WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2011; **11**:954–963
Published online 18 January 2010 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/wcm.921

SPECIAL ISSUE PAPER

Synchronization challenges in media access coordination for vehicular *ad hoc* networks

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ABSTRACT

Vehicular *ad hoc* networks (VANETs) can support a wide range of future cooperative safety and efficiency applications. However, the node density and high demand for wireless media in these networks can lead to the *Timeslot Boundary Synchronization Problem*, in which increased transmission collisions occur due to back-off timer synchronization. This paper proposes an enhancement to the wireless access in vehicular environments (WAVE) communications architecture to address this problem, called RAndom Propagation Initiation Delay for the Distributed Coordination Function (RAPID DCF). The effectiveness of RAPID DCF is evaluated through simulations of both single-hop and multi-hop emergency messages. In these simulations, RAPID DCF was able to improve message delivery rates by as much as 35% and reduce multi-hop message latency by as much as 18%. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS
VANETs; Timeslot Boundary Synchronization; wireless access in vehicular environments; emergency messages; vehicle heartbeat messages

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1. INTRODUCTION

Momentum continues to build for the deployment of vehicular ad hoc networks (VANETs) that will provide a key means for improving safety and efficiency on roadways. Bandwidth has been allocated for these networks, the wireless access in vehicular environments (WAVE) standards are in various stages of development, and large-scale test beds are being deployed. While the initial focus of these efforts has been on vehicle-to-roadside communications, the deployment of radio equipment in vehicles will also enable applications that rely on direct vehicle-to-vehicle communications in a VANET.

VANET applications will rely on multi-hop emergency messages and single-hop vehicle heartbeat messages, in which vehicles periodically transmit their position, kinematics, and other state data to nearby vehicles [1]. The multi-hop emergency messages include emergency SOS messages, post-crash warnings, and wrong-way driver warnings. These messages would be delivered *via* vehicle-to-vehicle communication to vehicles upstream of a dangerous situation. In addition, these messages could be relayed from vehicle to vehicle until they reach roadside radio equipment, where the appropriate emergency response could be triggered. In addition to these multi-hop messages, vehicles will broadcast single-hop, heartbeat messages at a very high frequency to enable a wide range of safety applications, e.g., cooperative forward collision warning, lane change warning, blind spot warning, cooperative collision warning, cooperative adaptive cruise control, highway merge assistant, and visibility enhancer.

Synchronization of demand for the wireless media in a VANET can occur in two ways. The clocks in the nodes can be synchronized *via* GPS, which are required equipment in each vehicle. At the application layer, the creation of messages might be synchronized using this common clock. At the media access layer, timeslot boundaries might also be synchronized using a common clock. Even without the use of a common synchronized clock, however, the timing of message transmissions and timeslot boundaries can become synchronized under a variety of situations, for example, when congestion in the network causes a number of nodes to delay their transmission. In addition to occurring during periods of heavy network congestion, this alignment can also occur due to the nature of multi-hop message propagation.

This synchronization can have an adverse impact on the performance of the network, through a mechanism called the timeslot synchronization problem. Through analytical models and simulation, this paper analyzes a variety of ways in which synchronization can adversely impact the performance of a WAVE-based VANET, with a particular focus on high-frequency vehicle heartbeat messages and multi-hop emergency messages.

In addition, the paper presents and evaluates strategies to mitigate this adverse impact including an extension to the Distributed Coordination Function (DCF), called RAndom Propagation Initiation Delay for the Distributed Coordination Function (RAPID DCF). RAPID DCF introduces small random delays throughout the back-off process to prevent Timeslot Boundary Synchronization both due to simultaneous message creation and due to network congestion. This approach provides two key advantages over previous approaches. First, it does not rely on an *a priori* assessment of the channel conditions when determining an appropriate back-off period. Thus, this approach works better than contention-window approaches for the types of unacknowledged broadcast messages, like the VANET heartbeat and emergency messages. Moreover, the adaptive mechanism in RAPID DCF introduces additional delays during the back-off process, enabling flexibility to respond to channel conditions that change after message creation. Second, because of the finer grained delays added by RAPID DCF, this approach can provide lower message latency and a reduced number of collisions compared to approaches that rely on changing the contention window (CW) size.

Simulations of vehicle heartbeat messages and emergency messages in WAVE networks demonstrate that the *Timeslot Boundary Synchronization Problem* does increase transmission collisions and message latency. Moreover, the simulation also shows that RAPID DCF can successfully mitigate this problem. RAPID DCF improved the ratio of errors to packets received by as much as 35% and reduced multi-hop message latency by as much as 18%.

2. RELATED WORK

Wireless vehicle-to-vehicle communication networks present unique characteristics not commonly seen in other mobile *ad hoc* networks [2]. The high relative velocities of vehicles cause dynamic network communications topology, in which the set of the nodes within radio range of a vehicle changes rapidly. This dynamic topology creates a challenge in the implementation of an efficient distributed system that mediates contention for the shared wireless media.

The WAVE standards adopt the Carrier Sense/Multiple Access (CSMA) approach of the IEEE 802.11 protocols. In this approach, transmitting nodes sense the media to make sure that it is idle before transmitting. This approach also includes a random delay and handshaking method to help prevent collisions of signals due to overlapping transmissions. Unfortunately, these features provide limited assistance for applications using unacknowledged broadcasts, as is the case with vehicle heartbeat messages.

The particular CSMA approach adopted by the WAVE standards is based on the 802.11 DCF with quality of service extensions specified in the 802.11e standard. In the DCF, when a frame arrives, it is put into the appropriate message queue, called an access category (AC), based on its priority. Each AC maintains a parameter called the CW size. A back-off timer is set to a random integer chosen from the interval [0 .. CW(AC) − 1], where CW(AC) is the contention window size for the channel. Before the back-off timer is started, the node must sense that the media has been idle for a period of time called the AIFS duration. Once the back-off timer is started, the value of the timer is decremented if the node detects that the media has been idle for another timeslot. If the node detects that the media has become busy, the back-off timer is halted. The medium then has to be idle for the duration of a SIFS period before the back-off procedure is allowed to resume. Once the back-off timer reaches 0, the node initiates its transmission.

For messages where the recipients are known, the DCF provides an acknowledgement (ACK) mechanism, which allows the back-off procedure to adapt to current network conditions. After sending a message, a node sets a timer while waiting for an ACK message. If the ACK message is not received before the timer expires, the node assumes that a collision has occurred. It reschedules the transmission of the previous message. First, though, it doubles the size of its CW, up to a maximum value called the CW_{max}. After it senses that its message has been received, the CW size is reset to its initial value, CW_{min}.

However, the DCF has limited ability to adapt to network conditions for unacknowledged broadcast messages, such as vehicle heartbeat messages and emergency broadcasts. Since no ACK is sent in response to these messages, nodes never detect that their transmission resulted in a collision and, consequently, never increase the size of their CW.

Other approaches allow for CW to adapt to network conditions without the ACK detection mechanism. For example, one dynamic adaptation algorithm enables each station to tune the size of the CW based on application requirements and channel conditions [3]. Rather than selecting a value from the interval [0..CW − 1], another approach has nodes select a back-off value from a sliding CW defined for each network flow [4]. The sliding window dynamically adjusts to changing network conditions.

Network layer VANET protocols also have an effect on media contention process. These protocols must operate well in both extremely sparse and extremely dense situations. In sparse situations, the protocols must forward the messages even in the face of network fragmentation which prevents the immediate forwarding of messages to all nodes. In dense situations, the protocols must manage scarce bandwidth and efficiently forward messages.

In sparse network situations, epidemic routing protocols employ a store and forward approach to handle situations where no path exists between the source and destination nodes [5,6]. In these approaches, each node contains a queue of messages to be delivered. When a node encounters another node, the nodes exchange the IDs of messages in their queues. Messages that have not been seen by a node will be exchanged.

In order to efficiently forward messages in dense network situations, the network protocols must manage contention for the bandwidth. Simple flooding of multi-hop messages can lead to the Broadcast Storm problem, in which collisions and message latency significantly increases with increases in node density [7]. Previous research has addressed the Broadcast Storm problem by attempting to limit the nodes that forward the messages, for example, by limiting retransmission to nodes further from the source than the last hop.

Efficient forwarding of messages in dense network situations also requires that the length of each hop be as long as possible. Various approaches make nodes furthest from the last hop most likely to forward the message. For example, a delay before forwarding can be imposed on nodes that is a function of the distance from the last hop [8,9]. The delay can also be a function of the number of new nodes that would be reached by forwarding the message [10].

Edge-aware routing protocols attempt to address both sparse and dense network situations [11]. In these protocols, nodes repeatedly broadcast emergency messages. By adjusting the probability with which a node repeats a message and the delay before the next repetition, nodes furthest from the source of the message are more likely to retransmit the message.

3. SYNCHRONIZATION ISSUES AND RAPID DCF

Concurrent message transmission, leading to collisions, can occur due to synchronization at both a macro-level and micro-level. Synchronization at the macro-level can occur when multiple nodes attempt to create or forward messages at the same time. At the micro-level, timeslot boundaries can become synchronized when multiple nodes are forced to pause their back-off timer due to a transmission. Both macro-level and micro-level synchronization can be addressed at the data link layer, for example, through extensions such as RAPID DCF.

3.1. Contention-window-based collision mitigation strategies

Adjusting the size of CW can significantly decrease the probability of transmission collisions. Consider a scenario in which a large number of nodes create messages at the same time. For example, with vehicle heartbeat messages sent at 10 Hz, all vehicles could initiate their messages on a tenth-of-a-second boundary. The primary mechanism for reducing the total number of collisions with the DCF would be an increase in the size of CW_{min}.

The relationship of the CW_{min} and the number of collisions can be illustrated using the following model. Assume an ideal radio propagation model and a scenario in which all nodes are within radio range of each other. Assume further that all nodes transmit their messages during a given tenth-of-a-second interval, i.e., there are no transmissions from a previous interval that must also be sent.

A collision will occur if two nodes choose the same value for the back-off timer. Thus, the probability that two arbitrary nodes will not cause a collision with each other is

$$\text{pr(no collision for 2 nodes)} = 1 - \frac{1}{CW_{min}}$$

Given n nodes within radio range of each other, the probability that none will create a collision with a given node is

$$\text{pr(no collision for } n-1 \text{ nodes)} = \left(1 - \frac{1}{CW_{min}}\right)^{n-1}$$

Furthermore, given that there are $n-1$ transmissions each period, the expected number of transmissions that will be received clearly by any given node can be expressed as

$$\text{E(clear transmissions)} = (n-1)\left(1 - \frac{1}{CW_{min}}\right)^{n-1}$$

From this equation, when all vehicles initiate transmission simultaneously, we can see that increasing the size of the CW_{min} (up to the point where all messages are still transmitted during a given interval) will increase the transmissions received.

3.2. The timeslot boundary synchronization problem

Consider two nearby nodes attempting to send a WAVE message at the same time. If we allow the CW size to adapt to channel conditions, we can provide some protection against transmission collisions. A transmission collision at other nearby nodes would occur only if the two nodes choose the same value for their back-off timer. However, if nodes initiate their transmissions at *approximately* the same time, a transmission collision may not occur even if the nodes choose the same value for their back-off timer. Indeed, a collision only occurs if their timeslot boundaries are aligned.

Consider node 1 in Figure 1, which creates a message at time t_1. After sensing that the media is idle for the required time, it begins its back-off timer. After the back-off timer expires, the node switches its radio from receive to transmit. This Rx − Tx turnaround time (t_{Rx-Tx}) lasts approximately 2 μs. After a propagation delay of approximately 0.5 μs ($t_{Propagation}$), the message would reach node 2. If node 2 is

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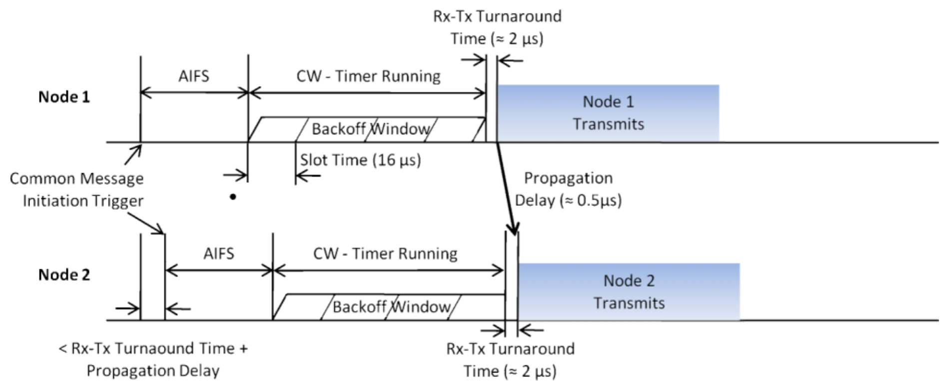

Figure 1. Near simultaneous message creation without collisions.

still monitoring the media, after a MAC-layer processing delay of approximately 1 µs (t_{MAC}), it would detect that the media is busy. At this point, it would halt its back-off timer and not create a potential transmission collision. On the other hand, a transmission collision would occur under these three cases:

(1) $t_1 > t_2$ *and* $t_1 < t_2 + t_{RX-TX} + t_{Propagation} + t_{MAC}$

(2) $t_1 = t_2$

(3) $t_1 > t_2$ *and* $t_2 < t_1 + t_{RX-TX} + t_{Propagation} + t_{MAC}$

We say that the timeslot boundaries of node 1 and node 2 are aligned if they satisfy one of the three cases above. Typical values for the length of time, $[2(t_{RX-TX} + t_{MAC} + t_{Propagation})]$, produce a total span of approximately 7 µs.

3.3. Timeslot boundary synchronization in WAVE-based VANETs

WAVE networks, in particular, tend to create alignment in timeslot boundaries. This alignment arises from the time synchronization mechanisms in the network, the multi-channel coordination function, common message initiation triggers, and congestion.

The on-board equipment will use GPS signals for both position information and as a universal timer. Applications

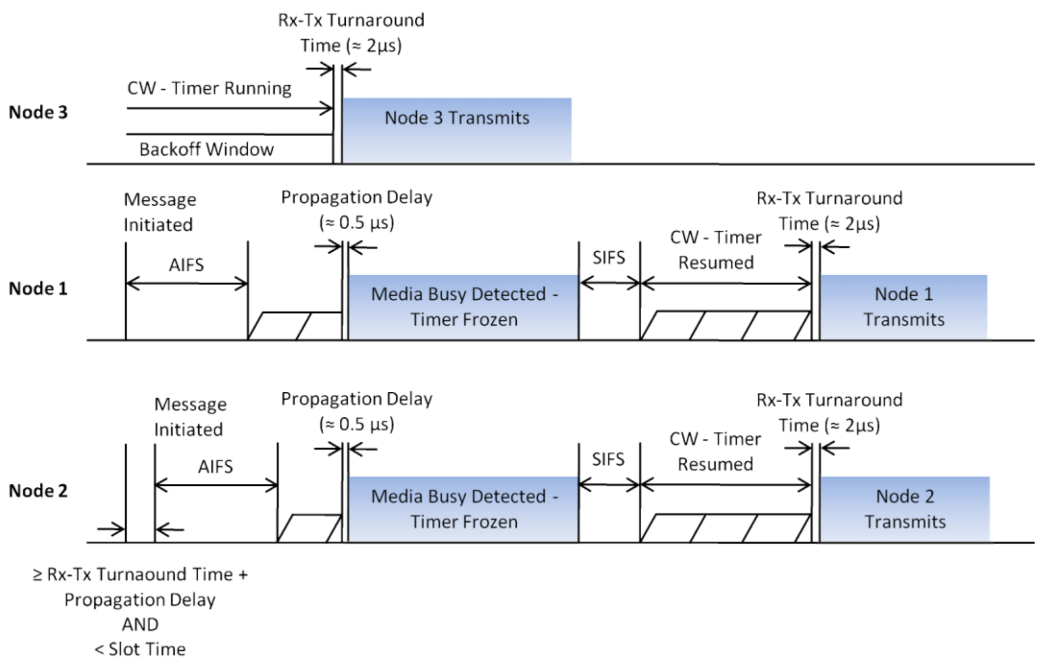

Figure 2. Near simultaneous message creation causing collision in congested network.

that use this common timer to trigger message creation may cause Timeslot Boundary Synchronization by triggering messages at common times.

Timeslot boundaries can also become aligned if messages are created near simultaneously due to common initiation triggers. In WAVE networks, multi-hop message propagation is one possible common trigger [12]. Here, Timeslot Boundary Synchronization can occur when two nodes forward the same multi-hop message.

The GPS timer will be used by all nodes for the WAVE Multichannel Coordination function. This function divides time into periods called the control channel (CCH) interval and service channel (SCH) interval. At the beginning of each interval, there is a 4 ms guard interval during which no transmissions are allowed. At the end of this interval, timeslot boundaries are aligned for any nodes with pending transmissions.

Network congestion provides a similar means for synchronizing the timeslot boundaries. If there is a transmission while multiple nodes are running their back-off timer, all nodes will freeze their back-off process during the transmission. At the end of the transmission, these nodes will restart their timers with the boundaries of their timeslots aligned.

For example, consider Figure 2 inset, in which the timeslot boundaries for nodes 1 and 2 initially are not aligned. However, while their back-off timers are running, both detect a transmission from node 3. After the transmission ends, their timeslot boundaries are roughly aligned, with the exception of small deviation in propagation time based on their distance from node 3. Because their timeslot boundaries are now essentially synchronized, they transmit their messages at the same time resulting in a collision.

3.4. Enhancing contention-window-based strategies

The primary drawback to contention-window-based collision mitigation strategies is that increases in the CW size increase message latency. On the other hand, the effectiveness of these strategies can be improved without a large increase in message latency, by addressing the Timeslot Boundary Synchronization Problem.

RAPID DCF directly addresses the synchronization problem at the link layer. RAPID DCF adds a pseudo-random delay to the SIFS in order to keep these boundaries from aligning due to congestion in the network. The length of the delay chosen from the interval is 0–16 μs, the length of one timeslot.

Moreover, since the AIFSD is calculated based on the SIFS, RAPID DCF also addresses the issue of timeslot synchronization when applications create messages at the same time, for example, when multiple nodes are attempting to forward a message simultaneously. Suppose node 1 and node 2 initiate message creation simultaneously, and both choose the same value for their back-off timer. Using standard DCF, a collision would occur. However, with RAPID DCF no collision will occur as long as the random AIFS delays chosen by node 1 and 2 are sufficiently far apart.

Now, assume that a third node transmits a message freezing both the back-off timers of nodes 1 and 2 (as was the case in inset Figure 2). Again, as long as the SIFS delays chosen by node 1 and 2 are sufficiently far apart, no collision will occur.

The collision mitigation effect of RAPID DCF can be compared to contention-window approaches. The net effect of staggering the timeslot boundaries in RAPID DCF is to decrease the chance of the collisions by approximately the same amount as increasing in the CW by a factor of

$$\frac{t_{\mathrm{Timeslot}}}{t_{\mathrm{Rx-Tx1}} + t_{\mathrm{Rx-Tx2}} + t_{\mathrm{MAC1}} + t_{\mathrm{MAC2}} + 2\,t_{\mathrm{propagation}}}$$

For a 16 μs timeslot, 2 μs Rx − Tx turnaround time, 1 μs MAC processing delay, and 0.5 μs propagation time, RAPID DCF produces the same reduction in the number of collisions as would be expected from increasing the CW by a factor of 2.29.

Therefore, RAPID DCF provides three key advantages over previous approaches. First, it does not rely on an *a priori* assessment of the channel conditions when determining an appropriate back-off period. Thus, this approach works better than contention-window approaches for unacknowledged broadcast messages, like the VANET heartbeat and emergency messages. Moreover, the adaptive mechanism in RAPID DCF introduces additional delays during the back-off process, enabling flexibility to respond to channel conditions that change after message creation. Third, because of the finer grained delays added by RAPID DCF, this approach can provide lower message latency and a reduced number of collisions compared to approaches that rely on changing the CW size.

4. SIMULATION SYSTEM

The WAVE Communications Architecture was implemented in the widely used, commercial network simulator Qualnet in order to evaluate the effect of RAPID DCF on the delivery of vehicle heartbeat and emergency messages in VANET. Existing, validated communication protocols were extended to reflect the changes described in the WAVE standards. In addition, the vehicle mobility patterns were based on simulations developed in the CORSIM microscopic vehicle simulator [13].

The WAVE physical layer is based on the IEEE 802.11a standard with modifications including [14,15]:

- *Allocated spectrum*: WAVE uses spectrum allocated at 5.9 GHz, and includes a channelization plan that calls for a single CCH and multiple SCHs. These simulations used the WAVE SCH 184, with a bandwidth of 10 MHz.

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DOI: 10.1002/wcm

- *Supported data rates*: The supported data rates in the 802.11p channels are half of the ones supported by 802.11a, and the simulations here assume that broadcast messages will be transmitted at 3 Mbps.
- *Timing changes*: Timing changes have been made to support the high relative velocities in the vehicular environment. These changes include a longer synchronization time for the orthogonal frequency-division multiplexing [16].
- *Transmission power levels*: The maximum transmission power allowed for private operations, such as vehicle heartbeat messages, is 28.8 dBm. In order to facilitate that fast multi-hop message propagation, this power transmission power was chosen for the emergency messages. For the vehicle heartbeat messsages, however, the transmission power level chosen was 13.4 dBm, which with a 0.3 dBm antenna mismatch loss rate, providing a radio range of approximately 150 m. Vehicle manufacturers have indicated that this radio range would be sufficient for most of the vehicle heartbeat applications [1].

The WAVE data link layer is based on the 802.11a standard with 802.11e extensions to support differentiated levels of service [17]. Changes in the WAVE data link layer include

- *Multi-channel coordination*: A multi-channel coordination function provides specific rules regarding monitoring of and transmission on the CCH and SCH [16]. By default each tenth-of-a-second interval is divided in half into a CCH interval and SCH interval. Dual-band radios, such as ones assumed for these simulations, may broadcast on an SCH during either interval. However, at the beginning of each interval, there is a guard interval, by default 4 ms long, during which no transmission is allowed on any channel.
- *Changes to the DCF*: The 802.11p makes a number of timing-related changes to the DCF. During the guard intervals, a channel busy indication is set during the guard intervals, which freezes the back-off timer [16]. In addition, the maximum size of the CW is 511, instead of 1023. The WAVE slot time is increased from 9 to 16 μs. The SIFS is increased from 16 to 32 μs. The AIFS varies as a function of the AIFS number associated with a class of traffic, the slot time, and the Short InterFrame Space (SIFS). Due to an increase in both the slot time and the SIFS, the AIFS is longer in WAVE. The AIFS for these simulations was set to the default for SCH background traffic, which is 144 μs [17].

For the multi-hop emergency messages, the network layer protocol incorporates mechanisms to address the problems that arise in dense network environments, addressing both the broadcast storm problem and creating long message hops. Vehicles are assumed to be equipped with GPS equipment, and the WAVE message format includes fields with the location of the message sender. Nodes use this position information and only forward the message if they are hearing the message for the first time and if the message was received from a node that is closer to the source of the message. However, before a node forwards the message it first waits for a period of time that is inversely proportional to its distance from the last hop.

User Datagram Protocol (UDP) is used for the transport layer. At the application layer, the most important characteristics of the messages include

- *Heartbeat message frequency*: In these simulations, messages are transmitted at the 10 Hz as called for by vehicle manufacturers [1].
- *Heartbeat message size*: The size of the application layer messages in these simulations is 362 bytes, which include the application layers headers, the message data, and digital signatures. The heartbeat messages may contain a range of fields, such as those specified by the probe vehicle service [18]. In addition, the integrity of messages will likely be protected by digital signatures and certificates [19].
- *Emergency message size*: The size of the emergency messages was set at 411 bytes. This message size is sufficient to include the application layers headers, the message data, and digital signatures [16].

The vehicle mobility in the simulation was based on vehicle traces from the microscopic vehicle simulator CORSIM [13]. CORSIM was used to simulate rush-hour traffic on I-880 in Hayward, California, based on traffic flow data collected on various dates in 1993 by the Freeway Service Patrol Evaluation Project at the University of California, Berkeley [20]. The density of traffic in these scenarios was approximately 125 vehicles per kilometer.

5. RESULTS

The results of the simulations show that RAPID DCF addresses the Timeslot Boundary Synchronization both for vehicle heartbeat messages, when a large number of nodes attempt to create heartbeat messages at synchronized intervals, as well as with emergency messages, where multiple nodes may attempt to forward the emergency messages simultaneously. The improvement in the message delivery rate for heartbeat messages, varied as a function of the CW Size, with a maximum improvement of 35% for small values of CW. In addition, RAPID DCF reduced the time required for the multi-hop message propagation by as much as 18%.

The vehicle heartbeat message simulations were run for a variety of different values for CW_{min}. The duration of each simulation was 30 s. In order to simulate the network under the heaviest loads, all of the nodes initiate their heartbeat messages simultaneously on each tenth-of-a-second boundary.

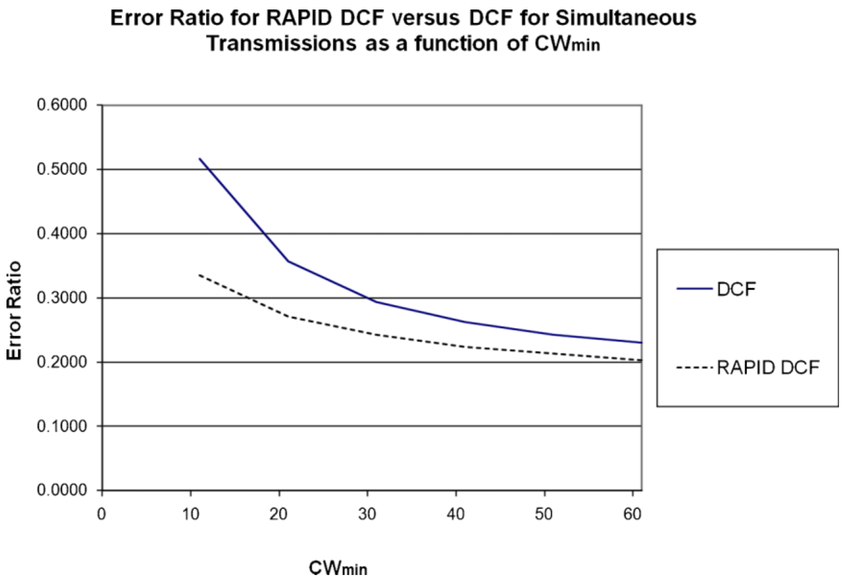

Figure 3. Ratio of packet collisions to packets received for vehicle heartbeat message scenarios.

At the end of the simulation, the ratio of collisions to packets received was calculated for the vehicles that were between the 2 and 8 km on the simulated highway for the entire simulation duration. Thus, the results excluded vehicles that entered or exited the highway during the simulation, as well as vehicles near the end-points of the simulated highway.

When a large number of vehicles attempt to create the vehicle heartbeat messages simultaneously, this small random delay improved the collision ratio especially for small values of the CW_{min}, as shown in Insert Figure 3. As expected, the performance of both DCF and RAPID DCF improve with larger values of CW_{min}.

When the CW_{min} is 11, RAPID DCF improves the error ratio by 35.2%, as shown in Table I. As the CW_{min} increases, the amount of improvement decreases to 11.6% for a CW_{min} of 61. Increasing the size of CW_{min} comes at the expense of increased message latency. Moreover, RAPID DCF offers the advantage of automatically fine-tuning its delay in response to congested network conditions.

In these scenarios, the large number of simultaneous transmissions gives rise to the Timeslot Boundary Synchronization Problem. In addition, this synchronization problem also arises in situations where there is media contention due to nodes attempting to simultaneously forward the same emergency message.

Table I. Improvements in ratio of packets collisions to packets received by RAPID DCF over 802.11 DCF with simultaneous message creation.

CW_{min}	Improvement (%)
11	35.2
21	24.1
31	17.5
41	14.7
51	12.3
61	11.6

To avoid timeslot synchronization, in the simulations of the multi-hop emergency message broadcast, the network layer protocol adds a delay of up to 256 μs, which is inversely proportional to the distance from the last hop. The resolution of the delay is measured in nanoseconds, rather than timeslots in order to help avoid Timeslot Boundary Synchronization. At 1.5 s in a simulation, a vehicle at the 2 km mark in the simulation issues an SOS message. There are roadside units placed every 1 km along the roadway, beginning at the 3 km mark and ending at the 8 km mark. The propagation time to each of these roadside units is measured.

With this fine-grained delay introduced by the network layer, the timeslot boundaries, which would otherwise be synchronized by the near simultaneous receipt of the message to be forwarded, are staggered in time by the near continuous nature of the delay imposed at the network layer. However, Timeslot Boundary Synchronization can still occur due to network congestion. This phenomenon is evident in the propagation time difference between the simulations that used RAPID DCF at the link layer and the simulations that used the WAVE DCF.

Figure 4 inset depicts the average message latency experienced at the roadside units over 30 simulations. At the roadside unit located 1 km from the message source, RAPID DCF reduce message latency by 8%. As the message travels further, network congestion increases due to an increase in the number of nodes forwarding the message. This increased congestion causes the *Timeslot Boundary Synchronization Problem* that adversely affects the performance of the system that uses the WAVE DCF. By successfully addressing this synchronization problem,

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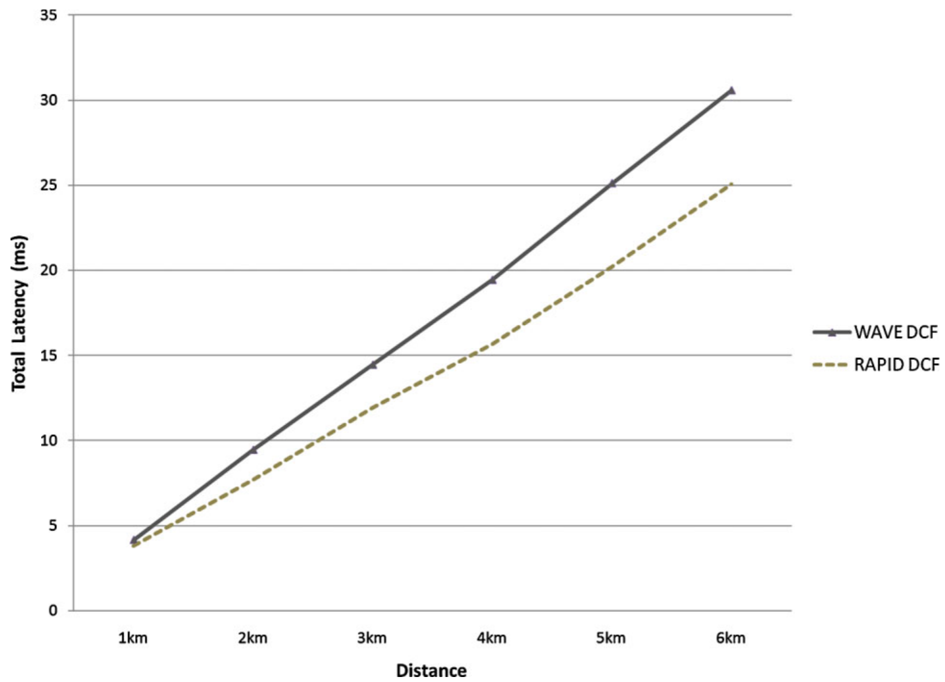

Figure 4. Multi-hop message latency with RAPID DCF *versus* WAVE DCF.

the reduction in message latency produced by RAPID DCF more than doubles to 18%.

6. CONCLUSIONS AND FUTURE WORK

This paper explored transmission collisions that arise in WAVE-based VANETs due to synchronization reasons. Two distinct types of synchronization were explored. When multiple nearby nodes create messages at the same time, collisions will occur unless all nodes chose a different initial value for their back-off timer. In addition, the synchronization of timeslot boundaries is also responsible for an increase in message collisions. Timeslot synchronization can be the result of both simultaneous message creation as well as back-off timer suspension due to congestion in the network.

This paper proposed RAPID DCF as a potential solution for these synchronization issues. Simulations of heartbeat messages in a VANET demonstrated the potential of RAPID DCF to improve the message delivery rate, especially for simulations with small values for CW_{min}. In these simulations, synchronization-induced collisions make up a larger proportion of the total number of collisions. Simulations of emergency message broadcasts showed that RAPID DCF can also address the *Timeslot Boundary Synchronization Problem* that arises when multiple nodes compete to forward a multi-hop emergency message. In these simulations, RAPID DCF reduced the multi-hop message latency by as much as 18%.

Future work, which the authors intend to perform, includes further study of RAPID DCF in different traffic scenarios and in support of different VANET applications. Further study will include parametric studies of RAPID DCF. Additional study will also include other applications in which synchronization is likely to occur, e.g., when multiple nodes respond to a service advertisement from roadside equipment. The authors also plan to evaluate timeslot boundary alignment in field tests to investigate this phenomenon with actual devices. These devices will automatically introduce random delay to a certain extent due to clock divergence and diverse processing speeds. While this delay may serve to limit the alignment, given the synchronization of these devices through GPS, the timeslot boundary alignment problem will likely remain a significant issue, especially in dense traffic situations.

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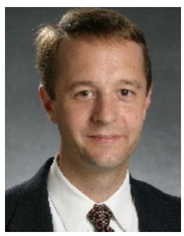

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