Interaction between EDCA and HCCA: Simulation Study of DSRC for Work Zone Safety

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Abstract—Recently, academic researchers and car manufacturers have directed major efforts to develop active safety systems for reducing car accidents. In particular, for work zones they proposed to use smart cones that send a warning radio message to vehicles when the smart cones detect the possibility of an accident. The dominant protocol for vehicular communication is Dedicated Short Range Communications (DSRC), where Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA) are the MAC protocol options. Even though two MAC protocols are specified in the standard, there has been no attempt to use two protocols cooperatively nor to study the performance of such hybrid system in an actual vehicular network. In this paper, we examine for the first time the performance of a system that exploits EDCA and HCCA concurrently in vehicular networks. In particular, we concentrate on interaction between two MAC protocols and how much the interaction affects system performance. In addition, we investigate whether the system is feasible for work zone safety applications, and suggest guidelines for improvements based on our simulation findings.

Keywords—work zone safety; DSRC; EDCA; HCCA; Interaction

I. INTRODUCTION

In a work zone, a large fraction of accidents are fatal crashes and injury crashes. According to a report from Kansas State [1], more than half of fatal crashes and a third of injury crashes happen in work zones. In an attempt to reduce such crashes, academic and industrial researchers have made efforts in developing safety systems that employ wireless transceivers [2][3]. In the safety systems, vehicles and Road Side Units (RSU) exchange vehicle status information and warning messages, and vehicles can recognize the risks of accidents when they receive the warning messages.

To improve safety, state and federal transport agencies (e.g., Caltrans) have developed smart cones that are equipped with wireless transceivers. Similar to RSUs, the smart cones are located in static position on the shoulder of a road and can communicate with vehicles for vehicle safety. More specifically, vehicles advertise their status information, (e.g., vehicle speed, position and acceleration), while smart cones generate a warning message after getting the status information and transmit the warning message to vehicles in a real-time manner.

Dedicated Short Range Communications (DSRC) [4] is considered as a de facto standard for vehicular communications, in which Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA) are specified as MAC protocols. EDCA has been normally employed as a MAC protocol due to its ease of deployment and capability to adjust to fast topology changes of vehicular networks. However, EDCA may induce an unpredictable delay that comes from its statistical access mechanism (i.e., binary random backoff in CSMA/CA). In particular, when vehicles are densely deployed, such a statistical mechanism engenders a long delivery delay and low Packet Delivery Ratio (PDR) [5]. For example, simulation results in [5] show that EDCA produces only 50~60% PDR when there are only 100 vehicles in 6.6km by 4.2km road segment. The other type of MAC protocol, HCCA, is specified for supporting real-time transmissions and allocates resources to time sensitive stations in time-division polled mode. However, to adapt to fast topology change of vehicular networks, HCCA may produce large protocol overheads (e.g., overhead for slot assignment, overhead for joining process). If smart cones are adopted in a work zone, they can forward the warning message to vehicles using HCCA, thus it seems that the delay and PDR requirements of work zone can be supported. However, HCCA is still not suitable for vehicle transmissions. Therefore, using only EDCA or HCCA is not enough to support real-time transmission in a rapidly changing topology, such as a work zone safety application in vehicular networks.

So, one may raise the question: "can we really improve a work zone safety system by leveraging EDCA and HCCA?". IEEE 802.11 defines a superframe structure for EDCA and HCCA coexistence, which works well when devices do not have high mobility and network size is small [9]. However, to the best of our knowledge, there have been no performance studies on EDCA and HCCA coexistence system when high mobility and large network size are considered. [5] examined performance of an IEEE 802.11 MAC protocol for a vehicle safety system. [6] compared EDCA and Point Coordination Function (PCF) in vehicular networks. [7] analyzed EDCA performance when EDCA is applied to vehicular safety messaging. [8] analyzed the delay of HCCA in vehicular networks. However, previous studies did not consider EDCA and HCCA coexistence scenario [5][6][7][8] or did not consider vehicular situations [9]. Thus, in this paper, we perform a simulation study on EDCA and HCCA coexistence system in which smart cones and vehicles cooperate for work zone safety. Especially, we focus on how EDCA and HCCA interact with each other and the interaction affects system performance.

The contributions of this paper are summarized as follows:

1) We examine the performance on EDCA and HCCA coexistence system in vehicular networks.
2) We show feasibility of such system for work zone safety.

3) We suggest guidelines for improving performance of the system.

The rest of this paper is organized as follows. In Section II, we briefly explain EDCA and HCCA. In Section III, we explain a work zone safety system. In Section IV and V, we analyze simulation results and suggest future guidelines for improvement of the system. Then, we conclude our work and present future works.

II. BACKGROUND

A. EDCA

EDCA is a mandatory channel access mechanism in IEEE 802.11e standard. EDCA is based on Distributed Coordination Function (DCF), but there are a number of differences between DCF and EDCA. First, EDCA defines four Access Categories (ACs) according to traffic types: AC_VO (voice), AC_VI (video), AC_BE (best effort), and AC_BK (background). In an EDCA-enabled station, there are four transmission buffers; each buffer is used for one AC. Second, each transmission buffer has an independent backoff entity, which performs a backoff procedure for the MAC frame in the transmission buffer. Third, each AC has different configuration parameters (Minimum Contention Window (CW), maximum CW, Arbitration InterFrame Space (AIFS), Transmission opportunity (TXOP)), which prioritize among different ACs.

B. HCCA

HCCA is an optional channel access mechanism in IEEE 802.11e. HCCA is based on Point Coordination Function (PCF), which is a polling-based, contention-free channel access mechanism. In HCCA, Hybrid Coordinator (HC) reserves a channel for certain amount of time and allocates channel resources to backoff entities. Since the polling-based mechanism of HCCA is deterministic, HCCA is appropriate for guaranteeing a delay bound of delay-sensitive applications [10]. To reserve the channel, HC sends QoS CF-Poll message after waiting for PCF InterFrame Space (PIFS). Since PIFS is shorter than any AIFS that EDCA devices must wait before a backoff countdown, HC can obtain the right for channel access earlier than EDCA stations.

III. WORK ZONE SAFETY SYSTEM

As illustrated in Fig.1, a work zone safety system consists of vehicles and smart cones. Vehicles periodically generate and disseminate a message that includes status information of the vehicles. For accessing a wireless channel, vehicles employ EDCA since its distributed nature enables the EDCA to adapt to fast vehicle topology changes easily.

The other system components, smart cones, are located in static position on the shoulder of the road. The smart cones are different from conventional cones in that the smart cones have wireless transceivers, thereby being able to communicate with vehicles. The smart cones generate warning messages when they perceive a possibility of vehicle accidents (e.g., detection of 150km/h vehicle in urban area), which is usually an output of processing vehicle status information. The smart cones employ HCCA mechanism in transmitting a warning message due to following reasons: 1) The warning message is delay sensitive and requires high communication reliability, thus must be supported by a deterministic mechanism like HCCA, 2) smart cone's static position helps keep the overhead small in a deterministic mechanism (e.g., overhead for joining, scheduling).

To enforce HCCA transmission scheduling, we deploy a Base Station (BS) on the shoulder of the road, which employs HCCA mechanism. BS establishes transmission schedule of cones and sends a poll message to each cone in a time slot designated for the cone. When receiving a poll message from BS, the cone is permitted to access the wireless channel.

IV. SIMULATION STUDY

In this section, we perform a simulation study of the safety system based on EDCA (HCCA) for vehicles (smart cones) using ns-2 simulator [12]. Specifically, we investigate the system according to non-controllable parameters (the number of vehicles and the number of smart cones) and controllable parameters (Contention Window (CW) size of EDCA and packet size of vehicle traffic). We define simulation scenarios like this based on the belief that we can improve system performances by configuring the controllable parameters. For each simulation scenario, we focus on how an interaction between EDCA and HCCA affects system performances. In addition, we study a feasibility of the system for work zone safety.

A. Simulation Setup

Fig.2 illustrates a topology for our simulation study. In the simulation, we consider a two-way one mile road segment with four lanes. Vehicles move along the road with a speed of 70km/h and smart cones are deployed on the shoulder of the road and located within a work zone of which length is 300m. In the middle of the road, BS is deployed.

We summarize default simulation settings in Table 1. For PHY layer protocol, we follow IEEE 802.11p [4]. In MAC
layer setting, we use default values of IEEE 802.11 [11] for backoff configuration parameters of EDCA (e.g., CW size, AIFS). In HCCA, we do not implement the Contention Free Period (CFP) due to following reasons. First, using CFP is not mandatory in IEEE 802.11 standard [11] since BS can provide transmission opportunity to stations (i.e., sending poll message to station) during Contention Period (CP). Second, in our topology, BS cannot reserve the channel for the entire network due to a limited transmission range, thus contention may happen during CFP. BS generates and sends poll message every 200ms. This means that each smart cone can grab an opportunity to access channel every 200ms. Vehicles (smart cones) generate status info message (warning message) every 100ms (200ms) and broadcast the message. This setting mimics a situation where smart cones gather vehicle information for 200ms and generate a warning message from that information. If there is no a possibility of accident during an interval, smart cones need not send warning message every interval. In this setting, when there is no possibility of accident, "sending message" refers to sending void message, which includes only the notification of work zone.

It is noted that even though EDCA is generally used for prioritized services, we only consider single service in our studies to focus on the interaction between EDCA and HCCA. Thus, we just use one Access Category (AC) for EDCA in our simulations. However, as a future work, we will consider multiple services in vehicular networks, on which vehicles use more than one AC.

We note that in our simulation, smart cones do not use EDCA together with HCCA. This is because HCCA is more likely to support high PDR than EDCA. To be specific, in HCCA transmissions, BS reserves a channel for smart cone’s transmission by annotating poll message with required duration (i.e., set Network Allocation Vector (NAV)). As a result, a fraction of vehicles defers their transmissions by overhearing the poll messages. On the other hand, in EDCA, there is not a mechanism for reserving channel before data transmission, thus, lot of transmission attempts by vehicles can induce packet collisions. Thus, sending warning message with HCCA is less likely to suffer from packet collision.

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>transmission range</strong></td>
<td>450m</td>
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<tr>
<td><strong>physical transmission rate</strong></td>
<td>6Mbps</td>
</tr>
<tr>
<td><strong>sending buffer size</strong></td>
<td>20 packets</td>
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<tr>
<td><strong>Slot schedule for HCCA</strong></td>
<td>Round-robin method</td>
</tr>
<tr>
<td><strong>Message length</strong></td>
<td>100byte (vehicle, smart cone)</td>
</tr>
<tr>
<td><strong>Number of vehicles</strong></td>
<td>Variable (80 is default)</td>
</tr>
<tr>
<td><strong>Number of smart cones</strong></td>
<td>Variable (10 is default)</td>
</tr>
</tbody>
</table>

**Table 1** Default system parameters

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1 Society for Automotive Engineers (SAE) [14] defines 100ms to be a default generation period for periodic vehicle message. [2] suggests one second for generation period of work zone warning message, but [2] only considers I2V communications, which is somewhat different from our situations. Thus, as a generation period of warning message, we choose 200ms which is close to average value of message generation period in [2]. However, these values are just default settings, which can change for more elaborate performance study.

**B. Performance Metrics**

Performance metrics in this study are as follows

- **Packet Delivery Ratio (PDR):** a ratio of the number of vehicles that receive a packet \(n_{\text{received}}\) to the number of vehicles within a transmission range of a sender \(n_{\text{target}}\).
- **Communication delay:** an interval between a packet generation time and a packet reception time.
- **Poll collision rate:** a ratio of the number of poll messages collided at smart cones \(n_{\text{poll\_collision}}\) to the number of poll messages sent by BS \(n_{\text{poll\_sent}}\).

It is noted that we define a new metric, a poll collision rate, to analyze unpredictable simulation results, which are caused by interactions between EDCA and HCCA. Specifically, in Fig.4, delay of HCCA is not bounded and its value is very large. Our conjecture on these counter-intuitive results is that poll messages collide with "hidden terminal" vehicle traffic. To prove this conjecture, we measure poll collision rate for each scenario. However, due to page limitations, we only depict the graph on poll collision rate in Section IV-C and IV-E.

**C. Impact of Number of Vehicles**

In Fig.3, we observe that PDR of EDCA (i.e., PDR of vehicle traffic) and that of HCCA (i.e., PDR of smart cone traffic) decrease as the number of vehicles increases. Obviously, the increase in the number of vehicles makes a network more congested, which leads to the decrease in PDR of EDCA. The interesting finding in Fig.3 is that PDR of HCCA also diminishes as the number of vehicles grows. By and large, it is believed that PDR of HCCA does not depend on the network load due to its deterministic characteristics. However, in this system, interactions with EDCA induce packet collision of HCCA, thereby reducing PDR of HCCA.

Fig.4 shows that delays of HCCA and EDCA are augmented as the number of vehicles increases. It is obvious that the growth in the number of vehicles leads to the increase in delay of EDCA due to EDCA’s intrinsic CSMA/CA mechanism.\(^3\) However, the delay of HCCA is also increasing, which is somewhat counter-intuitive. Moreover, delay of HCCA is long, which means that HCCA is no more suitable for most safety applications including "work zone safety system" [2]. The clue for this unpredictable outcome is an interaction between HCCA and EDCA. More specifically, our conjecture is that poll messages (i.e., traffic of HCCA) collide with vehicle status info message (i.e., traffic of EDCA) sent by hidden vehicles, thereby smart cones cannot send their warning messages at their designated time. Instead, the smart cones have to defer their transmissions until receiving the poll message in the next interval (e.g., after 200ms).\(^4\) Unfortunately, warning message may be generated within this interval, which leads to an increase in queuing delay. This conjecture is proved in Fig.5, which shows that poll collision rate rises as the number of vehicles increases.

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\(^1\) In Fig.4, the range of y-axis is so wide (0–7000) that EDCA delay seems to be flat.

\(^2\) In HCCA, BS cannot send the poll message immediately after collision because a retransmission mechanism is not specified for poll message.
D. Impact of the number of smart cones

In Fig. 6, we observe that PDRs of EDCA and HCCA do not depend on the number of smart cones. This is because network congestion does not increase even if the number of smart cones grows. In detail, only one smart cone attempts to access a wireless channel at a time. Thus, the number of devices that contend for channel access is same (i.e., one smart cone and multiple vehicles) even though the number of smart cones changes. The same argument can be applied to Fig. 7, on which delays of HCCA and EDCA traffic do not change as the number of smart cones varies.

E. Impact of Contention Window (CW) Size

As shown in Fig. 3, PDR of EDCA is below 50%, which is relatively low for supporting Quality of Service (QoS) of work zone safety applications. This is due to two properties of the broadcast mechanism: 1) lack of retransmission mechanism and 2) usage of fixed CW size (i.e., minimum CW size). Thus, CW size cannot adapt to variable network load, which results in low PDR. (e.g., 20% PDR when there are 200 vehicles in Fig. 3.) Based on the belief that control of CW size improves network performance [13], we observe performances according to CW size.
In Fig. 8, we observe that PDR of EDCA is augmented as CW size increases, which is quite obvious. An interesting observation in this figure is that PDR of HCCA decreases as CW size increases. Similar to Section IV-C, an interaction between HCCA and EDCA accounts for this result. In detail, when smart cones receive poll messages, they start packet transmission without carrier sensing. In other words, smart cones transmit packets regardless of whether channel is busy or not. Hence, as the channel is more occupied by others, corruptions of the smart cone’s packets happen more frequently. However, as is shown in Fig. 9, the fraction of channel-busy time caused by vehicle traffic grows as the CW size increases, which comes from reduction of collisions among vehicle traffics. As a result, a probability of collision between EDCA (i.e., vehicle status information message) and HCCA traffic (i.e., warning message) increases as CW size increases.

In Fig. 10, we observe that delay of EDCA increases and delay of HCCA decreases as CW size increases. The delay pattern of EDCA is obvious, but that of HCCA is somewhat counter-intuitive. The latter can be explained by Fig. 11, which shows that poll collision rate decreases as the CW size increases. To be specific, BS employs carrier sensing for poll transmission, and thus poll transmission is regarded as following CSMA/CA mechanism with PIFS and zero backoff count. Thus, the pattern of poll collision rate complies with pattern of EDCA. As a result, the poll collision rate decreases as CW size increases, which leads to a reduction of delay in HCCA.

F. Impact of Packet Size

In this subsection, we estimate performances according to packet size of EDCA traffic. It is noted that a generation rate of application-level data remains the same since application-level data are generated before packetizing the data. Thus, the pattern of poll collision rate complies with following CSMA/CA mechanism with PIFS and zero backoff count. For example, if the packet size of EDCA traffic is doubled, the packet generation interval should also be doubled, so the data generation rate remains the same.

As depicted in Fig. 12, we observe that PDRs of EDCA and HCCA increase as packet size increases. This is because the contention among vehicles and smart cones is reduced. Specifically, as the packet size grows, vehicles transmit less frequently, which leads to a reduction in the number of transmission attempts at a time. It is obvious that a reduction of transmission attempts leads to the decrease in contention, which in turn reduces packet collisions.

In Fig. 13, we observe that delay of EDCA increases as packet size of vehicles transmission grows. This is because the duration for transmitting EDCA packets is increased. On the other hand, the delay of HCCA is decreased as the packet size increases. As we explained in Section IV-C, delay of HCCA in this system is dominated by poll collisions. But, as depicted in Fig. 12, packet collision of EDCA and HCCA traffic is reduced, which can also be applied to poll message. As a result, the delay of HCCA diminishes as the packet size grows.

4 In Fig. 10, the range of y-axis is so wide (0–3000) that EDCA delay looks flat.
employed in IEEE 802.11 standard [11] or Forward Error
methods are to use Automatic Repeat reQuest (ARQ) that i s
guarantee reliable transmission of poll message. Simple

Thus, to improve delay performance, we must
previous section, the delay of HCCA is mainly caused by poll

As we discuss in Section IV-E, we also need to improve
PDR of EDCA when many vehicles share the channel. The
reasons of low PDR are two-folds: 1) lack of adaptation of
parameters to network conditions and 2) lack of retransmission
mechanism in broadcasting. As we can see in Section IV-E, the
increase in CW size improves PDR of EDCA and delay of
HCCA. However, the increase in CW size also decreases PDR
of HCCA. Thus, we have to find a balance between PDR of
EDCA, delay of HCCA and PDR of HCCA in controlling CW
size. Also, we find that the increase of packet size of vehicle
traffic induces improvements in PDR of EDCA and delay of
HCCA. However, as we explained in Section IV-F, long packet
size should be accompanied with long packet generation
interval. In this case, smart cones may not have enough vehicle
information and cannot generate warning message at a right
time. Clearly, one must find the appropriate packet size.
Another suggestion is to develop a reliable broadcasting

In this paper, we study the performance of a DSRC
vehicular network where EDCA and HCCA coexist to support
work zone safety. We find that the interactions between EDCA
and HCCA affect system performance, in some cases
producing somewhat counter-intuitive effects. Moreover, we
observe that the current combination of EDCA and HCCA
causes large delay in HCCA and low PDR in EDCA, making it
not suitable for supporting work-zone safety service. Through
an analysis of simulation results, we notice that poll message
collisions and high network load account for large delay of
HCCA and low PDR of EDCA, respectively. These results
pave the ground for possible improvements of the current
system, which will be the objective of our future work.

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5 In our study, we deploy up to 200 vehicles, which results in a quite long delay for most
safety applications. However, in practical situations, the maximum number of vehicles
can be larger than 200 (e.g., up to 300 vehicles in four lane one mile road according to
talk with Caltrans staff) even with high speed. When there are more vehicles, we can
easily expect without further experiments that delay of HCCA is much longer than
scenario of 200 vehicles.