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Towards low-delay and high-throughput cognitive radio vehicular networks[☆]

Nada Elgaml, Ahmed Khattab*, Hebat-Allah Mourad

EECE Department, Cairo University, Giza, Egypt

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Abstract

Cognitive Radio Vehicular Ad-hoc Networks (CR-VANETs) exploit cognitive radios to allow vehicles to access the unused channels in their radio environment. Thus, CR-VANETs do not only suffer the traditional CR problems, especially spectrum sensing, but also suffer new challenges due to the highly dynamic nature of VANETs. In this paper, we present a low-delay and high-throughput radio environment assessment scheme for CR-VANETs that can be easily incorporated with the IEEE 802.11p standard developed for VANETs. Simulation results show that the proposed scheme significantly reduces the time to get the radio environment map and increases the CR-VANET throughput.

Keywords: Cognitive radio; Spectrum sensing; Vehicular ad-hoc networks (VANETs); IEEE 802.11p; Medium access

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1. Introduction

Vehicular Ad-Hoc Networks (VANETs) are of paramount importance in Intelligent Transportation Systems (ITS) as they enable diverse road safety, traffic management, and infotainment (e.g., video and entertainment) applications. Such VANET applications are time-sensitive and throughput-hungry. Cognitive Radio (CR) networking has been recently exploited by VANETs to allow vehicles to use the unutilized spectrum in their environment, and hence, provide an efficient solution to tackle the throughput challenge of VANET.

The resulting Cognitive Radio Vehicular Ad-hoc Networks (CR-VANETs) face many challenges [1]. One of the most prominent challenges is how to allow a large number of vehicles to assess the occupancy of the different channels in their environment, and report such assessments back to where the decision-making process is carried out. Several channel sensing techniques [2–4] and cooperation schemes [5–7] have been particularly developed for CR-VANETs. However, such techniques typically have each vehicle sensing the whole (or a subset of) the available channels. Moreover, each vehicle then has to report its channel sensing information back to the decision-making node. Such channel sensing and information reporting processes reduce the CR-VANET throughput and induce significant delays that are not desirable for VANET applications. Furthermore, the CR decisions become quickly outdated because of the high mobility of the vehicles and might cause the CR-VANET transmissions to collide with the primary owners of the spectrum.

In this paper, we present a low-delay and high-throughput CR-VANET scheme that exploits the correlation in the vehicle sensing information to reduce the amount of time spent in sensing. In contrast to the existing literature which adopts explicit cooperation between the vehicles, our scheme relies on an implicit cooperation mechanism that significantly reduces the number of exchanged control packets. The proposed scheme introduces a simple slotted contention that can be easily implemented on top of the IEEE 802.11p standard [8], widely used in VANETs.

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* Corresponding author.

E-mail addresses: Nada.ELgaml1@Eng1.cu.edu.eg (N. Elgaml), akhattab@ieee.org (A. Khattab), hmourad@eece.edu.cu.eg (H.-A. Mourad).

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The remainder of this paper is organized as follows: In Section 2, we describe the system model. The proposed SC^2 protocol is presented in Section 3. The performance evaluation is presented in Section 4, and we conclude the paper in Section 5.

2. Network model

We consider a multi-lane rural highway with a homogeneous high-density vehicular traffic. The highway is divided into identical segments. Each segment has a road side unit (RSU) that controls the vehicles within the segment as described in [5]. The RSU collects the channel sensing information from the vehicles within its service area, and broadcasts the Radio Environment Map (REM) message with the final spectral decisions back to them. The segment boundaries are known to all vehicles. Each vehicle is equipped with a Global Positioning System (GPS) such that it is aware of its current segment.

The CR-VANET secondary network is composed of the vehicles moving along the highway with a uniform speed driven from a uniform distribution. The vehicles' arrivals are independent and thus can be modeled by a Poisson process. The inter-arrival times of vehicles have an exponential distribution with a mean that depends on the traffic density.

We assume M non-overlapping TV channels in the VHF band that correspond to M primary networks (PNs). The PN activity on its channel is modeled with a random ON–OFF process. The locations of the PNs are fixed, and the vehicles are not aware of such locations. All PNs have the same transmitting power which may cover more than one segment.

2.1. CR-VANET frame structure

In CR-VANET, time is typically divided into frames [5–7]. As shown in Fig. 1(a), a typical frame of IEEE 802.11p based CR-VANET protocol is composed of four phases: channel sensing phase, reporting phase, radio environment map broadcast, and data transmission phase. In the channel sensing phase, the vehicles sense the channel(s) of interest based on the adopted sensing algorithm. Then, they report such sensing information to the RSU on a common control channel (CCC) for decision making. Vehicles compete for the CCC access using IEEE 802.11p Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) contention. Once the RSU captures the needed channel sensing information, it produces a radio environment map (REM) that indicates which channels can be used by the vehicles in the RSU's segment and which channels are currently used by their respective PNs. Once the vehicles receive the REM, data transmission on the available channels takes place.

3. Single channel slotted contention (SC^2)

In this paper, we present the SC^2 approach for CR-VANETs with high vehicular traffic density. The SC^2 approach exploits the strong correlation in the channel sensing results of the vehicles within a road segment to reduce the amount of time needed for the RSU to develop an REM packet. This is achieved through the following three mechanisms:

3.1. Single channel random sensing

A road segment is typically limited to a few hundreds of meters due to the limited coverage range of the RSU. In CR-VANETs with high traffic density, the vehicles within a segment will be within the transmission range of the same TV transmitters, and hence, their assessments of whether a particular TV channel is currently in use will be highly correlated. Accordingly, the SC^2 approach has each vehicle within a road segment randomly selecting one out of the M available channels to sense with probability $1/M$. This does not only distribute the channel sensing load among the vehicles within a road segment, but also reduce the sensing time as shown in Fig. 1(b). If the number of vehicles in a road segment is n, the probability that each channel is sensed by at least one vehicle is

$$p_{sense} = 1 - \left(1 - \frac{1}{M}\right)^n. \quad (1)$$

As the number of vehicles is greater than the number of TV channels (i.e., $n > M$), p_{sense} approaches unity. This implies that the proposed single channel random sensing manages to have all the channels sensed with a high probability in high density CR-VANETs.

3.2. Slotted contention

Existing CR-VANET protocols typically have all the vehicles within the segment report their channel assessments using IEEE 802.11p CSMA/CA-based contention over the CCC [5–7]. This allows the aggregation node (whether the RSU in centralized protocols or a head vehicle in distributed ones) to produce the REM based on the information of all vehicles regarding all the channels. Consequently, the contention period of such approach should be selected large enough to not only accommodate the control packet transmissions of all the vehicles within the segment, but also to take the expected collisions that occur due to CSMA/CA contention given the high number of competing vehicles. Such a large contention period degrades the CR-VANET throughput and increases the delay. Furthermore, the length on the contention period, and hence, the length of the frame, will depend on the vehicle density. This will cause the jitter to be also dependent on the vehicular density.

In contrast, the SC^2 protocol proposes a slotted contention mechanism that is implemented using the IEEE 802.11p protocol. The SC^2 contention period is divided into M equal-length contention slots as shown in Fig. 1(b). This implies that the SC^2 contention duration is only dependent on the number of channels rather than the vehicular traffic density. The duration of a contention slot is set to be equal to the time of EEE 802.11p backoff mini-slots plus the time to transmit a control packet. A vehicle that randomly selected the ith channel will only compete for access of the ith contention slot. It will randomly choose a number in [0, $CW - 1$], where CW is the contention window, and will count down this number of mini-slots while listening to the CCC. If the vehicle finds that another vehicle has started the transmission of its control packet, the vehicle