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Distributed spatial reuse distance control for basic safety messages in SDMA-based VANETs ☆

Muhammad Awais Javed *, Duy Trong Ngo, Jamil Yusuf Khan

School of Electrical Engineering and Computer Science, the University of Newcastle, Callaghan, NSW 2308, Australia

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ABSTRACT

The periodic generation and transmission of basic safety messages (BSM) place a heavy burden on the load of a vehicular ad hoc network (VANET), where there also remain multiple packet collisions undetected due to the hidden terminals. In this paper, we propose a distributed scheme that controls the spatial reuse distance to improve the efficiency of BSM transmissions in space-division multiple access (SDMA) based VANETs. With the proposed SDMA structure, only vehicles located sufficiently far apart are allowed to reuse the same time slot to send their BSMs. The signal interference is thus reduced while the hidden-node problem is essentially alleviated. Multiple transmissions per SDMA road segment or 'cell' are also enabled using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), giving rise to a much better use of both space and bandwidth. To guarantee that the actual number of BSM transmissions does not exceed the maximum allowable in each SDMA cell, we further devise an adaptive scheme that adjusts the spatial reuse distance in accordance with the vehicle density. Because the global information of vehicle density is not available at individual vehicles, we propose a distributed algorithm that estimates the vehicle density and makes consensus to enhance the accuracy of spatial reuse distance estimation. As the transmission range is controlled accordingly, the mutual interference among the SDMA cells is further reduced. Importantly, the developed control algorithm can be distributively implemented by each vehicle with limited information exchange. To optimize the performance of the proposed solution, we also determine the optimal bandwidth utilization that maximizes the newly-defined criterion termed as 'safe range,' an important figure-of-merit in vehicular safety applications. Simulation results confirm the clear advantages of our proposal over the available approaches in terms of safety range, packet reception rate, end-to-end delay and BSM inter-arrival time in realistic network scenarios.

1. Introduction

Vehicular ad hoc network (VANET) is envisioned by the automotive industry as the future intelligent technology that enhances the safety and comfort level of road traveling. VANET architecture relies on the information exchange via inter-vehicle communication to provide vehicles with a neighborhood view for safety purposes as well as other traffic management applications [1,2]. In an emergency situation (e.g., the sudden braking of a vehicle), an event-driven warning message is issued which can also be propagated over a long distance using multi-hop packet transmission strategies [3–5]. For active safety applications such as collision avoidance, basic safety messages (BSMs) are periodically shared among the neighboring vehicles [6].

Among all the safety messages, BSMs create most of the network load due to their periodic transmission requirements [7]. In particular, each vehicle on the road is required to periodically broadcast its BSM packets which contain road traffic information (e.g., position, speed and direction) at a frequency of 10 Hz [8,9]. For a growing vehicle density, the equal transmit power allocation policy typically employed for BSM transmissions further increases the network load [10]. Due to such a high packet generation rate within a limited transmission time of 100 ms, the concurrent transmissions of BSM packets from the hidden vehicles may result in a large number of undetectable collisions. Furthermore, the broadcast communication defined in the IEEE 802.11 standard does not provide any RTS/CTS (Request to Send/Clear to Send) mechanism to deal with the hidden-node problem [11]. As a result, even more packet losses are expected at higher vehicle densities.

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* Corresponding author.
E-mail addresses: muhammadawais.javed@uon.edu.au (M.A. Javed), duy.ngo@newcastle.edu.au (D.T. Ngo), Jamil.Khan@newcastle.edu.au (J.Y. Khan).

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Adopting the space-division multiple access (SDMA) approach, several techniques have been proposed to improve the performance of the safety broadcast communication in VANETs. The work of [12] devises a fixed space–time mapping for the SDMA architecture, which offers a reduced bandwidth utilization for a decreasing number of users. Also advocating SDMA for inter-vehicle communication, [13] provides a simple space–time mapping based on cell size and channel reuse distance. In [14], centralized infrastructure such as road side units (RSU) is proposed to perform time slot allocation in SDMA. On the other hand, the protocol developed by [15] uses a hexagonal cell structure for SDMA where additional control messages are required to implement a distributed time slot allocation. SDMA technique is also employed in [16] with the purpose of isolating single-hop and multi-hop traffic.

The Adaptive Space Division Multiplexing (ASDM) scheme is proposed in [17] for VANETs. Here, time slots are assigned according to a mapping function that is based on the vehicle positions and the ASDM cell stagger for an even distribution of the time slots. By allocating empty slots to the vehicles according to their measured headway, the developed protocol improves the bandwidth utilization and increases the number of transmissions per every synchronization interval of 100 ms. However, because the frequency of BSM generation and transmission is limited to 10 Hz, the extra transmissions in a synchronization interval may not provide any safety enhancement at all [9,6]. Due to the restricted spatial reuse distance, the ASDM scheme must also use a short and fixed transmission range.

Power control is employed to improve the performance of safety messages. The Distributed Fair Power Adjustment for Vehicular Environment (D-FPAV) protocol in [18] controls the transmit power to limit the network load to a fixed maximum beacon load threshold (MBL) value. Similarly, [19] proposes a power adaptation technique that varies the transmission range and the contention window size in accordance with the vehicle density. In [20], vehicle density is estimated as part of the power control process. Transmission range control algorithms are devised by [21,22] for lane change warning and intersection collision avoidance applications. The work of [23] makes use of the delay values of BSM transmissions to adjust the transmission range. On the other hand, [24] utilizes channel occupancy statistics to control the transmission range while dynamically changing the packet generation rate according to the position error estimation. Other relevant techniques can be found in [25–31] for safety message performance enhancement.

In this paper, we propose a distributed spatial reuse distance control algorithm for SDMA (referred to as the DSC-SDMA algorithm) that aims to successfully deliver the BSMs in a timely fashion. Specifically, we divide the highway into road segments of a fixed size (termed as 'cells') and assign a fixed time slot from the synchronization interval to each cell. With the proposed SDMA approach, we only allow concurrent transmissions by vehicles located sufficiently far apart. While these vehicles usually play the role of the hidden terminals due to their spatial separation, our SDMA scheme ensures that they no longer strongly interfere with one another. Different from the existing solutions that map very small road spaces to fixed time slots [12,13,17], here we let multiple vehicles in a cell transmit within a time slot, and propose the use of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for medium access in each cell. Such an approach helps to overcome the typical issue of bandwidth under-utilization due to a large number of unoccupied cells in the available solutions.

Because all vehicles within a cell are allocated a fixed time slot, only a limited number of BSM transmissions can be supported per cell. As the actual number of BSM transmissions grows with higher vehicle densities, we propose a mechanism that dynamically changes the spatial reuse distance according to the vehicle density. The developed scheme guarantees that the number of BSMs generated in an SDMA cell is always kept below the maximum allowable limit. In a VANET, it is challenging to have a central entity responsible for estimating a global vehicle density and disseminating the estimated result to all vehicles. Therefore, we implement a distributed scheme in which the vehicle density is locally estimated and the spatial reuse distance locally controlled by individual vehicles. The proposed implementation is realized with limited information exchange among vehicles within a close neighborhood.

In the devised control algorithm, we configure the bandwidth utilization such that an optimal balance between a long spatial reuse distance and a high packet reception rate is achieved. Toward this end, we establish that the optimal bandwidth utilization is the one that maximizes the newly-defined metric termed as 'safety range'—the distance up to which the BSM packets are received with a probability greater than 90%. Simulation results show that the DSC-SDMA algorithm offers significant improvements over the existing solutions in the safety range, packet reception rate, end-to-end delay, and BSM packet inter-arrival time.

The rest of this paper is organized as follows: Section 2 presents the network model and introduces the SDMA structure as well as the spatial reuse distance control for BSM transmissions. Section 3 proposes the DSC-SDMA protocol with distributed vehicle density estimation and spatial reuse distance consensus. Section 4 selects the optimal bandwidth utilization and verifies the performance of the devised DSC-SDMA protocol by numerical simulations. Finally, Section 5 concludes the paper.

2. Space-division multiple access and spatial reuse distance control for basic safety message transmissions in a VANET

2.1. Highway VANET model

We depict in Fig. 1 a typical example of the network scenario under consideration. In both opposite directions of a multi-lane highway, moving vehicles are connected via wireless links to form a VANET. We assume that each vehicle is equipped with a Differential Global Positioning System (DGPS) that is capable of providing an accurate position measurement. To cooperatively maintain road safety, individual vehicles periodically generate and transmit BSMs to other vehicles on the road to exchange the safety information.

We assume that the BSMs are generated at the frequency of 10 Hz, i.e., 10 packets per second. One packet is sent by a vehicle in each synchronization interval $T_s = 100$ ms with a maximum transmission range of 1000 m [6]. As the vehicle density increases, the number of BSM transmissions simultaneously transmitted by the vehicles also goes up, causing stronger signal interference and more frequent packet collisions. Because vehicles located far apart on the highway can be hidden to one another, it is challenging to detect their potential BSM packet collisions too.

2.2. SDMA structure

To alleviate the adverse effects of packet collisions and hidden terminals, we propose an SDMA structure in that we divide the highway into segments of a fixed size (called 'cells'), each of length D_c as shown in Fig. 1. The cell width is equal to the width of the highway road, including multiple lanes. Assume there are N cells within a *spatial reuse distance* D_r, i.e., $D_r = ND_c$. Each cell is allotted an equal time interval T_c in the synchronization interval $T_s = 100$ ms as:

$$T_c = \frac{T_s}{N} = \frac{100\text{ ms}}{N}. \quad (1)$$

In SDMA, cells separated by a distance of D_r are allowed to reuse the same time slot of length T_c.