider the residual interference of the equation (12). Fig. 5 shows the performance of the proposed cross-layer approach, in terms of throughput, in both cases: without considering the interference (without Int.) and with taking into account the interference (with Int.). As depicted, the curves are almost superimposed indicating low power interference coming from distant neighboring in this environment. One might say that, despite the interference that was ignored in the first simulations, the throughput gain remains quasi-identical. The results can only strengthen the conclusions drawn previously.

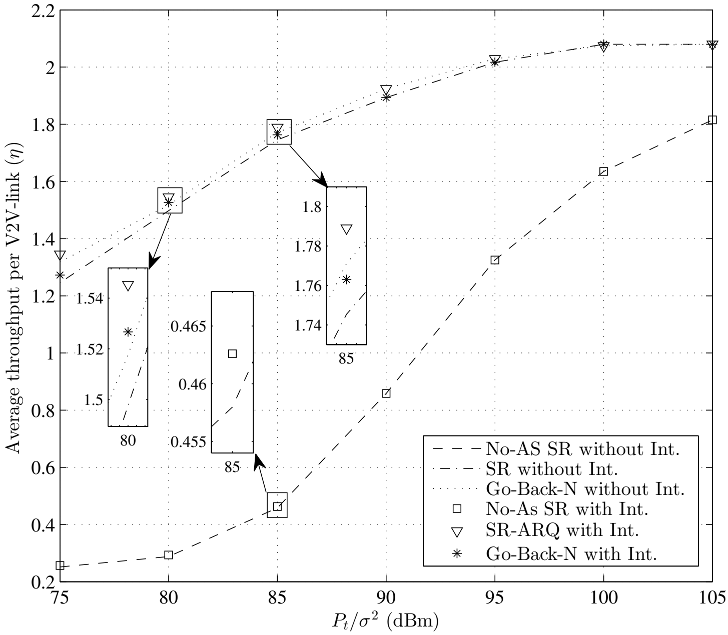

Fig. 5. Throughput comparison with and without taking into account the interference form vehicles outside the transmitter radio range, in a 4×4 - MIMO Rayleigh fading channel

4 Conclusion

In this paper, we investigated the performance of a cross-layer design based on a transmit antenna selection at the receiver side and an associated MAC protocol in VANETs. We showed a large throughput gain using the mixture between the antenna selection approach and the proposed MAC protocol compared to the case of no antenna selection jointly with the classical IEEE 802.11p MAC protocol which is not resilient against the node blocking problem. Similarly, we showed that despite the interference that a receiver may suffer from neighboring outside its radio range, this approach is effective in terms of throughput.

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