Enhancing Safety-Critical Message Dissemination in WAVE

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***Abstract*—The competing priorities of safety critical messages and infotainment messages present a significant challenge when designing effective IEEE 1609.4 protocol enhancements. In this paper, we investigate the latency reduction provided by an additional CCH check back midway through the Service Channel interval. Mathematical analysis and experimentation using simulations have shown that this method results in significant latency reduction. The maximum transmission delay for safety-critical messages can be reduced by approximately half whilst only reducing the Service Channel capacity by one quarter. As the work progresses, we will optimise the duration of the check back to find the best compromise between safety and infotainment.**

***Keywords*—latency reduction; VANET; WAVE; 1609.4; safety messages**

I. INTRODUCTION

In recent years, the interest in Vehicular Ad Hoc Networks (VANETs) has increased considerably, particularly to improve the safety and efficiency of transportation networks through wireless communications. VANETs comprise vehicles equipped with transceivers capable of exchanging information either Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I). While V2I communication requires huge infrastructure investment, V2V communication is more viable. The Wireless Access in Vehicular Environment (WAVE) standardised communication technology has been recently designed specifically for VANETs. WAVE includes the 1609 protocol family, as well as the IEEE 802.11p standard, a redesigned version of IEEE 802.11 that reduces the use of control packets and authentication in order to ensure swift delivery of data [1]. The 1609.4 protocol sits on top of 802.11p and allows for multi-channel communication over a single radio. Infotainment and safety applications can then coexist as the 1609.4 protocol [2] alternates periodically between a Control Channel (CCH) and one of six Service Channels (SCHs).

Infotainment applications in VANETs are aimed at enhancing the driving experience by providing non-safety applications, such as entertainment services [3]. Such services are transmitted as infotainment messages over one of the SCHs. Safety applications, on the other hand, are aimed at assisting drivers with real-time information about road and traffic conditions in order to reduce the number of accidents caused by human error. These applications are transmitted as safety-critical messages over the CCH. Examples of safety-critical applications are Cooperative Collision Warning (CCW), Electronic Emergency Brake Light (EEBL) and Slow/Stopped Vehicle Alert (SVA). Low latency communication is essential for these applications to be effective.

In this work in progress, we are particularly interested in improving dissemination of safety-critical messages while allowing the coexistence of infotainment applications. A number of solutions to this problem have already been proposed. Ghandour et al. [4] propose an enhancement in which the SCHs are made available for safety-critical messages, with nodes informing their neighbours of which SCH they intend to use for safety-critical transmissions. They also propose a second enhancement with the aim of mitigating the issue of synchronous collisions that can occur between transmitted safety-critical messages. This involves measuring the level of contention at the start of the safety-critical transmission interval and increasing the probability of transmissions being deferred if contention levels are high, spreading safety-critical transmissions out more evenly to reduce collisions.

Mak et al. [5] attempt to find a balance between safety-critical and infotainment transmissions by assuming safety only communications between vehicles by default while adopting a roadside access point to handle the coordination of infotainment services.

Jiang et al. [6] propose a number of alterations to 1609.4, including an ECHO protocol in which nodes receiving safety-critical messages rebroadcast them if they have not heard them recently. This improves the probability of reception due to multiple transmissions of the same safety-critical message, a useful enhancement for a protocol that operates in a dynamic environment in which packets can easily be lost. Their paper also outlines a Piggybacked Acknowledgement (PACK) protocol, which 'piggybacks' acknowledgements on safety messages to allow safety-critical broadcasters to get feedback on the performance of their safety-critical broadcasts and retransmit their safety-critical message if the failure rate is too high.

Our work in progress involves a simple solution that increases the time in which vehicles access the CCH for transmission of safety-critical messages. This solution preserves the overall time structure of the multi-channel communication in the 1609.4 protocol, while reducing latency.

The rest of the paper is organised as follows. Section II briefly reviews the time division in the 1609.4 protocol and provides a mathematical analysis of transmission delay.

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Section III details our proposed solution. Experimental results over a simulated VANET using NS-2 are presented in Section IV. Conclusions are presented in Section VI.

II. THE 1609.4 PROTOCOL

In the 1609.4 protocol, vehicles switch frequencies between the CCH and one of six different SCHs, while maintaining synchronisation with the Coordinated Universal Time (UTC) via Global Positioning System (GPS) devices. The time period in which vehicles are tuned to the CCH and then one of the SCHs is called the SYNC interval, which lasts 100 ms. More specifically, each SYNC interval comprises a CCH interval, which lasts 46 ms, followed by a SCH interval, which also lasts 46 ms. There is a 4 ms guard period before switching to the CCH and the SCH interval. This is illustrated in Figure 1. The SYNC interval repeats indefinitely.

Under the existing 1609.4 protocol, vehicles spend as much time on the SCHs as they do on the CCH. Given the importance of safety applications, we argue that safety-critical messages should be given a higher priority and greater access to the medium than infotainment messages, which are currently given equal access within each cycle. This is a very reasonable assumption considering the recent advancements in 4G/LTE that permit very high data rates and could be used for transferring large files that do not have significant latency requirements.

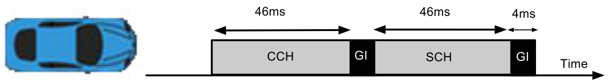

Figure 1. The SYNC interval in the 1609.4 protocol.

A. Transmission delay of safety-critical messages

We can perform mathematical analysis on this protocol under the assumption that the time at which a packet is sent within the SYNC interval is chosen randomly from a uniform distribution $\mathcal{U}(0\text{ms}, 100\text{ms})$. This is realistic because in a real world scenario there is no reason that an emergency event should fall within a specific interval. Additionally, this analysis assumes that the channel is clear upon transmission, and the packet, if sent at any point within the CCH interval, is received successfully. Under these assumptions, the expected delay $E[\text{Delay}]$ to receive a safety message sent on the channel may be calculated as follows:

$$E[\text{Delay}] = \delta + \sum_{\text{i}=1}^{4} \left(\frac{\text{duration}_i}{\text{duration}_{total}} \times \text{CCH Delay}_i \right) \quad (1)$$

where δ represents the average propagation delay for a packet sent using Nakagami Propagation [7], CCH Delay_i represents the average time between interval i and the next CCH interval. Note that (1) assumes four intervals, the CCH and SCH intervals plus two guard periods. Should a packet be sent within the CCH, the expected delay is simply δ.

Using (1) and the channel durations shown in Figure 1 we can calculate the expected latency for a packet within the 1609.4 protocol. The results of this are shown in Table I.

TABLE I. EXPECTED DELAY OF A SAFETY-CRITICAL PACKET IN THE 1609.4 PROTOCOL.

Interval	Duration (s)	CCH Delay (s)	Product
(1) CCH	0.046	0	0
(2) GUARD	0.004	0.052	0.00208
(3) SCH	0.046	0.027	0.01242
(4) GUARD	0.004	0.002	0.00008
Total	0.100		0.01458
		+ δ = 0.00215	0.01673

As shown in Table I, the expected delay for a safety-critical message sent under the assumptions listed previously is 0.01673 seconds.

III. THE PROPOSED SOLUTION

Currently, the main issue with the SYNC interval in the the 1609.4 protocol is the disproportionate amount of time spent by vehicles on one of the SCHs, which prevents detection of any safety-critical messages. Our proposed solution is therefore to introduce an additional CCH interval within the SCH interval to reduce the latency of safety-critical message delivery. In other words, vehicles now tune back to the CCH during the SCH to transmit/receive pending safety-critical messages. This second CCH interval, referred to as CCH_CHECK, occurs halfway through the SCH interval such that each newly created half of the SCH interval, referred to as SCH_1 and SCH_2 respectively, are of equal length. A 4ms guard period still exists before intervals. This is illustrated in Figure 2.

The CCH_CHECK is k ms long. The benefits gained by using different values of k are being investigated through ongoing research, with initial forays investigating the benefits of $k = 4$ ms. This initial value has been chosen as it allows sufficient time to send safety-critical messages without significantly impeding on the SCH duration.

Under this initial proposal, the CCH_CHECK is to be treated as a normal CCH interval for safety-critical messages, but is not used for low priority safety-critical messages. Should all nodes successfully transmit all queued safety-critical messages, they will wait until the full k ms have elapsed before returning to the SCH via a GUARD period. An alternative method is discussed in Section V.

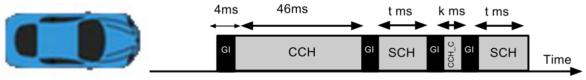

Figure 2. Our proposed schedule.

$$t = \frac{(46 - (2 \times \text{GUARD}) - k)}{2} = 19 - \frac{k}{2} \text{ ms} \quad (2)$$

Our proposed solution preserves the overall timing structure of the 1609.4 protocol, with a 100 ms SYNC duration split evenly between the CCH interval and the SCH interval. The SCH interval, however, now comprises a short CCH interval. The length of each SCH interval is half the remaining time period as shown in (2). The proposed intervals are summarised in Table II.

TABLE II. PROPOSED INTERVALS.

Interval	Duration (ms)
CCH	46
GUARD	4
SCH_1	$19 - \frac{k}{2}$
GUARD	4
CCH_CHECK	k
GUARD	4
SCH_2	$19 - \frac{k}{2}$
GUARD	4
Total	100ms

In the current 1609.4 protocol, when a safety-critical message is generated outside of the CCH interval, it is queued and sent in the following CCH interval. The worst-case scenario is when a safety-critical message is generated at the end of the current CCH interval and the time to transmit that message is longer than the time left in the CCH interval. In this case, the message is queued and scheduled for transmission at the beginning of the following CCH interval, which can cause a wait of 54 ms. In the proposed solution, there is at most a $27 - \frac{k}{2}$ delay; with $k = 4$ ms, this represents only a 25 ms delay, which is less than half the original delay.

It is important to note that at the beginning of a CCH interval in the existing 1609.4 protocol, there may be a high risk of packet collision because vehicles attempt to transmit all the safety-critical messages queued up since the last CCH interval, which may have accumulated over as long as 54 ms. The proposed solution reduces this to $27-\frac{k}{2}$. An open question that requires investigation is how long k should be in order to successfully transmit all the safety-critical messages generated in previous SCH intervals, including the guard periods.

The proposed solution inevitably has a detrimental effect on the transmission of infotainment messages. However, this detrimental effect is expected to be minimal in comparison to the positive effects on the dissemination of safety-critical messages, which is arguably the most important aspect of WAVE, particularly during emergency events.

A. Expected transmission delay of safety-critical messages

Using the same assumptions and calculations as those used in Section II-A, Table III provides a mathematical analysis of the expected delay of a packet which is sent using the proposed solution to neighbours within broadcast range of the transmitting node, with a value $k = 4$ ms. Note that the expected latency is 8.4 ms, which represents an improvement of $\frac{0.0084}{0.01673} \approx 50\%$. The minimum expected delay reduction is therefore $0.01673\text{s} - 0.0084\text{s} = 0.00833\text{s}$.

TABLE III. EXPECTED DELAY OF A SAFETY-CRITICAL PACKET IN OUR PROPOSAL FOR $k = 4$ MS.

Interval	Dur. (s)	CCH Delay (s)	Product
(1) CCH	0.046	0	0
(2) GUARD	0.004	0.023	0.00092
(3) SCH_1	0.017	0.0125	0.00213
(4) GUARD	0.004	0.002	0.00008
(5) CCH_CHECK	0.004	0	0
(6) GUARD	0.004	0.023	0.00092
(7) SCH_2	0.017	0.0125	0.00213
(8) GUARD	0.004	0.002	0.00008
Total	0.100		0.00625
		+ δ = 0.00215	0.0084s

The proposed reduction on the SCH interval reduces the amount of time available for transmission of infotainment messages. Our proposed solution reduces the SCH interval from 46 ms to $2 \times (19 - \frac{k}{2}) = 34$ms, when $k = 4$ ms, which represents a SCH capacity reduction of $\frac{46-34}{46} \approx 26\%$

Using the same method as shown in Table III after some simplification, (3) shows the expected delay with an arbitrary k value.

$$\frac{(k-54)^2}{400} + \delta \text{ ms} \tag{3}$$

IV. EXPERIMENTAL RESULTS

NS-2 [8] was used to simulate the 1609.4 protocol with the proposed solution with a value of $k = 4$ ms for the CCH_CHECK interval.

The simulations were ran 2,000 times with each simulation lasting 100 seconds. Within each run, one safety-critical message was sent. This is to represent one emergency event occurring in each run. The time the packet is sent is determined by the same uniform random distribution as used in the mathematical analysis in Sections III-A and II-A. A total of 100 simulated vehicles were spread across a 1 km road with 4 lanes. Each vehicle was randomly located within the road and in this initial simulation, vehicles were static. The Nakagami Propagation model was used for all simulations with a minimum transmission range of 250 m and an event horizon of 1km. Other parameters in 802.11p were set to their default values. When nodes receive a safety-critical message, their distance from the initial transmitting node and the time difference between transmission and reception of the message is recorded within a database. This is later used for analysis.

Since generating the data used in this document, several mobility traces using the Simulation of Urban MObility (SUMO) [9] tool have been generated that will enable the simulation of more realistic roads and vehicle movements. SUMO is an open source, highly portable, microscopic and continuous road traffic simulation package designed to handle large road networks. Also, added is the ability to send arbitrarily large numbers of messages within the simulation, which is to be used in later simulations.

Table IV tabulates the average delay for a single safety-critical message for different distances. Note that for those nodes within the broadcast range (0-250m), the improvement is between $8.4 - 8.8$ ms. This is very close to, but slightly higher than, the predicted value of 8.33 ms, as computed in Section III-A. When nodes are significantly outside the broadcast range, multi-hop transmissions pass the message onto all nodes until the event horizon is reached. The event horizon ensures packets are not forwarded indefinitely.

Figure 3 plots the average delay discretised in Table IV.

TABLE IV. AVERAGE DELIVERY DELAY FOR A SINGLE SAFETY-CRITICAL MESSAGE.

Distance	1609.4 protocol	Proposed solution	Improvement
0-100m	16.989 ms	8.278 ms	8.711 ms
100-200m	16.637 ms	8.286 ms	8.351 ms
200-300m	16.835 ms	8.054 ms	8.781 ms
300-400m	21.864 ms	12.762 ms	9.102 ms
400-500m	28.679 ms	20.700 ms	7.979 ms
500-600m	34.156 ms	25.359 ms	8.797 ms
600-700m	38.809 ms	28.832 ms	9.977 ms
700-800m	43.418 ms	31.740 ms	11.677 ms
800-900m	46.950 ms	34.883 ms	12.068 ms

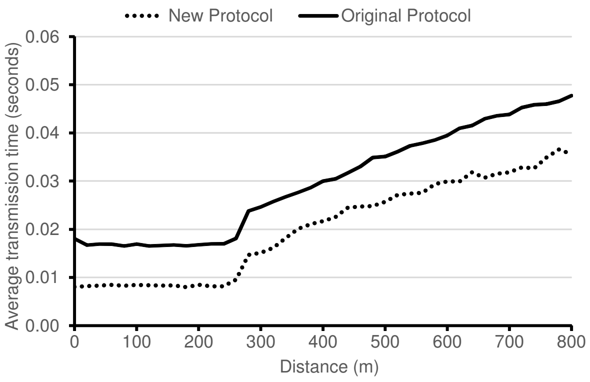

Figure 3. Average delivery delay for a safety-critical message sent at a random instant of time within the simulation.

An important metric to analyse is the latency incurred when safety-critical messages are generated at the very end of the CCH interval, i.e., generated at 46ms into the cycle, which represents a worst-case scenario. Let us recall that under the 1609.4 protocol, these messages would be queued to be sent in the next CCH interval. In the proposed solution, these messages can now be sent within the CCH_CHECK interval. Table V shows the improvement attained by our proposal for nodes within the broadcast range of the transmitting node.

TABLE V. LATENCY TO ONE HOP NEIGHBOURS FOR THE TRANSMISSION OF A SINGLE SAFETY-CRITICAL MESSAGE GENERATED AT THE END OF THE CCH INTERVAL.

1609.4 protocol	Proposed solution	Improvement	Reduction
55.61 ms	26.60 ms	29.01 ms	52.2%

As can be seen in Table V, the reduction in latency in this worst case scenario is over 52%, a significant reduction.

V. FURTHER RESEARCH

Our work will next explore the advantages gained by the modification of the k value. We intend to focus on the range $k = \{2..16\}$ ms to ensure that sufficient time is available for the SCH interval. Additionally we will investigate benefits gained by immediately returning back to the SCH if there are no messages to be sent during the CCH_CHECK. An example case we may investigate is that if no messages are sent within the first $\frac{k}{2}$ milliseconds then those inactive nodes can re-tune to the SCH and continue offering infotainment services. An additional point of investigation is how our modified protocol handles heavy busy environments, with particular interest in how effectively collisions are handled.

We would like to examine the effects of our protocol on a real-world WAVE application such as EEBL, comparing the existing 1609.4 protocol with our proposed solution in an appropriate SUMO simulation. We will compare the performance of our solution with similar solutions proposed by others.

VI. CONCLUSION AND FUTURE WORK

This paper presented our work in progress on enhanced dissemination of safety-critical messages in the 1609.4 protocol for VANETs. Specifically, we presented the idea of introducing CCH interval within each SCH interval. Our initial results are greatly encouraging and appear to satisfy our objective, which is to attain a significant reduction in safety-critical message latency with minimal reduction in SCH duration. We are continuing to investigate the benefits generated by the introduction of this short CCH interval and explore alternative modifications. As part of our future work, we are interested in finding the best trade-off between the enhancement of safety-critical message dissemination and the reduction in service channel capacity.

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