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Abstract

This paper investigates the performance of vehicle platoon intra-communications in the presence of node relaying cooperation. In the proposed scenario, all nodes are allowed to relay the signals of other entities towards the next/final destination. This improves channel conditions by mimicking large scale (virtual) antennas thus achieving \emphcooperative diversity. The scenario considers a platoon of J vehicles assisted by a set of relay nodes. These potential relays include the same vehicles of the platoon, as well as base stations (BSs) and/or road-side units (RSUs). The objective is to evaluate the delay experienced by a packet transmitted by the leader towards all the vehicles of the formation. Each vehicle and each relaying-able node is considered to relay the correctly received message to the remaining entities, but most importantly to all the vehicles of the platoon. We consider that if a given transmission attempt is not successfully received by all entities, then the transmitter and relays with a correct copy of the transmission engage in a persistent retransmission scheme that stops only when the packet has been correctly received by all the vehicles. Instantaneous and ideal feedback is used in all calculations. The criterion used to consider a packet correctly received by the destination is that the instantaneous signal-to-interference-plus-noise ratio (SINR) surpasses a reception threshold. It is assumed that the destination nodes store a copy of all the received transmissions over consecutive time slots and antenna elements. These signals are processed using ideal maximum ratio combining (MRC) to obtain a more reliable copy of the information (i.e. using time and/or retransmission diversity). Multiple antennas are used by all the vehicles and nodes of the network under analysis. Novel spatial and temporal correlation tools are introduced in the channel model with Rice fading statistics and co-channel interference. Results suggest that RSUs can considerably reduce delay of platoons with large numbers of vehicles or large distances between elements. The degree of improvement also depends on channel correlation and the number of co-located antennas.

Cooperative Vehicle Platoon Intra-communications over Space-Time Correlated Rice fading Channels with co-channel Interference

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***Abstract*—This paper investigates the performance of vehicle platoon intra-communications in the presence of node relaying cooperation. In the proposed scenario, all nodes are allowed to relay the signals of other entities towards the next/final destination. This improves channel conditions by mimicking large scale (virtual) antennas, thereby achieving the concept of *cooperative diversity*. The scenario considers a platoon of J vehicles assisted by a set of relay nodes. These potential relays include the same vehicles of the platoon, as well as base stations (BSs) and/or road-side units (RSUs). The objective is to evaluate the delay experienced by a packet transmitted by the leader towards all the vehicles of the formation. Each vehicle and each relaying-able node is considered to relay the correctly received message to the remaining entities, but most importantly to all the vehicles of the platoon. We consider that if a given transmission attempt is not successfully received by all entities, then the transmitter and relays with a correct copy of the transmission engage in a persistent retransmission scheme that stops only when the packet has been correctly received by all the vehicles. Instantaneous and ideal feedback is used in all calculations. The criterion used to consider a packet correctly received by the destination is that the instantaneous signal-to-interference-plus-noise ratio (SINR) surpasses a reception threshold. It is assumed that the destination nodes store a copy of all the received transmissions over consecutive time slots and antenna elements. These signals are processed using ideal maximum-ratio combining (MRC) to obtain a more reliable copy of the information (i.e. using time and/or retransmission diversity). Multiple antennas are used by all the vehicles and nodes of the network under analysis. Novel spatial and temporal correlation tools are introduced in the channel model with Rice fading statistics and co-channel interference. Results suggest that RSUs can considerably reduce delay of platoons with large numbers of vehicles or large distances between elements. The degree of improvement also depends on channel correlation and the number of co-located antennas.**

I. INTRODUCTION

The number of objects connected to the cloud is growing dramatically. The high mobility of these "things" make wireless technology a key ingredient in the *Internet-of-things* (IoT). Wireless is synonymous with flexible infrastructure, pervasiveness, and over-the-air management. This has paved the way for new and more challenging applications [1].

A new generation of industrial connectivity has been recently emerging. Applications such as autonomous vehicles require high quality of service, safe-critical control, wide-geographical coverage, and ultra-low latency [1]-[3]. *Vehicle platoons* are formations of coordinated autonomous or semi-autonomous cars that make decisions as a single entity. Vehicles of a platoon usually have similar routes or destinations. This makes traffic-flow and network management more efficient, as platoons can reduce processing complexity by offloading functionalities to lead cars and/or edge/cloud servers. Platoons are thus the basis of future automated e-transportation systems (including, trucks, fleets, freight-liners, etc). One key enabler of platoons is the coordination and reliable (real-time) exchange of information between contiguous cars or between cars and edge/cloud servers. Simulations have shown the advantages of platoons over single autonomous vehicles in urban environments [5][6]. Propagation models have been largely studied for platoon communications considering the reflections on the floor or other nearby obstacles [7]-[9]. Queuing effects on the delay distribution of platoon communications over uncorrelated channels with link adaptation have been presented in [10]. Experimental MAC (medium access control) protocols for platoons have been investigated in [11].

This paper addresses the calculation of the delay distribution of a cooperative vehicle platoon. All the nodes (including vehicles of the platoon, base stations or road side units) are able to relay the information of source nodes towards the rest of the entities. This has been called cooperative diversity (see [12][14]). We measure the latency experienced by a packet transmitted by the lead car of the platoon towards all the elements of the platoon in the event of a high priority message such as an "emergency brake" signal. This means all entities stop their transmissions and focus exclusively on transmitting, receiving and/or relaying the message from the leader. It is assumed that the packet is processed by all relaying-able nodes, and those with a correct copy proceed to re-transmit it to the remaining nodes (if necessary). This process is repeated until the packet reaches the last element of the platoon. It is also assumed that immediate retransmissions are enabled in case the packet is not correctly received by the destination nodes (*ideal and instantaneous feedback*). Correlation between retransmissions is considered, as well as spatial correlation using an extension of the lineal correlation channel model presented in [15]-[18]. This allows us to introduce large numbers of antennas at the road side units (RSUs), thus mimicking the performance of 5G links to assist the communication of the platoon. Co-channel interference is also assumed to emulate multiple platoon scenarios. All nodes are assumed to use a multiple antenna transceiver over space-time correlated Rice channels. The contributions of this paper are as follows:

1) Space-time correlation modelling of cooperative vehicle platoon communications targeting ultra-low latency.
2) Evaluation of the trade-off between using a base station (5G-like) to assist in the relaying of information inside the platoon or using multi-hop technology between the vehicles of the platoon.
3) Evaluation of more accurate wireless parameters for platoons, for example line- and non-line-of-sight conditions via Rice distribution with different Rice factors.
4) This work includes the effects of reflections on the floor between contiguous vehicles of the platoon.

The remainder of this paper is organized as follows. Section II describes the system model and assumptions. Section III consider the statistics of the received signal distribution at the different nodes of the network, while Section IV investigates the expressions for latency of a packet to be received by all the elements of the platoon. Section V presents sketches of the statistics of latency for different scenarios. Finally, Section VI presents the conclusions of the paper.

Notation: vector (e.g. $\mathbf{x}$) and matrix variables (e.g.$\mathbf{A}$) are denoted by bold lower and upper case letters, respectively. $f_{X|Y}(x|y)$, $F_{X|Y}(x|y)$ and $\bar{F}_{X|Y}(x|y)$ denote, respectively, the probability density (PDF), cumulative distribution (CDF), and complementary cumulative distribution functions (CCDF) of the random variable X conditioned on the random variable (r.v.) Y. $x \sim \mathcal{CN}(\mu, \gamma)$ denotes that x is a circular complex Gaussian r.v. with mean μ and variance γ. $(\cdot)^H$ and $(\cdot)^T$ are the transpose and Hermitian vector transpose operators, respectively. $\Psi_{X|Y}(i\omega)$ is the characteristic function (CF) of the random variable X conditioned on a specific value of the r.v. Y, where ω is the frequency domain variable in radians, and $i = \sqrt{-1}$. $\mathbf{I}_n$ denotes the identity matrix of order n, $\mathbf{0}_n$ and $\mathbf{1}_n$ denote the column vectors, respectively, of zeroes and ones of length n. $|\cdot|$ is the absolute value operator when applied to a scalar variable or the set cardinality operator when applied to a set variable. $E[\cdot]$ is the statistical average operator, while $E_X[\cdot]$ is the statistical average operator over the probabilistic space of the random variable X.

II. System model

A. Scenario description

Consider the vehicle platoon formation with a set $\mathcal{J} = \{1, 2, 3, \ldots, J\}$ of J vehicles depicted in Fig. 1 and a set $\mathcal{R} = \{0, 1, \ldots, R\}$ of R potential relays of information ($\mathcal{J} \subset \mathcal{R}$). The relay nodes can be constituted by the same vehicles of the platoon with a correct copy of the original information, base stations (BSs) of cellular infrastructure, road side units (RSUs) or even drones or other vehicles that can assist the communication of the platoon. Each vehicle is considered a network entity with the ability to initiate, terminate or relay communications to other entities. The main RSU or BS is assumed to have the relay index $j = 0$. The distance between any node j and node k is denoted by $d_{j,k}$.

Each node j is assumed to have a multiple antenna transceiver with M_j elements, with optimum processing based on maximum ratio combining (MRC) over space and time elements (perfect channel estimation). The channel between the

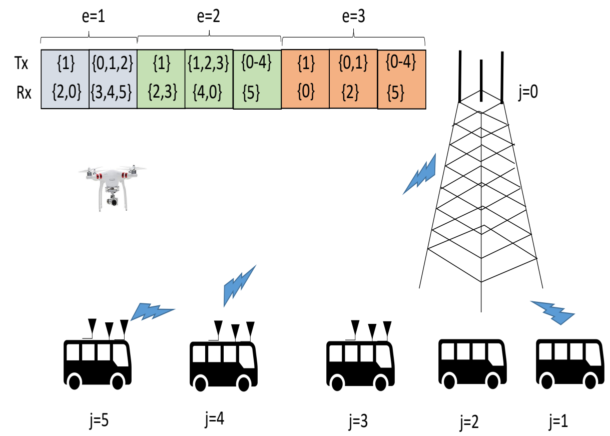

Fig. 1. Vehicle platoon network scenario with beam-forming.

mth antenna of node j and the nth antenna of node k in time-slot t is denoted by $h_{j,k}^{m,n}(t)$ and will be modeled as a circular complex Gaussian random variable with variance $\gamma_{j,k}^{m,n}$ and mean $\mu_{j,k}^{m,n}$: $h_{j,k}^{m,n}(t) \sim \mathcal{CN}(\mu_{j,k}^{m,n}, \gamma_{j,k}^{m,n})$. The Rice factor is thus defined as $\kappa_{j,k}^{m,n} = \frac{|\mu_{j,k}^{m,n}|^2}{\gamma_{j,k}^{m,n}}$. Channel variances will be calculated using a distance power model: $\gamma_{j,k}^{m,n} \sim (d_{j,k}^{m,n})^{-p}$, where p is the path-loss exponent. All calculations assume that the speed of the platoon formation does not impact the coherence time of the channel and the main parameters of the transmission system. All transmissions take place over the same bandwidth, but some protocol expressions can be adapted when the RSU or BS transmit in different frequency bands. The main variables used in this paper are listed in Table I.

The cooperative scheme takes place over a random number of attempts in order to correctly transmit a packet from the leader towards all the elements of the formation. The transmission period of each packet, defined as the number of time slots required to deliver a packet from the leader to all vehicles of the platoon, will also be called *epoch-slot* and its length will be denoted by the random variable l.

B. Protocol operation

This paper focuses on the evaluation of the statistics of latency of a packet at the head of the queue in the lead car to be transmitted towards all the remaining vehicles in the formation. The network is assumed to operate in time-slot synchronization. In each time-slot of a transmission period, the original packet is (re)transmitted by all the vehicles and relaying-able entities of the platoon that have a correct version of the original packet. It is assumed that all vehicles, (except the lead car) stop any of their current transmissions and are thus only advocated to the (re)transmission of the packet coming from the lead car. The transmission protocol assumes the packet is relayed sequentially by each vehicle or node with a correct version of the original transmission towards the remaining entities using a combination of space and time diversity.

The set of relay nodes with a correct version of the original transmission and that relay it to the remaining entities in

Algorithm 1: Algorithm cooperative retransmission diversity.

1) Set epoch slot indicator to zero $e = 0$
2) Initialize a new transmission period $e = e + 1$
3) Lead car broadcasts information to all entities in time slot $t = 1$.
4) Evaluate the set of nodes that correctly decode the information using SINR threshold: $\mathcal{T}_t = \{k|\Gamma_k(t) > \beta\}$.
5) Generate the set of relays for the next time slot: $\mathcal{R}_{t+1} = \{1, \mathcal{T}_t\}$
6) if $\mathcal{J} \subset \mathcal{R}_2$ then go back to step 2
7) New time slot of the current transmission period $t = t + 1$
8) Relays retransmit the original information
9) Go back to step 4

time slot t is denoted by $\mathcal{R}_t$. If the packet transmitted by the relaying-able entities in time slot t is not correctly received, then it is assumed that an immediate retransmission is requested from all terminals with a correct copy of the packet for time slot $t + 1$. All the copies of the signal transmitted and retransmitted are stored in the memory of the target entities, where they are processed to produce a more reliable copy of the original transmission. These steps are repeated continuously until the signal is correctly received by the destination, and eventually by all the vehicles of the platoon. While the retransmissions are assumed to occur instantaneously, all the results in this paper can be adapted to consider delay of the feedback channels. The main idea of the instantaneous retransmission diversity scheme proposed in this paper is to evaluate the ability of the wireless component to achieve the lowest possible latency of transmission. In this manner, it will be possible to estimate the performance of the physical layer algorithms to achieve values of latency that can be considered as ultra-low latency and thus be useful in autonomous driving scenarios. The algorithm for transmission and retransmission is also described in Table 1.

Consider the example in Fig. 1. The first time slot of the first epoch slot (denoted by $e = 1$) has the road side unit ($j = 0$) and the second vehicle ($j = 2$) to have correctly decoded the initial packet transmission from the lead car ($j = 1$). In the second time slot, the first two vehicles and the RSU transmit ($\mathcal{R}_2 = \{0, 1, 2\}$), allowing vehicles 3 to 5 to correctly decode the information. Finally, in the last two time slots a coalition of all the entities allows the final element of the platoon to receive the information from the leading vehicle in three time slots.

C. Signal model

The signal transmitted by node j is denoted by the vector variable $\mathbf{w}_j = [w_j(0), w_j(1), \ldots, w_j(M_j - 1)]^T$ of M_j QAM symbols to be transmitted across the M_j antennas of the node. The signal received by node k in time slot t from all the transmitters can be expressed as follows:

$$\mathbf{r}_k(t) = \sum_{j\in\mathcal{R}_t} \mathbf{H}_{j,k}(t)\mathbf{w}_j + \mathbf{v}_k(t) + g_k \mathbf{1}_{M_j}, \qquad (1)$$

TABLE I

LIST OF MAIN VARIABLES.

Variable	Meaning
$h^{m,n}_{j,k}(t)$	Channel between antenna m of terminal j and antenna m of terminal k in time slot t.
M_j	Number of antennas of node j.
e	Transmission interval indicator
l	Length of an Tx period
P_j	Tx Power terminal j
$\rho^{(k,\tilde{m},\tilde{n})}_{j,m,n}$	Correlation coefficient between the signal of antenna m in slot n with the signal of antenna $\tilde{m}$ in slot $\tilde{n}$
$\gamma_{j,k}$	Channel variance between node j and node k
σ^2_v	Noise variance
ν	Interference variance
β	Correct packet detection SINR threshold
$\Gamma_j(t)$	SINR of terminal j in time slot t
$\mathbf{w}_j$	precoded Signal transmitted by terminal j
$\mathbf{r}_{k,}(t)$	Rx Signal in antenna m
$\mathbf{v}_{k,n}(t)$	Noise vector in antenna m
N_{co}	Parameter of time correlation
M_{co}	Parameter for space correlation
$\mathcal{R}_t$	Set of relay and transmission nodes in time slot t

where $\mathbf{H}_{j,k}(t) = [h^{m,n}_{j,k}(t)]$ is the multiple antenna or MIMO (multiple-input multiple-output) matrix array channel, $\mathbf{v}_k(t)$ is the column vector of zero-mean complex circular Gaussian noise with co-variance matrix $\mathbf{I}\sigma^2_v$: $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}_{M_j}, \sigma^2_v\mathbf{I}_{M_j})$, where $\mathbf{0}_{M_j}$ and $\mathbf{I}_{M_j}$ are, respectively, the vector of zeros and the identity matrix of order M_j, σ^2_v is the noise variance, and g_k is the interference term modeled as $g_k \sim \mathcal{CN}(0, \nu)$ that is assumed to be invariant across a full transmission period.

Let us now consider that the transmitted symbol complies with the following power constraint: $E[\mathbf{w}^H_j\mathbf{w}_j] = P_j$, where $(\cdot)^H$ is the Hermitian vector transpose operator. The receiver processes the signals received by all the antennas. This paper assumes that the combination of Tx and Rx beam-forming achieves the maximum performance of diversity combining for the number of Rx and Tx channel pairs. This leads to the well-known formula for the *instantaneous* signal-to-interference-plus-noise ratio (SINR) of the MRC system considering perfect channel estimation:

$$\Gamma_k(t) = \frac{\sum_{j\in\mathcal{R}_j}\sum_{\tilde{t}=1}^{t}\sum_{m=1}^{M_j}\sum_{n=1}^{M_k}\tilde{P}_j|h^{m,n}_{j,k}(\tilde{t})|^2}{|g_k|^2 + \sigma^2_v}, \qquad (2)$$

where $\tilde{P}_j = \frac{P_j}{M_j}$. It is assumed that a packet is correctly received by the intended destination is the instantaneous SINR exceeds the reception threshold β:

$$\Pr\{\Gamma_k(t) > \beta\} = \Pr\{\text{packet correctly received by vehicle } k \text{ in time-slot } t\}. \qquad (3)$$

This assumption is mainly intended to activate the retransmission of packets. In practice, packets need to be processed and after hard symbol decision decoding it is possible to evaluate if the packet has errors or not via a redundancy check or other mechanisms. Packets that still contain errors after this stage are considered to be handled by upper layer error control.

For convenience, all channel variables will be expressed using a linear correlation model similar to the one used in [20], which in our context will be written as follows:

$$h_{j,k}^{m,n}(t) = \mu_{j,k}^{m,n} + \alpha_{j,k}^{m,n}(t),$$

where

$$\alpha_{j,k}^{m,n}(t) = \sqrt{1-\xi_{j,k}^{m,n}(t)}Z_{j,k}^{m,n}(t) + \sqrt{\xi_{j,k}^{m,n}(t)}G_{j,k}, \quad (4)$$

where the variables $Z_{j,k}^{m,n}(t)$, $G_{j,k}$ are identically and independently distributed (*i.i.d.*) zero-mean complex circular symmetrical Gaussian random variables with variance $\gamma_{j,k}$. Note that the previous correlation model complies with $E[\alpha_{j,k}^{m,n}(t)\alpha_{j,k}^{\tilde{m},\tilde{n}}(\tilde{t})] = \gamma_{j,k}\rho_{j,m,n}^{k,\tilde{m},\tilde{n}}(t,\tilde{t})$, where $\rho_{j,m,n}^{k,\tilde{m},\tilde{n}}(t,\tilde{t}) = \xi_{j,k}^{m,n}(t)\xi_{j,k}^{\tilde{m},\tilde{n}}(\tilde{t})/\gamma_{j,k}$ is the correlation coefficient between the signals of antenna m and antenna $\tilde{m}$ of terminal j, antenna n and antenna $\tilde{n}$ of terminal k in time slots t and $\tilde{t}$. The correlation model employed here captures asymmetrical correlation scenarios with a reasonable theoretical tractability and complexity. In addition, this theoretical correlation model can be fitted to realistic values of correlation in the parameters ξ. The objective of this paper is to exploit the theoretical tractability advantage of this model to predict the performance of cooperative platoon systems with space time correlation. The values of the correlation parameters ξ can also be approximated by the following formula:

$$\xi_{j,k}^{m,n}(t) = e^{i\frac{2\pi n}{M_{co}}}e^{i\frac{2\pi m}{M_{co}}}e^{i\frac{2\pi t}{N_{co}}},$$

where N_{co}, and M_{co} can be adjusted for different temporal and spatial statistics of the channel correlation. Note that with this definition, the correlation coefficient becomes: $\rho_{j,m,n}^{k,\tilde{m},\tilde{n}}(t,\tilde{t}) = e^{i\frac{2\pi(n-\tilde{n}]}{M_{co}}}e^{i\frac{2\pi(m-\tilde{m})}{M_{co}}}e^{i\frac{2\pi(t-\tilde{t})}{N_{co}}}$. The LOS component can be obtained using the two-ray model to consider reflections on ground:

$$\mu_{j,k}^{m,n} = \frac{\sqrt{\gamma\kappa}}{4\pi}\left(\frac{e^{2\pi i\tilde{d}_{j,k}^{m,n}}}{\tilde{d}_{j,k}^{m,n}} + \Gamma\frac{e^{2\pi i\bar{d}_{j,k}^{m,n}}}{\bar{d}_{j,k}^{m,n}}\right),$$

where $\tilde{d}_{j,k}^{m,n} = d_{j,k}^{m,n}/\lambda$ and $\bar{d}_{j,k}^{m,n} = d_{j,k}^{m,n}/\lambda$ are, respectively, the direct and ground reflected electrical distances between antenna m in vehicle j and antenna n in vehicle k. Γ is the reflection coefficient over asphalt and λ is the operational wavelength of the wireless carrier.

III. STATISTICS OF CORRECT SIGNAL RECEPTION

In this section we deal with the evaluation of the probability of correct reception of the signal transmitted in different links and using the cooperative algorithm described in the previous sections. Let us substitute the correlation model described by (4) in the expression of the SINR in (2):

$$\Gamma_k(t) = \frac{\psi_k(t)}{I_k + \sigma_v^2}, \quad (5)$$

where

$$\psi_k(t) = \sum_{\tilde{t}=1}^{t}\sum_{j\in\mathcal{R}_t}\sum_{m=1}^{M_j}\sum_{n=1}^{M_k}\tilde{P}_j\left|\mu_{j,k}^{m,n} + \sqrt{1-\xi_{j,k}^{m,n}(\tilde{t})}Z_{j,k}^{m,n}(\tilde{t})\right.$$
$$\left. + \sqrt{\xi_{j,k}^{m,n}(\tilde{t})}G_{j,k}\right|^2, \quad (6)$$

and $I_k = |g_k|^2$ is the interference term. Consider now the previous expression conditional on an instance of the random variables $G_{j,k}$. Under this assumption, the expression in (6) becomes the summation of the squares of Gaussian complex variables $\sum\sqrt{\tilde{P}_j(1-\xi_{j,k}^{m,n}(\tilde{t}))}Z_{j,k}^{m,n}(\tilde{t})$ each one with a mean given by $\sqrt{\tilde{P}_j}\mu_{j,k} + \sqrt{\tilde{P}_j\xi_{j,k}^{m,n}(\tilde{t})}G_{j,k}$. Therefore, the variable $\psi_k(t)$ conditioned on an instance of random variables $G_{j,k}$ has a non-central chi-square distribution with n degrees of freedom. The conditional characteristic function (CF) of $\psi_k(t)$ can be thus written as (see [19] for details of chi-square distributions):

$$\Psi_{\psi_k(t)|G_{j,k}}(i\omega) = \prod_{\tilde{t},j\in\mathcal{R}_t,m,n}\frac{1}{1-i\omega\tilde{\gamma}_{j,k}^{m,n}(\tilde{t})}e^{u_{j,k}(\tilde{t})},$$

where $\tilde{\gamma}_{j,k}^{m,n}(\tilde{t}) = \tilde{P}_j|1-\xi_{j,k}^{m,n}(\tilde{t})|\gamma_{j,k}$,

$$u_{j,k}(\tilde{t}) = \sum_{\tilde{t}=1}^{t}\sum_{m=1}^{M_j}\sum_{n=1}^{M_k}\delta_{j,k}^{m,n}(\tilde{t})\left|\mu_{j,k}^{m,n} + \sqrt{\xi_{j,k}^{m,n}(\tilde{t})}G_{j,k}\right|^2, \quad (7)$$

and $\delta_{j,k}^{m,n}(\tilde{t}) = \frac{i\omega}{1-i\omega\gamma_{j,k}^{m,n}(\tilde{t})}$. The unconditional distribution can be obtained by averaging over the PDF of the random variables $G_{j,k}$. In this paper we conduct the averaging process using numerical methods and simulations to obtain the relevant reception statistics. However, the models allow for closed-form expression derivation.

Let us now rewrite the reception probability expression in (3) using the explicit expression for the SINR in (5) as follows:

$$\Pr\{\Gamma_k(t) > \beta\} = \Pr\left\{\frac{\psi_k(t)}{I_k+\sigma_v^2} > \beta\right\} =$$
$$\Pr\{\psi_k(t) > \beta(I_k+\sigma_v^2)\}$$
$$= \Pr\{\psi_k(t) - \beta I_k > \beta\sigma_v^2\} = \Pr\{\theta_k(t) > \beta\sigma_v^2\}. \quad (8)$$

The characteristic function considering interference can be therefore expressed as follows:

$$\Psi_{\theta_k(t)}(i\omega) = \Psi_{\psi_k(t)}(i\omega)(1+i\omega\nu)^{-1}.$$

The back-transform can be calculated as follows [19]:

$$F_{\theta_n}(y) = \int_{i\omega}\Psi_{\theta_n}(i\omega)e^{i\omega y}d(i\omega),$$

which yields the expression for the statistics of correct packet reception.

IV. Latency statistics

Each packet transmission is considered as correctly received if and only if the instantaneous SINR if above the designed threshold β. If this is not achieved an immediate retransmission is provided by the source vehicle and the relay nodes. Retransmssions are stored in memory and combined to improve SINR conditions. The probability mass function of this number of attempts for a packet to be correctly received can be therefore written as the average of all possible sequences of sets of relays or nodes with a correct version of the original transmission in consecutive time slots ($\mathcal{R}_1, \mathcal{R}_2, \ldots, \mathcal{R}_n$) that end with correct reception for the vehicles of the platoon ($\mathcal{J} \subseteq \mathcal{R}$). This can be written as follows:

$$\Pr\{l = q\} = \sum_{\mathcal{R}_q; \mathcal{J} \subseteq \mathcal{R}_q, \mathcal{J} \not\subseteq \mathcal{R}_u, u<q} q \Pr\{\mathcal{R}_1 \subseteq \mathcal{R}_2 \subset, \ldots, \mathcal{R}_q\},$$

where

$$\Pr\{\mathcal{R}_1 \subseteq \mathcal{R}_2 \subseteq, \ldots \mathcal{R}_q\}$$
$$= \prod_{u \leq q, k \in \mathcal{R}_u} \Pr\{\Gamma_k(u) > \beta | \Gamma_k(u-1) < \beta\}$$
$$= \prod_{u \leq q, k \in \mathcal{R}_u} F_{\Gamma_k(u)|\Gamma_k(u-1)<\beta}(\beta).$$

This expression denotes the joint probability of correct reception of different nodes in the network at different time slots conditional on the incorrect reception in the previous attempts. It can be shown using Bayes- theorem that

$$F_{\Gamma_k(q)|\Gamma_k(q-1)<\beta}(\beta) = \frac{F_{\Gamma_k(q)}(\beta)}{F_{\Gamma_k(q-1)(\beta)}} \quad (9)$$

Therefore we can express the CCDF (complementary cumulative distribution function) as follows:

$$\bar{F}_{\Gamma_k(q)|\Gamma_k(q-1)<\beta}(\beta) = \frac{F_{\Gamma_k(q-1)}(\beta) - F_{\Gamma_k(q)}(\beta)}{F_{\Gamma_k(q-1)}(\beta)}$$

By using the expression in (8) we obtain:

$$\bar{F}_{\Gamma_k(q)|\Gamma_k(q-1)<\beta}(\beta) = \frac{F_{\theta_k(q-1)}(\beta\sigma_v^2) - F_{\theta_k(q)}(\beta\sigma_v^2)}{F_{\theta_k(q-1)}(\beta\sigma_v^2)}$$

V. Results

Consider a platoon scenario with a fixed number of vehicles in the platoon ($N = 6$), variable spacing from 5 to 20 meters, with a road side unit located at a variable distance of 30 and 60 meters from the center of the platoon (d_{rsu}). The number of antennas at the vehicles is also variable between $M_{veh} = 4$ and $M_{veh} = 8$ elements and the number of antennas at the road side unit is kept variable between the following values $M_{rsu} \in \{50, 150, 300\}$. The transmission power is also kept constant for all the entities of the network. The channel between contiguous vehicles uses a two ray model for the line-of sight component. An interference source is assumed in all simulations with 3dB power above noise background. The main parameters used in this section are listed in Table II.

The results for latency versus inter-vehicle distance are presented in Fig. 2 for a variable number of antennas at the RSU and at the vehicles with a fixed distance of the RSU to the center of the platoon equal to $d_{rsu} = 60m$. The results with a RSU distance set to $d_{rsu} = 30m$ is given in Fig. 3. It can be observed that the assistance of the road side unit only becomes relevant for distances close to the platoon, and for inter-vehicle distances that are relatively long. The correlation factors also affect the distribution but in a less evident manner. These effects grow with the number of antennas at the RSU. The number of antennas at the RSU also plays an important role in the latency gain of cooperative diversity. With these results it is possible to conclude that the assistance of the BS to intra-platoon communications is only relevant when the intra-platoon technology fails or is compromised, particularly when obstacles, shadowing, or too many vehicles are adopted in the platoon, or equally when the inter-vehicle distance is increased too much. The number of antennas at each vehicle also plays a role in improving the intra-platoon communication and reduce the advantages of using a BS as relay.

TABLE II
Simulation parameters.

Variable	Meaning	value
d_{veh}	Intra-vehicular distance	5-25 m
d_{rsu}	RSU distance	{30,60}
$\beta/(I+\sigma_v^2)$	Decoding threshold	0 dB
λ	Operational wavelength	10 cm
J	No. of vehicles	6
N_{co}	Temporal correlation factor	5,10
M_{co}	Spatial correlation factor	5,10
κ_{LOS}	Rice factor NLOS	-3 dB
κ_{NLOS}	Rice facor LOS	-20 dB
P_{rsu}	RSU Tx power	20 dBm
P_{veh}	Vehicle Tx power	3 dBm
η	Noise density	-120 dBm/Hz
BW	Bandwidth	100 MHz

VI. Conclusions

This paper has confirmed the benefits of using the concept of cooperative diversity in vehicle platoon intra-communications to reduce latency in space -time correlated channels. The results show that the increase of the number of antennas at the vehicles and at the road side unit contribute to reduce latency of the number of transmission time intervals that are necessary for a packet of the leader to be received successfully by all the elements of the platoon. The use of road side unit with large MIMO has proved to yield considerable reductions of latency, almost making it constant for any vehicle spacing distance and size of platoon. The effects of the number of antennas at the BS is more noticeable for inter-vehicle distances relatively higher and for platoons with large numbers of elements. On the contrary, when the distances are short between vehicles then the benefits of BS relaying are reduced.

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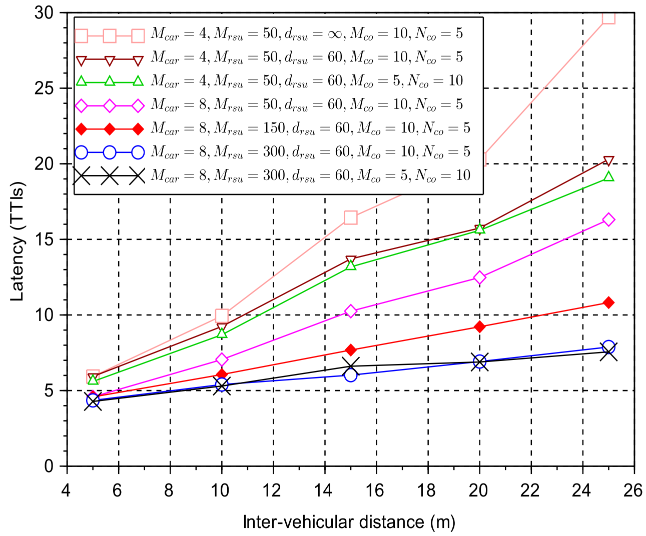

Fig. 2. Average Latency (D) vs distance between vehicles (d_{veh}) for a platoon formation with $d_{rsu}=60$ variable number of antennas at the RSU and at the vehicles of the platoon.

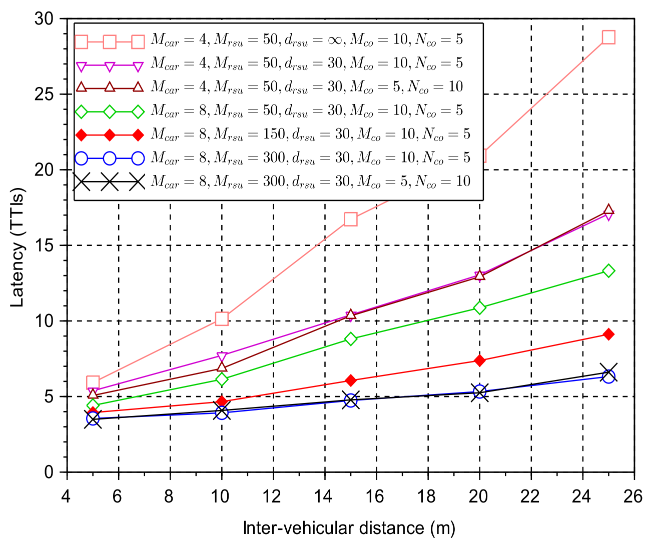

Fig. 3. Average Latency (D) vs distance between vehicles (d_{veh}) for a platoon formation with $d_{rsu}=30$ variable number of antennas at the RSU and at the vehicles of the platoon.

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