IEEE 1609.4 DSRC Multi-Channel Operations and Its Implications on Vehicle Safety Communications

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Abstract

This paper provides an overview of IEEE 1609.4, a work in progress standard for multi-channel operations over the 5.9GHz Dedicated Short Range Communications (DSRC) spectrum. In the U.S., the DSRC spectrum is organized into several channels. IEEE 1609.4 defines a time-division scheme for DSRC radios to alternately switch within these channels to support different applications concurrently. We describe the main features of IEEE 1609.4 in detail and discuss the main concerns with the original protocol design. In particular, we focus on those issues that can have a significant impact on vehicle safety communications. While IEEE 1609.4 is currently being updated and revised, this paper is intended to contribute to the technical discussions, and to bring attention to the most relevant and critical issues. This paper also contains results from software simulations conducted to study vehicle safety communications under stressful but realistic conditions. These results confirm concerns for the currently proposed scheme and provide a motivation for updating and revising the standard.

1. INTRODUCTION

1.1 DSRC Overview

DSRC is a 75MHz wide spectrum band at 5.9GHz allocated by the U.S. Federal Communication Commission (FCC) for exclusive vehicle-to-vehicle and infrastructure-to-vehicle communications [1, 2]. A similar band was recently allocated in Europe for the same use [11].

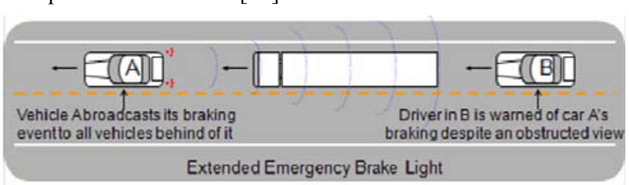

Figure 1 Vehicle safety communications example

The allocation of the DSRC spectrum is primarily intended to support public safety applications that reduce the number and severity of motor vehicle accidents, save lives, and improve traffic flow. The availability of effective localized communications supporting timely information sharing among vehicles and infrastructure would enable the development of a wide range of safety applications to prevent or reduce the impact of accidents. An example of vehicle-to-vehicle applications is shown in Figure 1.

The U.S. FCC also explicitly allows for non-safety DSRC applications to encourage development and deployment of DSRC technologies.

The U.S. DSRC spectrum is made up of seven 10MHz wide channels, as shown in Figure 2. Channel 178 is the control channel (CCH), which is the default channel for common safety communications. The two channels at the ends of the spectrum band are reserved for special uses. The rest are service channels (SCH) available for both safety and non-safety use. Advertisement messages broadcast over the CCH to provide information on which services are currently available on which service channels, so that radios can tune to a service channel if desired.

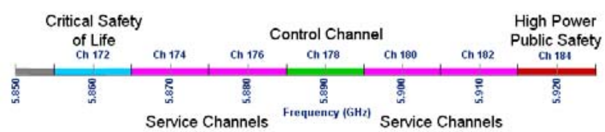

Figure 2, DSRC spectrum and channels in the U.S.

1.2 DSRC Protocol Stack

As shown in Figure 3, the DSRC stack incorporates a number of protocols and corresponding standards. An amendment to the IEEE 802.11 standard [3], known as IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) [4], provides the basic radio standard for DSRC. IEEE 802.11p is limited by the scope of IEEE 802.11, which is strictly a MAC and PHY level standard meant for single physical channel operations. All the complexities related to the DSRC multi-channel setup and operational concepts are taken care of by the upper layer IEEE 1609.x protocols. In particular, IEEE 1609.3 covers the WAVE connection setup and management [5], while IEEE 1609.4 sits right on top of IEEE 802.11p and enables operation of upper layers across multiple channels, without requiring knowledge of PHY parameters [6].

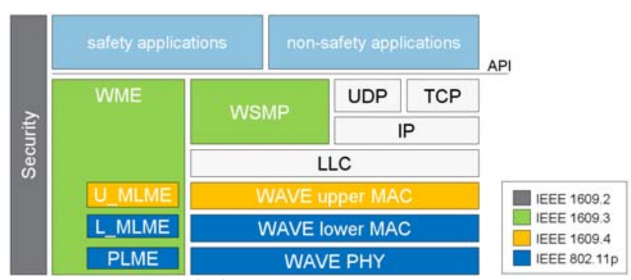

Figure 3, DSRC standards and communication stack

This paper focuses on IEEE 1609.4. It was introduced mainly to address the following question:

> *How does a DSRC onboard unit, with a single radio, support concurrent safety and non-safety*

communications if these activities are segregated into different channels?

The rest of the paper is organized as follows: Section 2 provides an IEEE 1609.4 primer; Section 3 discusses known issues for this standard; Section 4 describes the simulation setup used in evaluations; Section 5 analyzes the simulation results; And section 6 gives a summary of efforts and proposals to improve the standard.

2. IEEE 1609.4 STANDARD PRIMER

2.1 History and Purpose

Version 1 of all the IEEE 1609.x standards was finalized and published in 2006 and 2007. IEEE 1609.4, for example, has a publication date of November 29, 2006 [6]. Version 1 of this standard family was classified as trial use standards intended for prototyping and experimentation over a period of two years. Currently, the IEEE 1609 standardization committees have started the process of addressing issues encountered in the trial period and updating the standards accordingly. The discussions of IEEE 1609.4 in this paper are based on version 1.2 [7].

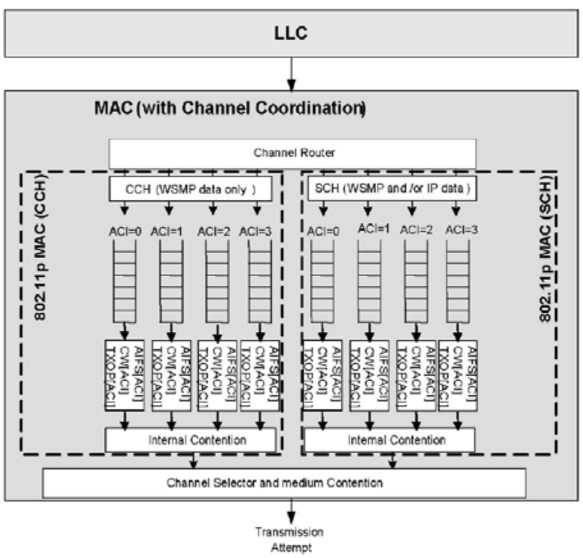

Figure 4 IEEE 1609.4 works on top of the IEEE 802.11p MAC

As shown in Figure 4 above, IEEE 1609.4 describes its scope as covering multi-channel operations of IEEE 802.11p radios. In particular, it describes the operation of control channel and service channel interval timing, and channel switching and routing.

2.2 Multi-Channel Operation Approach

As illustrated in Figure 5, IEEE 1609.4 describes a concept of channel intervals in which time is divided into alternating Control Channel (CCH) and Service Channel (SCH) intervals. The general concept calls for each interval to be 50ms long. A pair of a CCH and SCH intervals forms a Sync interval. There are ten Sync intervals per second. This is motivated by a desire to map Sync intervals to the generally assumed 10Hz vehicle safety messaging rate. The start of a CCH interval is aligned with the start of a Coordinated Universal Time (UTC) second (see section 2.4) or multiples of 100ms thereafter.

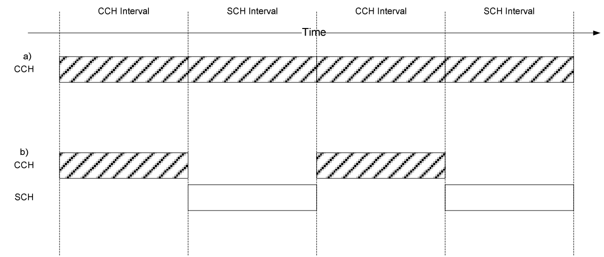

Figure 5 Channel intervals and continuous/alternating channel access

It is generally envisioned that a DSRC onboard unit should, by default, be tuned to the CCH to send and receive safety messages continuously. If it is engaged in some non-safety application communications in a SCH, then it is expected to actively switch between CCH and SCH channels for the duration of the service session[1]. With this alternating channel access, the DSRC radio is used for safety communications during CCH intervals and used for other applications during SCH intervals.

Each DSRC radio, even if it is in continuous access on the CCH, is expected to track the start and end of CCH and SCH intervals at all times. The concept is that such a radio would send safety messages during the CCH interval for the benefit of other nearby radios that might be engaging in alternating channel access.

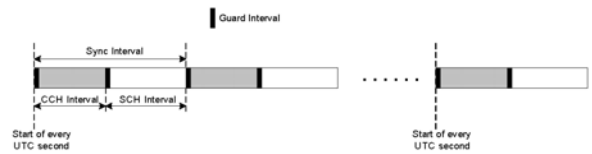

Figure 6 CCH, SCH, Guard and Sync intervals

The standard further defines a Guard interval at the start of each channel interval, be it SCH or CCH. This is meant to account for "radio switching and timing inaccuracies among different devices." Accordingly, the Guard interval is defined as the sum of the Sync_Tolerance and Max_Channel_Switch_Time parameters. Sync_Tolerance describes the expected precision of a device's internal clock in aligning to the UTC time. Max_Channel_Switch_Time is the time overhead for a radio to be tuned to and made available in another channel. Currently, the assumed value for the Guard interval ranges from 4 to 6 ms.

If a radio is actively switching channels, it suspends MAC activities at the start of a Guard interval. After the channel switching and at the end of the Guard interval, it starts the communications activities in the new channel or resumes such activities if they were suspended from the last Sync interval.

2.3 Transmission and Reception While Switching Channels

Transmission is not allowed to start in the Guard interval. If a transmission is not finished at the start of a Guard interval, there is an optional mechanism to cancel the transmission. The current

[1] The mechanisms for advising services available on SCHs and service session setup are covered in IEEE 1609.3.

standard, however, suggests that efforts should be made to avoid such instances through careful scheduling.

Generally, messages not sent during a particular channel interval are kept in queues corresponding to that channel until the next cycle. However, there is also an interface to describe an expiry time for DSRC specific data frames so that the MAC may purge the frames if they are not transmitted in time.

For a receiver, if a Guard interval starts while it is still in the reception process of a frame, it is required to instruct the PHY to abandon the reception.

The current standard recognizes the likelihood of simultaneous transmissions at the end of a Guard interval if multiple radios have pending frames in their queues. It requires the radio to declare media busy during Guard intervals in order to have all transmission attempts subject to random back-off at the start of each channel interval.

2.4 Time Synchronization

The IEEE 1609.4 scheme necessarily requires all devices to maintain synchronization with boundaries of seconds within a common time reference. Global Positioning System (GPS) reception is generally the preferred method of keeping precise timing. If a device does not have direct access to precise timing sources, it can acquire timing information over the air from other devices.

The over the air time synchronization method works by taking advantage of time information present in the WAVE Timing Advertisement frames [4]. The time information describes, in microseconds, the timing difference from the last UTC second start. A device must achieve a certain synchronization level with the UTC time to be a provider of timing information over the air.

2.5 Anonymity and MAC Address

There is general agreement to support anonymity in vehicle safety communications (e.g., to prevent routine speeding ticket issuance based on permanent and unique IEEE 802.11 MAC addresses used in safety communications).

Since SCH communications may reveal the identity of a device (and its owner), it is necessary for the MAC address used in the CCH to be decoupled from the one used in the SCH. The MAC address used in the CCH also needs to be changed at some level of frequency. The exact mechanisms and timing parameters remain the subject of debate at this moment.

3. KNOWN ISSUES OF IEEE 1609.4

3.1 Inefficient Channel Utilization

The clearest issue with IEEE 1609.4 is channel utilization. While a device is allowed to stay on the CCH and send and receive vehicle safety messages at all times, it is generally expected that it should schedule its safety message transmission during the CCH intervals to accommodate the safety needs of vehicles nearby that are actively channel switching to engage in other applications in SCHs. This effectively more than doubles the communications density during the CCH interval on the CCH in comparison to all devices using the full CCH all the time for safety communications. In turn, over the air safety message performance for all vehicles suffers.

3.2 No Differentiation of Distances to Service Coverage Areas

A vehicle is in one of the three following states at any time:

1. Within the coverage area of some service offered on a SCH
2. Outside of a service coverage area but close to it
3. Far away from any locations where some services are offered on SCHs

For a vehicle in the first state, scheduling safety message transmissions according to CCH intervals to accommodate other vehicles participating in channel switching is reasonable.

For a vehicle in the second state, it still should schedule its safety message transmissions accordingly to accommodate neighboring cars already in the coverage area. But it should enjoy better reception performance of safety messages outside of the CCH intervals from vehicles even further away from the service area.

For a vehicle in the third state, it has no need to schedule anything. It should use the CCH all the times.

The problem for IEEE 1609.4 is that there is no mechanism whatsoever to help a vehicle understand which state it is in. Therefore, all vehicles need to schedule safety transmissions conservatively as in states 1 and 2.

3.3 No Migration Path to Multi-Radio Devices

There are many reasons to assume single radio based DSRC platforms and, in turn, the need for the IEEE 1609.4 standard. These reasons are generally economic in nature, but also touch technical/engineering ones as well. Multiple radios obviously cost more money, but this cost could go down quickly. Multiple RF grade cables and the manufacturing process of installing them in the car are hidden but important costs that are unlikely to go down much over time. The placement of multiple antennas poses a challenge in vehicle design and can introduce adjacent channel interference problem [8].

Nevertheless, if and when such issues are resolved, there is every reason to expect multi-radio based DSRC platforms to be deployed. And they should be able to take full advantage of the DSRC spectrum. However at this time, there is no clear understanding of how IEEE 1609.4 compliant single radio devices would co-exist with multi-radio devices.

3.4 Likely Synchronized Collisions at Start of a Channel Interval

Last but not the least, there is a high likelihood for synchronized collisions at the start of a channel interval among devices with accumulated frames ready to be sent. This problem is briefly discussed in this subsection and will be demonstrated further in the simulation results later.

A troubling example of this scenario is vehicle safety communications. Assuming vehicle safety applications are not implemented with a full understanding of the underlying IEEE 1609.4 layer to schedule the generation of safety messages carefully according to the CCH intervals, it would be quite likely for safety messages to be generated during Guard and SCH intervals. In fact, if the upper layer applications are not explicitly designed around IEEE 1609.4, more than 50% of safety messages could be generated outside of CCH intervals. All those messages are queued up and ready to contend for channel access at the start of the next CCH interval.

Let's consider a potential scenario. Assume there are 100 vehicles in a local area and all are generating safety messages at 10Hz as commonly expected. On average, more than 50 vehicles would have one safety message each in the queue at the start of a CCH interval. The random back-off mechanism of IEEE 802.11, with a contention window size of 16 for broadcast frames, simply is not meant to resolve this scale of channel access contention. Let's further say that after 1 time slot, 6 vehicles' radios count to zero and transmit. All six frames collide with each other and are mostly lost among the intended audience. This leaves 44 vehicles still waiting and all of their back-off counters already reduced by 1. So another round of collisions will almost certainly happen, then another round, and so on and so forth. Eventually, all 50 vehicles' messages will likely collide with one or another and become lost. An example of synchronized collisions is visually illustrated in Figure 14 in Section 5.

4. SIMULATION SETUP

4.1 IEEE1609.4 Emulation in NS-2

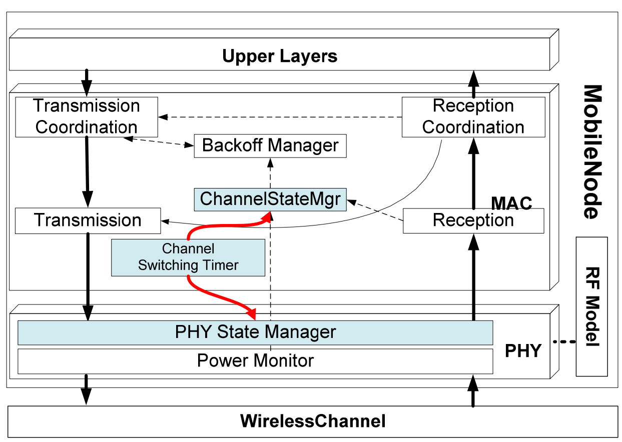

Figure 7 Modification to NS-2 simulator for IEEE 1609.4 emulation

The simulator used is NS-2 release version 2.33 [9]. In this version, a completely overhauled IEEE 802.11 simulation engine design and implementation is introduced [10]. Figure 7 shows the modular design of the IEEE 802.11 MAC and PHY. The colored modules and signaling paths are new or modified components used in this study to model IEEE 1609.4 channel switching.

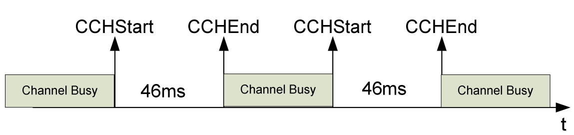

Figure 8 Channel state in IEEE 1609.4 emulation

This study is intended to evaluate vehicle safety communications performance in the CCH while radios are participating in IEEE 1609.4 compliant channel switching activities. As such, it is not necessary to simulate two or more concurrent channels per se. All that is necessary is to emulate the behaviors on the CCH to achieve the goal. In short, the strategy is to disable the radio at proper times to correspond to Guard and SCH intervals. This is illustrated by Figure 8.

A new module Channel Switch Timer is created to manage channel switching timing and generate events in the NS-2 simulator. It signals the Channel State Manager in the MAC at the start and end of every CCH interval. In turn, the Channel State Manager declares the channel available or busy accordingly. In this study, the Guard interval is modeled as 4ms so each CCH interval is effectively 46ms.

The Channel Switching Timer also informs the PHY of channel switching events. The PHY abandons unfinished receptions by setting an error flag for the MAC to declare CRC check failure. In other words, start of a Guard interval terminates all the active transmissions and receptions of safety messages.

The following are some other modeling decisions in this study:

- All messages have the same priority and are transmitted with ACI =1 (AIFSN=3, CW window=15)
- Each node utilizes UTC time for synchronization, timing jitter among neighboring nodes is not modeled

4.2 Simulation Scenario and Environment

In all the simulations, the road is modeled as a straight highway. The two ends are, however, connected so the road is looped. This road should be envisioned as a circle, but with the RF propagation going along the circle rather than penetrating it. In this manner, there are no boundary effects and all data points collected are useful.

The table below lists other major parameters used in the study. The vehicle density used here represents a stressful but plausible scenario. It is equivalent to an 8-lane highway with 40m/car/lane.

Table 1 Simulation parameters

Vehicle Density	400 cars on 2000m of road
Transmission Range with no fading (m)	200 and 400
Messaging Frequency (Hz)	3, 5, and 10
Message Payload (Byte)	75 and 150
Modulation and Coding Rate	QPSK and ½ Coding Rate (i.e., 6 mbps)
Fading Model	Rayleigh

The total size of a frame is the sum of IEEE 802.11 MAC and PHY overhead plus the message payload listed in the table. 75Byte should be considered a very light weighted safety message size. 150Byte, while doubling the payload size, is still a moderate size if consideration for security is factored in.

The transmission powers used correspond to 200m and 400m reception ranges in an ideal channel with no fading or interference. However, a Rayleigh fading model is used in this study and it reduces the reception to 75% at a little more than half of the ideal range.

4.3 Safety Message Scheduling

In this study, three modes of communication are modeled:

1. No Channel Switching: base line usage of 100% of the CCH for safety messaging
2. Straight Application of 1609.4: naïve use of channel switching (i.e., the applications are unaware of channel switching and keep generating messages without regard to CCH intervals)
3. Optimized Scheduling with 1609.4: vertically integrated design so that no messages are generated during SCH and Guard intervals

The third mode is designed to address the synchronized collision issue as discussed in the previous section. In this mode, the message generation frequency *f* is adjusted to *f * (100 / 46)*. The non-CCH intervals, however, are ignored and not counted in applying this new frequency. In other words, the optimized scheduling is intended to generate the same number of messages but with all of them scheduled uniformly over only the CCH intervals. This effect is illustrated in Figure 8. The default scheduling method, at 20Hz, generates half of the messages in the SCH intervals. The optimized scheduling approach, however, keeps them all in the CCH intervals.

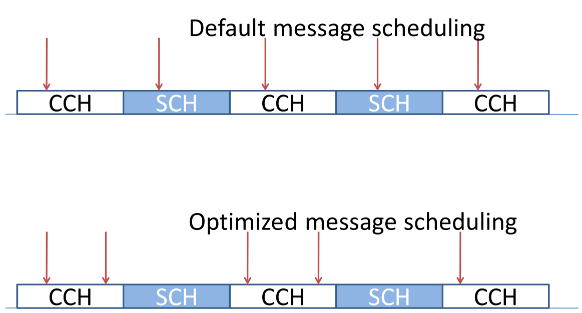

Figure 9 Optimized safety message scheduling

5. SIMULATION RESULTS AND ANALYSIS

This section analyzes simulation results obtained through the setups as described in the previous section. Most of the figures presented here show safety message reception performances vs. distance. In these figures, the X-axis is the distance from the transmitter of a safety message, and measured in meters. The Y-axis is the reception probability. Therefore, the reading of this type of figure is: given a certain simulation scenario, at a certain distance from a sender, what is the probability for a safety message from that sender to be received? Each figure compares results of three simulation scenarios. These three correspond directly to the three modes described in section 4.3.

The first three figures show the results from relatively light scenarios. All vehicles are configured to transmit 75Byte safety messages using power with a theoretic range of 200m. These three figures differ in the message generation frequency parameters. These are 3Hz, 5Hz, and 10Hz correspondingly.

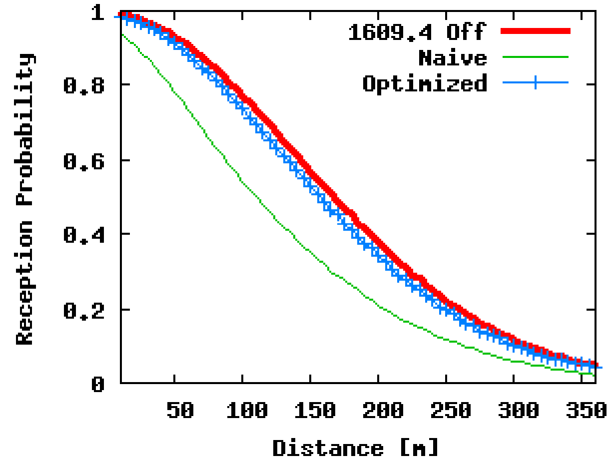

Figure 10 Safety message reception vs. distance, 75Byte, 200m, 3Hz

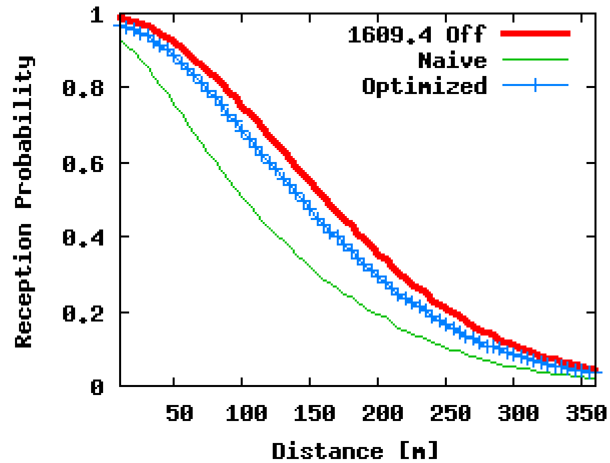

Figure 11 Safety message reception vs. distance, 75Byte, 200m, 5Hz

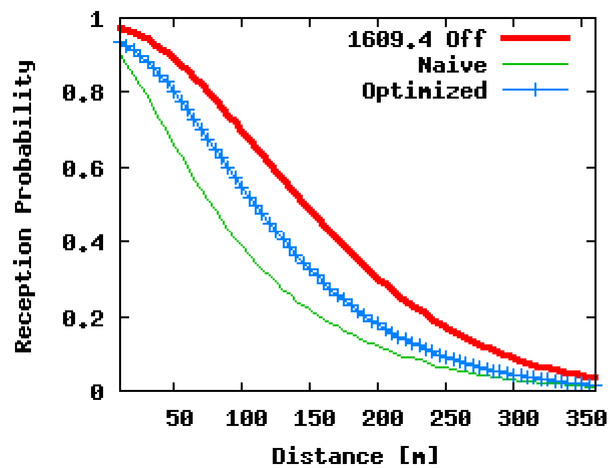

Figure 12 Safety message reception vs. distance, 75Byte, 200m, 10Hz

Figure 10 clearly illustrates the difference between the naïve and optimized safety message scheduling approaches. The naïve scheduling approach suffers from inevitable synchronized collisions as explained in section 3.4. Therefore, it has a significant drop in reception probability even at distance 0. The optimized scheduling approach, however, shows very little difference from the reference scenario in which there is no channel switching and all of the CCH capacity is available for use by safety communications. This is only possible because this figure represents the least stressful scenario in the simulation matrix (i.e., with the smallest message size, lowest transmission power and lowest messaging frequency).

As channel load increases from Figure 10 to Figure 12, the gap between the *Optimized* and *1609.4 Off* curves increases as expected.

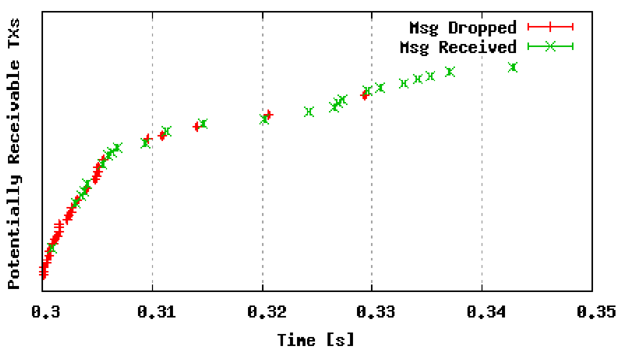

Figure 13 Safety message collisions and receptions over a CCH interval

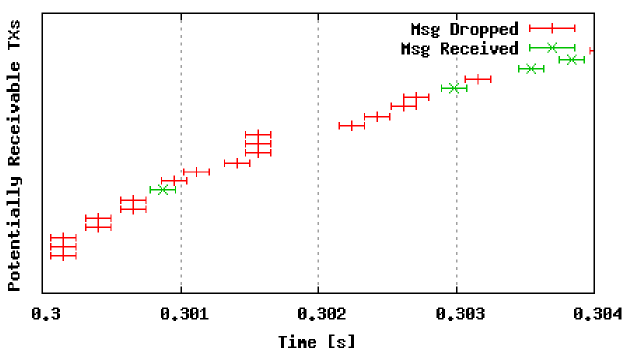

Figure 14 Synchronized collisions at the beginning of a CCH interval

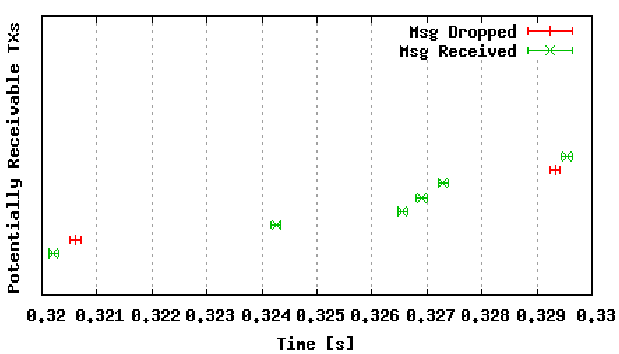

Figure 15 Safety message receptions in the middle of a CCH interval

In order to illustrate the nature of synchronized collisions better, three more figures are plotted to show safety message collisions and receptions from a single receiver's perspective. Figure 13 shows a particular receiver's experience over one CCH interval. The simulation scenario is the same as illustrated by the naïve curve in Figure 11. The X-axis is the time over one CCH interval. All transmissions that have sufficient received signal strength for reception in the absence of interference are plotted along the Y-axis. Each transmission is marked as either a successful reception or a dropped frame. Figure 14 zooms in to the first 4ms of the results shown in Figure 13 to highlight the synchronized collisions in greater detail. Each frame is now a horizontal bar showing the frame duration. Any frames that overlap with other frames experience collisions. Please note that not all frames in collisions are dropped because significantly different received signal strength could allow a frame to be successfully captured. For contrast, Figure 15 zooms in to the middle of results shown in Figure 13, by which point the synchronized collisions are over.

The next three figures, from Figure 16 to Figure 18, show safety messaging performance in relatively more stressful scenarios. The safety message payload is doubled to 150Byte. The transmission power used also rises to give a theoretical reception range of 400m.

As expected, the gap between the *Optimized* and *1609.4 off* curves grows bigger. However, something surprising shows up in Figure 18. The *Naïve* and *Optimized* curves cross over each other. The optimized scheduling approach is no longer strictly better than the naïve scheduling approach as one would expect.

This unexpected result is caused by the much higher channel load generated in the scenarios plotted in Figure 18. Because more than half of the safety messages are destined to collide with each other at the start of CCH intervals with the naïve scheduling approach, the rest of the CCH intervals are open for the other half of safety messages generated. These remaining safety messages can therefore have somewhat acceptable reception performances. With the optimized scheduling approach, however, all the safety messages are generated within CCH intervals and they compete throughout these periods. An essentially saturated channel results in poor reception performance for all.

What is alarming about results shown in Figure 18 is that it is not an unrealistic scenario. As described in section 4.2, 150Byte, as safety message size, is not an excessively large assumption. The transmission power, considering the fading model applied, produces an effective reception range of only 200m, which is not excessive either. The 10Hz messaging frequency is also considered by many as the default safety communication setting.

Yet with IEEE 1609.4 channel switching turned on, the safety communication performance becomes unacceptably poor, regardless of the scheduling approaches used. Therefore, the results shown in Figure 18 highlight the concern of inefficient channel utilization as described in section 3.1.

To illustrate this point further, let's examine the safety communication performances shown in Figure 18 from a different angle. The next two figures are plotted to show the distribution of time intervals between successfully received safety messages from the same sender. The X-axis is the distance from a sender, in meters. The Y-axis is the time gap between successfully received messages. Four curves are plotted in each figure. Both the average and median values are shown. Additionally, distribution of 10% to 90% and 30% to 70% are illustrated in colored bars.

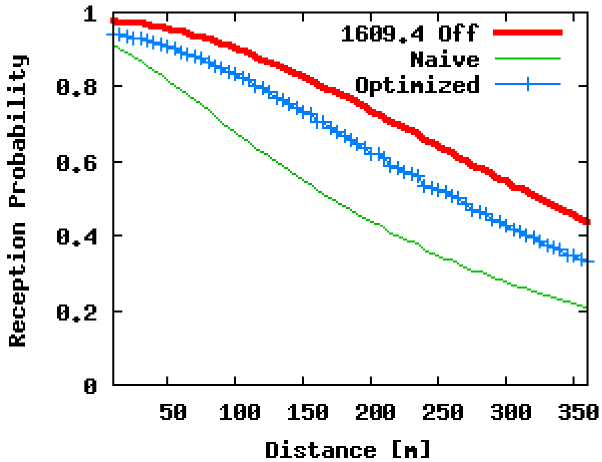

Figure 16 Safety message reception vs. distance, 150Byte, 400m, 3Hz

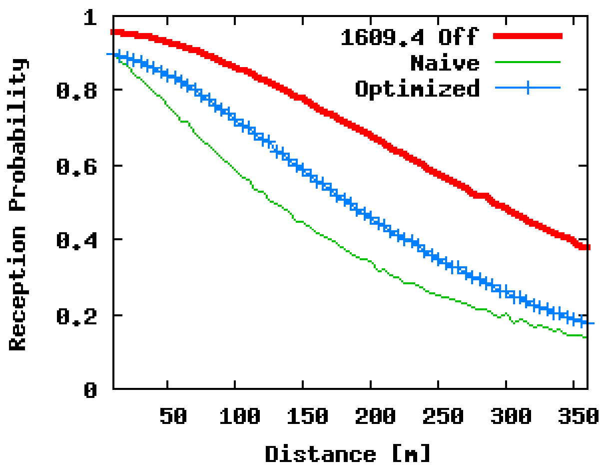

Figure 17 Safety message reception vs. distance, 150Byte, 400m, 5Hz

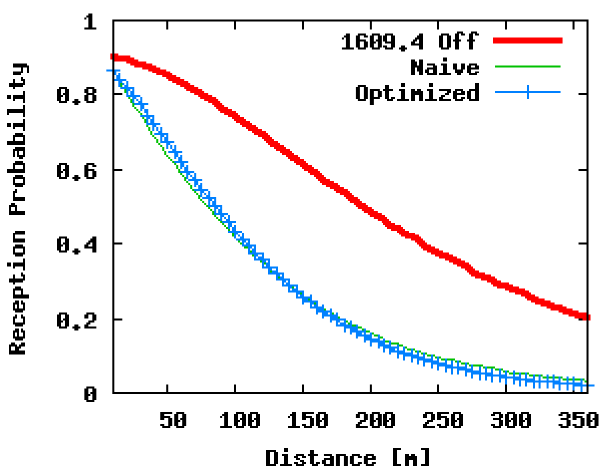

Figure 18 Safety message reception vs. distance, 150Byte, 400m, 10Hz

It is obvious that from vehicle safety communications' point of view, it is important for vehicles to receive status update from each neighbor vehicle sufficiently frequently and in an evenly timed manner. Therefore, it is highly desirable to have low average inter-message delays as well as small spread of such delays.

Figure 19 illustrates the inter-message delays when IEEE 1609.4 channel switching is turned off. In comparison, Figure 20 shows the result when channel switching is turned on and the optimized scheduling approach is used. It is open to interpretation as whether the performance shown in Figure 19 is good enough for vehicle safety applications. But the result shown in Figure 20 is unlikely to be acceptable.

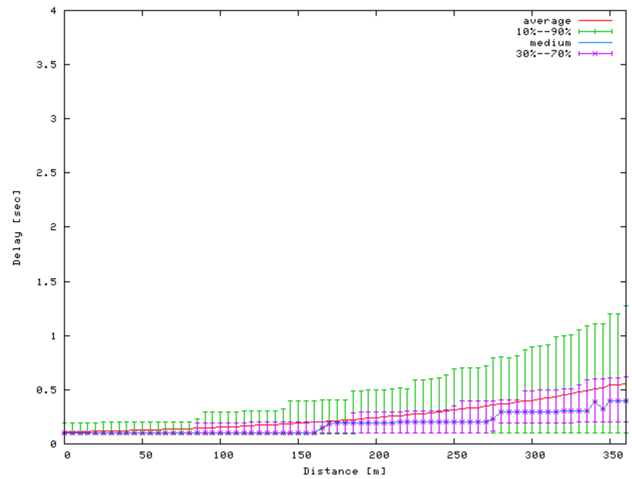

Figure 19 Inter-received message delays, 150Byte, 400m, 1609.4 off

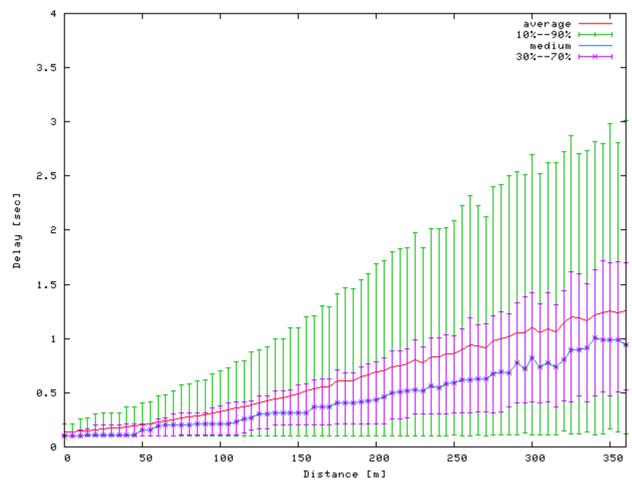

Figure 20 Inter-received message delays, 150Byte, 400m, Optimized

6. RELATED WORK AND ALTERNATIVE APPROACHES

While this paper describes concerns from vehicle safety communications' point of view, Wang and Hassan examined the issue from the other direction and questioned what channel capacity could be left for non-safety applications [14].

Prior to the formulation of IEEE 1609.4 in its current form, there have been proposals of alternative approaches for DSRC multi-channel operations. Mak *et al.* described a design in which a road side unit coordinates multi-channel operations for vehicles around its coverage [12]. This proposed approach is still based on time division oriented channel switching, but addresses the issue raised in section 3.2. Another proposal bypasses the time-division oriented scheme altogether [13]. Based on the principle that vehicle safety communications is highly redundant (i.e., not all vehicles need to listen to all safety messages all the time), a *Peercast* protocol concept was proposed to enable devices to asynchronously switch channels. With this protocol, all safety messages piggyback information on other recent and nearby high priority safety messages. Consequently, a vehicle engaged in non-safety activities in a SCH would be able to efficiently determine if it needs to spend more time on the CCH.

Recently, Kenney et al presented a more plausible proposal because it is designed to revise IEEE 1609.4 based on its current form. This approach calls for 1 bit of extra information to be carried in vehicle safety messages to indicate a device's multi-channel intention or capability (i.e., if it is a multi-radio platform). For example, assuming this bit is used to indicate intention, the system works in the following manner:

- Vehicles monitor neighbors' advertised information and adapt behaviors based on the make-up of their neighborhood
- For a single-radio vehicle
    - It may stay on the CCH all the time, or switch to a SCH during SCH intervals if some services are needed
    - It only sets the bit to 1 to indicate intention to switch to an SCH on next SCH interval; else it sets the bit to 0
- A multi-radio vehicle leaves one radio on the CCH all the time, and always sets this bit to 0 to indicate its intention to remain on the CCH
- If a vehicle finds its neighbor(s) or itself with the intention bit set, it schedule safety messages during CCH intervals
- Else, this vehicle sends safety message on the CCH at any time

This proposal solves the issue raised in section 3.2. It is also able to address the migration issue when and if multi-radio devices become viable.

7. CONCLUSION

This paper presented the basic concepts underlying the design of IEEE 1609.4 standard on DSRC multi-channel operations. It further discussed main concerns with the standard in its current form. Simulation results were presented to illustrate such concerns from vehicle safety communications' point of view:

- The time division oriented channel switching approach is inefficient in channel utilization.
- This design forces upper layer applications to be aware and implemented around the details of IEEE 1609.4 mechanisms.
- Even if upper layer applications are optimized for IEEE 1609.4 operations, the simulation results show that a realistically stressful scenario quickly renders the effort moot.

While IEEE 1609.4 is currently being updated and revised, this paper is intended to contribute to the technical discussions, and to bring attention to the most relevant and critical issues.

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