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On the performance of cooperative vehicular networks under antenna correlation at RSU

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A B S T R A C T

Vehicular communications is gradually becoming mature after decades of exciting developments and thriving advances. Resultantly, these advances have opened new possibilities for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications to meet the requirements of safety applications and future self-driving technologies. While performance limits of single link vehicular communications have been well analyzed in the literature, only incremental growth has been shown in the domain of multi-antenna communications. Another major concern is that the existing works mostly assume independent fading at the antennas mounted on road side unit (RSU), thus neglecting the impact of channel correlation. Our work addresses this issue by evaluating packet error probability for two renowned antenna correlation models i.e., constant correlation (CC) and exponential correlation (EC), under Nakagami-*m* fading. We also consider cooperation between intermediate vehicles to ensure reliable communication from the source vehicle to the RSU. More specifically, we derive closed-form expressions of packet error probability for three cooperative techniques, namely, single helper selection (SHS), multi-hop cooperative selection (MCS) and multiple helper selection (MHS). We quantify the performance variations for different numbers of intermediate helper vehicles, and for varying values of fading parameter and correlation coefficients. Finally, we validate our mathematical derivations by performing extensive simulations in MATLAB.

1. Introduction

Vehicular networking has evolved rapidly in recent years mainly due to the advancements in automobile industry and ad-hoc networking [1]. By enabling wireless communications among vehicles, many useful applications for vehicle safety and infotainment can be implemented. Data exchange in vehicular network utilizes either single hop communication or multi-hop communication. For single hop communication, a high transmit power signal is sent to reach the required propagation distance in a single hop. It is useful when advertising a single event (e.g. brake). Moreover, it is usually preferred when line-of-sight exists between source and destination vehicles. On the contrary, multi-hop approach uses a small transmit power of the source and covers the distance to the destination by means of multi-hop relaying [2]. It is mostly useful when querying for a service or disseminating warning information. Multi-hop approach is usually favored when line-of-sight does not exist between source and destination vehicles. This scenario is commonly observed in urban environment with fast paced vehicles.

To extend range of communications in a vehicular network, fixed infrastructure in the form of road side units (RSUs) are placed at suitable geographical locations. RSUs act as the first point-of-contact (POC) to the on-board unit (which is a wireless transceiver mounted on the vehicle). The RSU usually comprises of multiple short-range antennas to enhance the capacity of the network. It processes the information sent by various vehicles and helps vehicles by providing different services such as road safety and infotainment. The road safety service helps to reduce the impact of accident by alarming the driver and updating the information about a possible emergency situation [3]. For instance, smart streets [4] and intelligent traffic tracking system update the drivers through vehicular communications regarding nearby and farther traffic conditions. Other major services that RSU provide are the availability of high speed Internet, peer to peer file transferring and online gaming on the road.

2. Related work

For provisioning of uninterrupted services, a reliable communication link between vehicles and the RSU is considered mandatory. The communication between vehicles and RSU is generally regarded as vehicle-to-infrastructure (V2I) communications.

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Recent works on V2I communications largely focus on clustering algorithms [5], RSU placement [6], and protocol designing [7]. However, limited work has been done to investigate the performance of V2I communications when RSU is equipped with multiple antennas. In this regard, Gavilanes et al. in [8] performed comparative analysis of on-field measurements of four different antenna types (i.e. monopole antenna, patched antenna, dipole antenna and Yagi antenna) for vehicular networks. The radiation patterns show that the correlation of the received signals is dependent on the mobility of vehicles with respect to a particular RSU. Ledy et al. in [9] used ray tracing tool to propose a mathematical model fully compliant with 802.11p. Subsequently, the authors in [10] studied multiple antenna approaches against short-term fading vehicular communications conditions. Through simulations, the authors proved that a multiple-input multiple-output (MIMO)-extended IEEE 802.11p physical layer model performs better than plain IEEE 802.11p. In [11], the authors considered omni-directional antenna at RSU to investigate the performance of V2I links in highway scenario. By varying the density of vehicles in the network, it was shown that the location of RSU holds considerable importance against channel-caused adverseness. A comparative analysis of IEEE 802.11p and IEEE 802.11p-long term evolution (LTE) was provided for MIMO channels in [12]. For different scenarios, the antenna radiation patterns were simulated and it was concluded that IEEE 802.11p performs acceptably well for sparse network topologies while IEEE 802.11p-LTE shows enhanced performance even in dense urban vehicular scenarios.

From the perspective of cooperative communication, recent studies indicate significant performance improvements as compared to direct communication. In [13], Das et al. has provided a cooperative communication technique which minimizes the retransmission of messages. The said scheme, although, improves the throughput of network, yet it does not always ensure the selection of best helper vehicle in the network. The authors of [14] provided game-theoretic model to efficiently access the internet services in vehicular networks. To further improve the cooperation mechanism, the authors of [15] extended the work of [16] (which minimized the hidden terminal problem) for multichannel clustering scenario. Liu et al. in [17] investigated the problem of data dissemination in downlink infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communication scenario. Load balancing in cooperative vehicular networks was studied in [18]. More specifically, a cooperative load balancing approach was adopted to maximize the system performance under specific delay tolerance constraints for emergency messages. Game-theoretic approach in cooperative vehicular networks was adopted by the authors of [19] to improve the reliability of messages. Simulation results indicate that game-theoretic approaches in cooperative vehicular networks help in minimizing propagation delay with improved broadcast reliability.

3. Motivation and contribution

From the above discussion, it can be observed that the studies on multi-antenna RSU consider statistical independence of radio links. We argue that the assumption of statistical independence of fading links oversimplifies the analysis and fails to provide critical insights. Therefore, its timely[1] and more realistic to quantify the performance variations in vehicular communications under correlated fading at RSU. Moreover, to the extent of authors' knowledge, there are no results reported on cooperative vehicular communications with multiple antennas at RSU. Motivated by these observation, main contribution of our work can be summarized as:

- We study the impact of two correlation models for multiple antennas at RSU i.e., constant correlation (CC) model and exponential correlation (EC) model. By considering different number of antennas at RSU, we characterize the performance improvements for both CC and EC models.
- We propose three cooperative techniques, namely single helper selection (SHS), multi-hop cooperative selection (MCS) and multiple helper selection (MHS) and derive closed-form expression of packet error probability for each. The links are assumed to be Nakagami-*m* faded which is a versatile fading model as compared to conventionally used Rayleigh fading.

The rest of the paper is organized as follows Section 4 discusses system model. Sections 5 and 6 discuss single helper selection and multiple helper selection schemes, respectively. Section 7 provides discussion on numerical results. Finally, Section 8 concludes this work.

4. System model

We consider a hybrid uplink V2V and V2I system consisting of a source vehicle, V_s, intermediate helper vehicles $V = \{V_i \mid i = 1, 2, \ldots N\}$ and an RSU having $M > 1$ antennas, as shown in Fig. 1. Both V_s and V_i are assumed be equipped with single antenna.[2] We also assume that all links are independent and identically distributed (i.i.d) Nakagami-*m* faded and follow a block fading model such that fading during a single block is invariant but changes randomly from one block to another. The transmission takes place in two phases by dividing a single block of time into two time slots. Although using two phases of transmission halves the transmission capacity, yet it helps in enhancing the diversity gains by relaying the information from source to destination [22]. During the first phase, V_s broadcasts its signal to a particular i-th helper vehicle. The helper vehicle is chosen based on the channel state information (CSI) of the links between V_s and intermediate vehicles. Let V_s transmits a signal x with power P to a helper vehicle. Then, the received signal at V_i, can be written as

$$y_{V_sV_i} = \sqrt{\frac{P}{d_{V_sV_i}^{\alpha}}} h_{V_sV_i} x + n_{V_sV_i}, \quad (1)$$

where $h_{V_sV_i}$ is the channel amplitude gain between V_s and the i-th helper vehicle, $n_{V_sV_i}$ is the additive white Gaussian noise (AWGN) at V_i with zero mean and variance $N_0, d_{V_sV_i}$ is the distance between V_s and i-th vehicle and $\alpha$is the path loss exponent. The source chooses the helper vehicle which has the best instantaneous signal-to-noise ratio (SNR), i.e.

$$\gamma_{V_sV_{i^*}} = \max_{i \in N} \gamma_{V_sV_i} \quad (2)$$

where $\gamma_{V_sV_i} = \frac{P}{d_{V_sV_i}^{\alpha} N_0} \mid h_{V_sV_i} \mid^2$ and i^* represents the index of selected helper vehicle. The signal sent by V_s is also received at the RSU through direct link, thus, the signal received at j-th antenna of RSU which can be written as

$$y_{V_sR}^{(j)} = \sqrt{\frac{P}{d_{V_sR}^{\alpha}}} h_{V_sR}^{(j)} x + n_{V_sR}^{(j)}, \quad (3)$$

[1] To enable high data rates and low latency connections, it is envisioned that technologies like millimeter wave (mmWave) and massive MIMO will play a pivotal role in vehicular communications [20]. In fact, mmWave-based automotive radars have already been developed. These technologies require to perform beamforming through large antenna arrays experiencing correlated channels [21].

[2] Analysis for multi-antenna vehicles will be presented in the future work.