

Design of 5.9GHz DSRC-based Vehicular Safety Communication

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Abstract: *The automotive industry is moving aggressively in the direction of advanced active safety. Dedicated Short Range Communication (DSRC) is a key enabling technology for the next generation communication-based safety applications. One aspect of vehicular safety communication is the routine broadcast of messages among all equipped vehicles. Therefore, channel congestion control and broadcast performance improvement are of particular concern and need to be addressed in the overall protocol design. Furthermore, the explicit multi-channel nature of DSRC necessitates a concurrent multi-channel operational scheme for safety and non-safety applications. This paper provides an overview of DSRC based vehicular safety communications and proposes a coherent set of protocols to address these requirements.*

Keywords: *DSRC, Vehicular Safety Communication, Broadcast, IEEE 802.11p*

1. Motivation and Introduction

Automotive safety, in terms of fatalities/injuries per mile driven, has been steadily improving in the United States for the last two decades. However, the total numbers of injuries and fatalities have remained relatively flat due to the increasing number of vehicles and total miles driven. To further reduce injuries and fatalities, vehicle safety needs to go beyond traditional passive safety technologies such as airbags and seatbelts. Current active safety systems (e.g. ABS, ESP, Mercedes-Benz's Brake Assist Plus,) support drivers in critical situations to avoid accidents or mitigate the impact.

tems. These systems provide an extended information horizon to warn the driver or the vehicle systems of (potentially) dangerous situations in a much earlier phase. Figure 1 (a) and (b) show two such scenarios.

This paper provides an overview of the nature of vehicular safety communications and proposes a roadmap for its communication protocol design. It should be noted that this roadmap is not comprehensive. Security, for example, is not covered in this article.

2. DSRC Overview

In 1999, the U.S. Federal Communication Commission allocated 75MHz of Dedicated Short Range Communication (DSRC) spectrum at 5.9GHz to be used exclusively for vehicle-to-vehicle and infrastructure-to-vehicle communications. The primary purpose is to enable public safety applications that save lives and improve traffic flow. Private services are also permitted in order to lower cost and to encourage DSRC development and adoption.

As shown in Figure 1 (c), the DSRC spectrum is divided into seven 10MHz wide channels. Channel 178 is the control channel, which is generally restricted to safety communications only. The two channels at the edges of the spectrum are reserved for future advanced accident avoidance applications and high powered public safety usages. The rest are service channels and are available for both safety and non-safety usage.

The DSRC radio technology is essentially IEEE 802.11a adjusted for low overhead operations in the DSRC spectrum. It is being standardized as IEEE 802.11p [1]. The overall DSRC communication stack between the link layer and applications is being standardized by the IEEE 1609 working group.

The Department of Transportation and the automotive industry are aggressively developing DSRC technologies and applications. Their joint effort has identified safety applications enabled by DSRC and evaluated DSRC radio performance [2]. Some prototype vehicles and applications were demonstrated at events such as the ITS World Congress 2005.

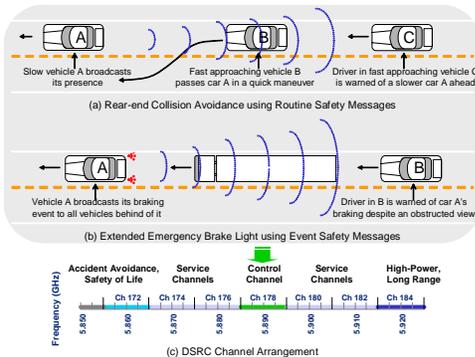


Figure 1: DSRC Channel Arrangement and Control Channel Safety Communication Examples

Communication-based active safety is viewed as the next logical step towards what we call pro-active safety sys-

3. Vehicular Safety Communication Operational Concept

3.1. Control Channel Link Layer Behavior

The basic link layer behavior of safety communications in the control channel can be defined as *single-hop, uncoordinated, broadcast messaging* in an *unbounded system* consisting of *all neighboring equipped vehicles* in a *dedicated channel*:

- **Single-hop:** Most of the identified safety applications are based on direct communication among vehicles within range of one another. So far, there is no need for “networking” capabilities in the basic DSRC communication design. There are scenarios in which multiple hops of message forwarding is desired (e.g. propagating hazard warning along a roadway). These cases are best served by application level protocols which have contextual knowledge such as a digital map. Additionally, rebroadcast schemes for broadcast performance enhancement are not multi-hop in the proper sense.
- **Uncoordinated:** Vehicular safety communication is entirely distributed. There is no coordinator to facilitate orderly channel access.
- **Broadcast:** Safety communication in general is targeted at vehicles for where they are rather than who they are.
- **Messaging:** Safety communications consists of self-contained messages. Each message is short and usually mapped to a single frame.
- **Unbounded system:** While one DSRC radio communicates only with its nearby neighbors, such neighbor-to-neighbor communication can stretch without bound to great distances. Link layer activities cannot be analyzed as a bounded system such as a cell in the cellular phone system.
- **All neighboring equipped vehicles:** All DSRC equipped vehicles (and infrastructure) communicate with one another within range frequently all the time. Scalability is of key concern in safety communication design.
- **Dedicated channel:** All common safety messages are exchanged in the control channel. Non-safety usage in the control channel is limited to occasional advertisements of private applications in the service channels, and is insignificant to overall channel load. Therefore, control channel communication design can and should focus on safety.

3.2. Safety Messaging Fundamentals

In simplistic terms, a multi-vehicle accident is caused either by drastic behavior changes (e.g. hard braking) of at least one car, or by vehicles unwittingly staying on their collision courses. The former scenario demonstrates the need for what we term event safety messages while

the latter case shows the value of routine safety messages. Figure 1 (a) illustrates a scenario in which routine safety messages help enhance safety even when the involved vehicles move in perfectly normal manners on the road.

Accordingly, we define these two types of safety messages below. The definitions are the foundation for all protocol designs in this paper.

- **Routine safety messages:** These are status messages regularly sent by vehicles. A routine safety message remains meaningful for a few seconds so that a receiver can predict the movement of the sender during this time unless otherwise notified. This definition is applicable to messages sent by infrastructure as well (e.g. intersection announcement of traffic light status).
- **Event safety messages:** These are triggered by changes in vehicle behavior (or infrastructure status) that break the continuity implied by routine safety messages defined above (e.g. hard braking).

3.3. Safety Applications

Vehicular safety communication is largely **non-interactive** in nature. Most safety application concepts follow a general pattern:

- Collect sensor information and broadcast vehicle’s own status to neighboring vehicles via routine or event safety messages.

While separately and in parallel,

- Aggregate information from other vehicles and infrastructure.
- Analyze, continuously, for pre-defined trigger conditions (e.g. potentially dangerous situations).
- Inform or warn the driver in an appropriate manner if applicable.

As such, a vehicle sending a safety message is generally not expecting a response at the application level to that particular message. A receiver responds to incoming messages by informing or warning its own driver if necessary without communicating back to the sender(s).

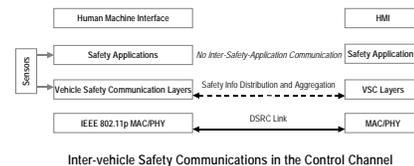


Figure 2: Vehicular Safety Communication Operational Concept

As shown in Figure 2, the operational concept of vehicular safety communication in the control channel can be generalized as:

Safety communication is not application-to-application. Instead, an intermediate layer is responsible for safety information distribution and aggregation among vehicles and infrastructure. Applications work by continuously analyzing the aggregated information to look out for potential trigger conditions.

Simply put, the sender of a safety message cannot dictate how the message should be processed and interpreted by other vehicles. Rather, it is the responsibility of the receiving vehicle’s system to disseminate relevant safety information to appropriate application(s). For example, car A in the Figure 1 (b) scenario should simply send an “I-am-braking” message rather than an “You-have-to-brake” message. One particular advantage of this operational concept is that it allows for future enhancement of safety applications while maintaining compatibility with existing ones.

4. Safety Communication Protocols and Mechanisms

Vehicular safety communication in the roadway environment presents many challenges. Figure 3 (a) shows how received power values of DSRC broadcast messages vary at different distances from the sender on a freeway with light to medium traffic [4]. Figure 3 (b) and (c) show the estimated Ω and m parameter values while fitting the general Nakagami model to these data. The wide distribution of received power at all distances makes “reliable” broadcast difficult even if there is no interference since a node may not be able to hear the message. It also elevates the potential for MAC level collisions because the carrier sense mechanism is similarly affected, particularly when the channel load is heavy. Therefore, it is necessary to introduce *congestion control* and *broadcast performance enhancement* for DSRC safety communication in the control channel.

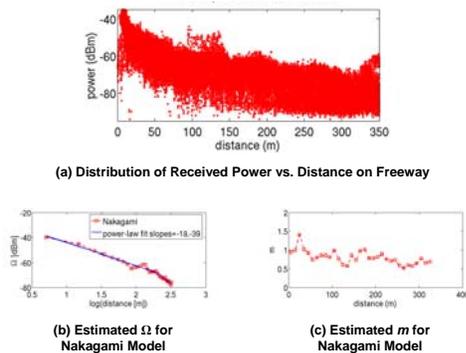


Figure 3: DSRC RF Propagation on Freeway

This section proposes a set of protocols and mechanisms to address these requirements. Since DSRC has an explicit multi-channel configuration, support for multi-channel operation is also discussed.

4.1. Control Channel Congestion Control

4.1.1. Motivation and Requirement

Figure 4 (a) further illustrates the need for channel congestion control. The top curve shows the broadcast reception rate at different distances from the sender if there is no interference. The lower curve shows the performance for broadcast transmissions with the same power, but in a congested channel¹.

Because routine safety messages dominate control channel load, and have a relatively long useful life of a few seconds, it is natural to design a congestion control scheme around adjusting their generation frequency and transmission power.

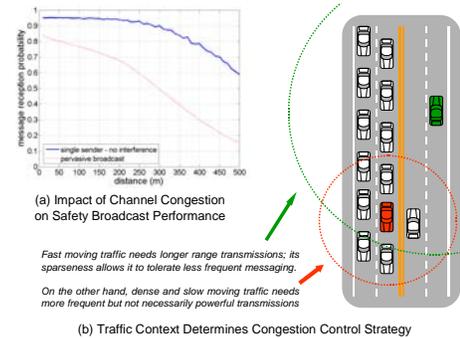


Figure 4: Motivation and Consideration for Control Channel Congestion Control

As Figure 4 (b) shows, cars in different traffic contexts have different communication strategies for adjusting these two parameters. Therefore, the requirement is:

Each vehicle should regulate its routine safety message generation rate and transmission power according to its traffic context so that overall channel load would be maintained at a reasonable level.

4.1.2. Channel Congestion Metric

Mathematical analysis shows that, at practical channel stress levels, a radio’s broadcast performance depends only upon message size and *communication density* around it [6]. *Communication density* can be described as the number of carrier sensible events per unit of area and unit of time. Essentially, it is the product of vehicle density, message generation rate, and transmission range.

Figure 5, presents an example that broadcasts of the same power has the same reception performance in different

¹ In the congested scenario simulation, vehicle density is 160 cars per km road. Each car sends 250Byte messages at 10Hz. The RF model is two-ray ground with Rayleigh distribution (which is the same as Nakagami with m set to 1).

scenarios that have the same overall communication density².

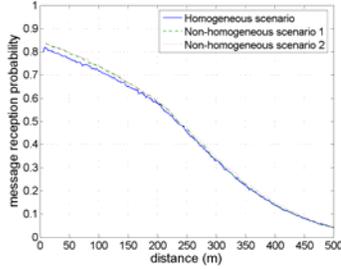


Figure 5: Validating Communication Density Concept

Therefore, given a common message size, *communication density* is the natural metric for measuring channel congestion.

4.1.3. Congestion Control Scheme

One tactic for a sender to implement distributed congestion control is to monitor its communication performance and adjust accordingly. This approach assumes that communication performance is predominately affected by congestion. For example, congestion control in TCP works well over wired networks because these links are essentially reliable and any packet loss can be attributed to network congestion. Conversely, TCP becomes problematic over lossy wireless links [11]. Given the multitude of factors that affect vehicular safety communication performance, this approach is not advisable.

The alternative approach is for each sender to understand the overall competition for channel usage and adjust accordingly. This means that each vehicle needs to ensure that its contribution to communication density is a fair share of a targeted channel congestion level.

Therefore, control channel congestion control should be done in the following steps: (1) Listen and estimate the number of neighboring nodes. (2) Adjust routine safety message transmission power and generation rate.

² In the homogeneous scenario, vehicle density is set at 100 cars per km road; all cars broadcast at 20Hz at a power for 480m. The other two simulations are configured in a manner similar to the one shown in Figure 4 (b). In non-homogenous scenario 1, the left side has 160 cars per km road and all broadcast at 10 Hz to 240m. The right side has 80 cars per km road and all broadcast at 15Hz to 480m. In the non-homogeneous scenario 2, the left side has 67 cars per km road and all broadcast at 16Hz to 360m. The right side has 133 cars per km road and all broadcast at 9Hz to 480m. All simulations use two-ray ground with Rayleigh fading. Please note that all transmission ranges specified here are theoretic reception ranges according to the configured transmission powers. Due to Rayleigh fading, the intended reception ranges (i.e. 75% reception rate while there is no interference) are usually no more than half of these theoretic ranges.

For the second step, safety applications should provide guidance on desired transmission range according to the vehicle traffic context. A congestion control module then calculates the corresponding message generation rate.

One key concern with the steps listed above is timing. A listen-estimate-adjust cycle may take much longer than the fluidity of a dynamic mobile environment allows. For example, a vehicle approaching a crossroad takes a bit of time to realize the increase in number of cars around it. As it adjusts for the extra competition on the channel, it is already moving beyond the spot. Accordingly, congestion control may require a protocol through which vehicles indicate in messages their local vehicle density and channel load to share with vehicles further away.

4.2. Broadcast Performance Enhancement

4.2.1. Motivation and Requirement

In order to improve the reach and coverage of safety messaging, mechanisms that enhance broadcast performance are desirable. Therefore:

The communication stack should attempt to improve the average reception rate of routine safety messages while ensuring the best possible reception rate for each event safety message in the timeliest manner³.

4.2.2. Broadcast Performance Feedback

Due to the pervasive broadcast nature of safety communication, an individual vehicle is able to quickly collect feedback on its recent broadcast message, if other vehicles piggyback some acknowledgements in their messages. In turn, safety application(s) can be informed of performance of each broadcast message, which may be selectively retransmitted if necessary.

We propose a Piggybacked Acknowledgement (PACK) protocol design [7], which places the following information in each outgoing safety message:

- Sender’s position (which is already needed for safety communication)
- The intended range of reception
- A randomly generated message ID
- IDs of most recently received messages (of which this sending node is within their intended ranges)
- The reception time ($time_{earliest}$) of the earliest message in the acknowledgment list

As node A receives a message M_B from node B , A is able to infer feedback on its recently transmitted message M_A if and only if two conditions are met: B is within the intended range of M_A , and the attached $time_{earliest}$ in M_B is

³ Channel access latency for safety broadcast has been shown to be generally acceptable (i.e. mostly within 20 ms) even in very stressful simulation scenarios [5]. It is therefore not discussed here.

earlier than the time M_A is sent⁴. As such, A can determine a feedback of positive or negative acknowledgement (ACK or NACK) for M_A depending on whether the ID of M_A is found in M_B .

Not all feedback are equally useful. An ACK from a nearby node provides little information since the reception is expected. However, a NACK from this node means much more and possibly indicates a collision.

A simple method to evaluate a feedback's usefulness is the logarithmic function, which is viewed as a natural choice in information theory [3]. That is, the surprisal value in receiving a message m is $S(m) = -\log(p)$ where p is the probability of m being chosen from the total message space. Accordingly, the information value of an ACK or NACK from distance d is:

$$I(ACK) = -\log(p(d) \cdot p(d))$$

$$I(NACK) = -\log((1 - p(d)) \cdot p(d))$$

where $p(d)$ is the probability of a message being received at distance d . The extra $p(d)$ term in the formula addresses the chance for the sender to receive the feedback message in return⁵.

Therefore, a sender can assess a broadcast message's performance by scoring all subsequently received feedback. Assuming the purpose of scoring is to detect broadcast failure (i.e. the reception rate within intended range is below a certain threshold), the formula is:

$$S_{failure} = \frac{\sum I(NACK) - \sum I(ACK)}{FeedbackCount}$$

$$= \frac{\sum_{d \in NACK} -\log((1 - p(d)) \cdot p(d)) - \sum_{d \in ACK} -\log(p(d) \cdot p(d))}{FeedbackCount}$$

Figure 6 (a) and (b) show the validity of this concept by plotting individual broadcast message's reception rate against its failure score in a simulation scenario⁶. Both show a very clear correlation between the failure score and actual broadcast performance. Plot (a) is based on 100% attempted feedback while (b) is produced with realistic parameters of 20 IDs per message and 30ms maximum decision delay.

⁴ This timestamp comparison helps prevent inferring false NACKs. It necessarily requires a highly accurate clock at each DSRC module, which is feasible with GPS. GPS is needed for positioning information anyway.

⁵ This is a simplification that assumes both nodes transmit at the same power and the environment is generally symmetric for RF propagation between the two.

⁶ Vehicles are placed on a linear road at 200 cars per km of road. Each vehicle is configured to broadcast 250 Byte messages at 10Hz. The intended transmission range is 200m. The RF model used is two-ray ground with Rayleigh distribution.

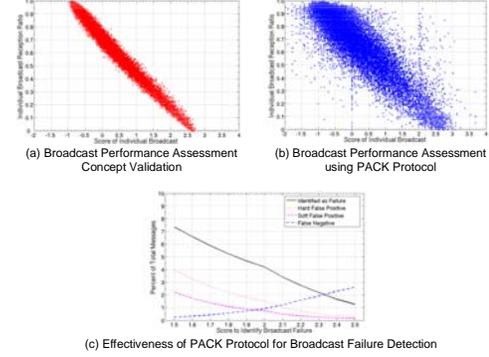


Figure 6: Broadcast Performance Assessment Method and Its Effectiveness for Failure Detection

Figure 6 (c) further shows the PACK protocol's utility in broadcast failure detection based on results shown in (b). For this evaluation, broadcast failure is arbitrarily defined as less than 20% reception rate within range. Actual such failures account for 3.6% of all messages. The top curve shows the percentage of messages detected as failure using score threshold shown on the X-axis. The second curve shows the false positive percentage. As expected, the false positives account for a significant fraction of the ones identified. The situation improves a lot, however, if messages with reception rate between 20% and 30% are not grouped into false positive. The last line shows the false negative percentage rate.

4.2.3. Echoing Routine Safety Messages

While channel congestion control limits the number of frames sent over the air, each frame does not have to contain only one safety message. Safety message content proper is small (i.e. on the order of 50Byte). The frame is much larger and includes security overhead (i.e. on the order of 200Byte [2]) in addition to the MAC/PHY overhead. Therefore, piggybacking another safety message does not significantly affect the overall safety communication quality.

We therefore propose an ECHO protocol that proactively "echoes" others' messages to improve the safety broadcast quality in general. The protocol works as following:

- Each sender includes a recently received routine safety message body in its own frame.
- Each receiver compares the message ID of the echoed message with history of recent receptions. It passes unheard messages up and discards messages already received.

In this approach, each routine safety message is on average sent twice, which results in a general improvement of the message reception rate.

4.2.4. Echoing Event Safety Messages

Event safety messages are relatively rare, but demand much better reception rates than routine safety messages.

Accordingly, the ECHO protocol is designed differently for event safety messages to create a controlled flooding effect:

- Each sender is required to echo a recent (e.g. originated within last 100ms) and nearby (e.g. within 100m) event safety message.
- If there are more than one such messages, the sender is required to include the IDs of the additional event safety messages as well.

In this way, an event safety message is echoed multiple times resulting in dramatic improvement in its receptions.

4.3. Concurrent Multi-channel Operation for Safety and Non-safety Applications

4.3.1. Motivation and Requirement

Safety messages are mostly transmitted on the control channel. Non-safety communications are largely restricted to service channels. A vehicle with a conventional single-channel radio needs to switch back and forth amongst the channels in order to support both types of communications at the same time. Therefore:

A concurrent multi-channel communication mechanism is required so that sufficient safety broadcast messages on the control channel are received to maintain adequate and timely safety awareness, while non-safety communication on service channels is supported in the most efficient manner feasible.

4.3.2. Related Work

So far three approaches have been proposed [8, 9, 10]. They are all based on some synchronization-oriented schemes. The common theme is to arrange for all vehicular DSRC radios to be on the control channel when their neighbors are transmitting safety messages.

In general, building elaborate synchronization schemes on top of a CSMA link is likely to be problematic. Such synchronization schemes give up substantial channel bandwidth by design. Furthermore, it starves out non-safety communication when safety communication is heavy in the control channel.

The fundamental problem with these schemes is that they attempt to listen to all safety messages. Adequate safety awareness does not require receiving all safety messages *per se*, and can be maintained if:

- Routine safety messages from all nearby neighbors are heard every few seconds, and
- All event safety messages from nearby vehicles are received without excessive delay.

4.3.3. Peercast Concept

The protocol concept described below relies on trusting peer vehicles' description of recent control channel safety

messaging activities through the ECHO protocol described above. We therefore name it Peercast.

- A vehicle operating in a service channel must regularly switch back to the control channel and transmit its safety messages as usual.
- Periodically (e.g. every 100ms), it is required to return to the control channel and listen for a few (e.g. 2-3) messages from its neighbors.
- While on the control channel:
 - If it hears no event safety message either directly or indirectly, it may return back to the service channel.
 - Else if it hears a nearby event safety message either directly or indirectly, it passes up the message to safety applications and may return to the service channel.
 - Else if it hears indication of an event safety message with an unknown ID, it is required to stay on the control channel to capture the repetition or echoing of that message before eventually returning to the service channel.
- It must return to the control channel at any time if requested by a safety application.
- It must return to the control channel every a few seconds for a short while (e.g. 500ms) to reorient itself with other vehicles' routine safety messages.

Through the ECHO protocol for event safety messages described above, any safety message's assertion of recent and nearby event messages (or the lack thereof) is trustworthy. As such, a radio undergoing non-safety operations in a service channel has high confidence of detecting the (non-)existence of relevant event safety messages even if it spends little time on the control channel and receives just a few safety messages from its peers. The adequate safety awareness requirement is therefore satisfied. On the other hand, the service channel utilization level is high. Most importantly, this Peercast scheme scales well, i.e., a dense safety communication environment does not starve out non-safety application communications.

5. Summary

This paper presents the operational concept of 5.9GHz DSRC-based vehicular safety communication. The overall DSRC communication architecture in the draft IEEE 1609 standard contains two parallel stacks: one for TCP/IP based communications and the other one for safety messaging. This paper contributes to the safety stack design.

In particular, the fundamental nature of the pervasive broadcast messaging oriented safety communication system is examined. Three key challenges, namely channel congestion control, broadcast performance enhancement and concurrent multi-channel operation, are defined. To address these challenges, a coherent set of protocols,

grounded on differentiating routine and event safety messages, is proposed.

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