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Application-value-awareness cross-layer MAC cooperative game for vehicular networks

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ABSTRACT

In vehicular ad-hoc networks (VANETs), numerous safety related applications have a stringent requirement for the upper latency limit for transmission of messages between vehicles. Thus, it is necessary to design a high-efficiency medium access control (MAC) method that can ensure the allowed upper limit of message delivery delay is satisfied. In this study, we propose the concept of application value (i.e., the value of a conveyed packet), and correlate it with the waiting time of a packet determined by the delay of each concerned message. Subsequently, we design an inter-vehicle cross-layer cooperative game model taking into account the global optimal utility of the participants. Next, we theoretically prove the existence of an equilibrium using a Markov decision process (MDP), and provide a concrete approach to obtain the channel access probability of a node according to the best response method. Finally, we present the results of a partially observable MDP (POMDP) and of the extensive numerical analyses of the performance indicators such as the access delay, throughput, and packet delivery rate (PDR). These are compared with the IEEE 802.11p protocol in saturated and unsaturated states. These comparisons show that the proposed cross-layer MAC cooperative game method guarantees the message transmission delay when the channel is nearly saturated, enabling a successful delivery of the messages within the time limit and providing a strong support to delay-sensitive safety related applications.

1. Introduction

Vehicular ad-hoc networks (VANETs) are a distinct type of mobile ad-hoc network involving moving vehicles and roadside units. VANETs can facilitate a variety of attractive applications, which are usually classified into the following two main categories: 1) safety applications (e.g., collision avoidance, safety warnings, and remote vehicle diagnostics) and 2) infotainment applications (e.g., file downloading, web browsing, and video streaming) [1]. Because safety applications provide drivers information regarding a critical situation in advance, they have strict requirements for communication reliability and delay. In contrast, infotainment applications are used for improving the driving comfort and enhancing the efficiency of a transportation system, and these applications are more throughput-sensitive than delay-sensitive [2]. However, because of the new characteristics of VANETs such as a frequently changing topology, fast-fading channel, and non-ignorable Doppler effect, the communication protocols, including in particular, the medium access control (MAC) protocol, have to be redefined to overcome these nontrivial challenges.

To address these issues, the Wireless Access in Vehicular Environments (WAVE) standard has been proposed by IEEE, which is composed of the IEEE 802.11p MAC/PHY protocol, together with the IEEE 1609 protocol family (denoted by IEEE 1609.x) as the higher-layer standard to serve Intelligent Transportation Systems (ITS) applications in multichannel operation, networking service, and security [3]. In particular, the WAVE standard amends and extends the IEEE 802.11 standard at the PHY and MAC layers. At the PHY layer, IEEE 802.11p works on several channels within the frequency band spanning the 5.9 GHz (5.85–5.925 GHz) range dedicated to ITS known as the DSRC (Dedicated Short-Range Communications) band. This 75 MHz band is divided into one central Control Channel (CCH) to transmit safety- and management-related messages, and six Service Channels (SCHs) for various applications (e.g., infotainment) data. At the MAC layer, The IEEE 802.11p uses

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the Enhanced Distributed Channel Access (EDCA) MAC sub-layer protocol designed based on that of the IEEE 802.11e with some modifications. Especially, the medium access rule in IEEE 802.11p is the same as that in IEEE 802.11 standard, i.e., when the nodes have messages to transmit, they compete for the wireless channel through the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism.

However, even if safety related messages are transmitted in reserved channels, when the vehicle density is high and the wireless channel is close to saturation, the medium access method of IEEE 802.11p in WAVE is unable to ensure the channel access delay and the delay may increase indefinitely, i.e., the transmission of packets within the valid time is not guaranteed. As mentioned earlier, latency is often a significant attribute to consider in most safety applications. The application requirements for packet access delay are more stringent particularly when the vehicle is moving at a high speed, and in this situation if the delay of the packet of safety messages is not guaranteed, it will have very serious consequences. For example, in case of highway automated following driving, the vehicles have a high speed, and the relative distance between two vehicles is also close. If an emergency brake burst occurs in one vehicle, a timely message is needed to be sent promptly to notify the vehicle behind it. Thus, packet delay is a critical factor such that if the first vehicle cannot access the channel in time, the concerned message cannot be issued within its limited time, and the consequences can be disastrous. Therefore, it is essential to ensure that the message is successfully transmitted within the time limit determined by the delay requirement of the packet.

To ensure that the messages are successfully issued before they fail, it is necessary to distinguish the packets according to the different delays of same class (e.g., safety or infotainment) messages that are waiting to be sent through the competing channel., i.e., it is important to perceive the value of each packet of same class messages. Depending on the waiting time of the packets in its queue, different values can be assigned to the packets, establishing a one-to-one relationship between the packet delay and its value. In the competition between the nodes for the wireless channel, the packet value is considered as an important factor. Based on the packet value, each node has a different channel access probability. Therefore, it is important to ensure that each packet is successfully transmitted within its validity period. Therefore, we can consider the packet value in the design of a medium access approach, so that each vehicle can evaluate its own value according to the waiting time of the current packet during their competition for the wireless channel. This is to ensure that each packet can be sent in the dedicated channel in time, improving the channel performance in the near saturation condition.

At one hand, with the extensive deployment of DSRC-enabled vehicles, the communication efficiency between vehicles is becoming more important. So we can optimize the overall performance of the network by cooperative behavior of participants. On the other hand, because message receiver need to take necessary actions to avoid accidents, the successful receiving of beacon messages is more important than blind transmitting. By participants' mutual cooperation, the channel access timing of vehicles can be planned reasonably to ensure that the safety messages concerned by each vehicle can be successfully received. Therefore, we can consider the cooperative game of vehicles in design of medium access algorithm to improve the communication efficiency between vehicles in VANETs.

To this end, it is critical to redefine the competition algorithm that can distinguish the different vehicle packet values of the same class messages and assign them different transmission probabilities. In this manner, the entire network can guarantee the requirements of delays for different packets and ensure the packet is successfully sent within the time limit and then successfully received by other nodes for whom the message is of concern. In this study, we add the factor of packet value to the medium access game of a vehicle, and adjust the transmission probability of each vehicle with it, so that the messages of each vehicle can be sent in time. And it is necessary to highlight that the medium access method we proposed is not used between safety and infotainment messages but works within each channel, which is a dynamic priority adjustment for packets of the same class messages. The main contributions of this paper are as follows: (i) proposing a new concept of application value (i.e., packet value) and establishing the relationship between the packet value and waiting time of the current packet of same class application, (ii) constructing a cross-layer game model to adjust the channel access probability of each node using the complete information in the vehicular environment based on packet value of same class message, (iii) proving the existence of equilibrium by the MDP, showing that it is the solution of the Bellman fixed point equation, (iv) providing the method for solving the optimal policy equilibrium, and analyzing the channel performance according to the solution of a partially observable MDP.

The remainder of this paper is organized as follows. Section 2 discusses the related work. In Section 3, we introduce a traditional non-cooperative medium access game, describe the cross-layer cooperative medium access game model in detail, and provide the proof and solution of the equilibrium. Moreover, the solution of the partially observable MDP is presented in Section 4, and the numerous comparative analyses that were conducted are discussed therein. Section 5 concludes this paper and suggests the future work.

2. Related work

There are numerous research studies on MAC. Here, we only mention a few studies that are most closely related to our work. Lee et al. [4] developed a non-cooperative game model for backoff-based random-access MAC protocols (e.g., slotted Aloha, 802.11 DCF function), proved that this game model is equivalent to the contention resolution algorithm in such protocols. And they revealed the deficiencies of existing MAC protocols in achieving global optimal scheme through this model. But they only focused on the contention resolution mechanism instead of carrier-sensing-based MAC protocols (e.g., CSMA/CA) that consists of both contention avoidance and collision resolution algorithms. Cui et al. [5] generalized the random access game model, showed that the random access game model provides a general framework for designing contention based MAC. And gave several examples of how to design random access games. But they only studied the static game, and did not consider the dynamic repeated game closer to actual MAC. Ju et al. [6] modeled and analyzed a MAC protocol of cooperative communication with a game theoretic approach, and incorporated an incentive mechanism into the model to ensure that it can achieve a Nash equilibrium. But they only considered two participants in the game model and it is difficult to extend this model into a game of multiple nodes. Considering the impact of a multi-relay link interference on relay selection and dynamic spectrum sharing, Cui et al. [7] proposed a completely distributed relay MAC scheme for wireless cooperative networks based on the Stackelberg game framework with only a one-hop local channel state information (CSI). In this scheme, the source nodes that have their own information to send act as leader users, whereas the others act as follower users. Dermed et al. [8] presented a new model called the Markov games of incomplete information (MGII) that imposes a mild restriction on the partially observable stochastic games (POSGs) while overcoming their primary computational bottleneck. Moreover, the authors showed how to convert an MGII