Multi-Channel Medium Access Control for Dedicated Short Range Communications

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Abstract

This paper describes a medium access control (MAC) protocol to enable multi-channel operation for dedicated short range communication (DSRC). In particular, we focus on the challenge of supporting potentially high-bandwidth commercial or infotainment communications between vehicle and roadside in hotspots over several service channels, while concurrently enabling time-critical vehicle-vehicle communication for safety in a separate channel. In our architecture, within hotspots, communication is aided by one of the access points in the hotspot. This access point is designated the Coordinating Access Point (CAP). Outside hotspots, communication is for safety only and is conducted in an ad-hoc fashion. The CAP protocol design leverages IEEE 802.11 PCF and DCF, modified for multi-channel operation. The design objective is to maximize utilization of the service channel used for non-safety communication while meeting the Quality of Service (QoS) constraints of the safety communications. The performance of 802.11 DCF, PCF, and the CAP extension is quantified by simulation in NS-2. The mobility model represents a 4-lane freeway at maximum vehicular traffic flow derived from the SHIFT traffic simulator. The CAP design is shown to significantly enhance the performance of both safety and non-safety communication.

KEYWORDS: Wireless LAN, DSRC, WAVE, Vehicular Communication, IEEE 802.11, PCF, DCF

I. INTRODUCTION

The United States Department of Transportation has declared that the reduction of vehicular fatalities is a top priority [5]. As part of this agenda governments and the automotive industry have been working closely together in an effort to transform 802.11 into a technology able to make automotive travel safer. Examples of such efforts are:

1) the emergence of an 802.11 based standard, i.e., 802.11p [29], for a spectrum labeled Dedicated Short Range Communications allocated by the Federal Communications Commission (FCC) [4] with priority for safety communications,
2) the release of requirements [6] for vehicle-vehicle communications for safety applications by the Vehicle Safety Communications Consortium (VSCC) comprised of the automotive OEMs in partnership with the National Highway Traffic Safety Administration (NHTSA), and
3) the release of requirements for roadside-vehicle communications for collision avoidance at intersection [7] and the creation of the Cooperative Intersection Collision Avoidance (CICAS) consortium ¹ to design and prototype a system.

The idea of using 802.11 to make automotive travel safer is as follows. By collecting surrounding vehicles locations and dynamics over the wireless link, an on-board warning application determines and warns the driver when a collision is likely with other vehicles. The danger may be due to emergency braking, blind spots, low visibility from heavy fog, red light violations, and more [1]. With proliferation of the 802.11 wireless technology, the radio has become so affordable that it is now found on large numbers of consumer mobile devices. Hence the interest in using it to make automotive travel safer.

This paper explores the challenge of using an 802.11-like radio in the vehicle to support both safety and non-safety applications. Table I shows some examples of the safety and non-safety applications envisaged for the DSRC spectrum established in the literature [6]–[8]. The labels Safety of Life, Safety, and Non-Safety were created by the FCC. The most safety critical, as one can see, is the Safety of Life. For example, the collision warning messages are Safety of Life. In general, the safety and safety of life messages are expected to report information like the position or speed of the sender, motion status like stopped, braking hard, turning, or road condition information like ice, slippery, congestion.

It is currently common for people to use 802.11 wireless systems through a non-mobile Access Point (AP) to conduct commercial transactions, download audio and video files, RSS and podcasting, etc. The FCCs ruling says both the safety and non-safety uses should be supported by DSRC. Therefore the problem targeted by this paper is important. A solution is required for the successful operation of the DSRC spectrum. To quote the FCC [4]:

¹http://www.its.dot.gov/cicas/index.htm
We conclude that it is possible to license both public safety and non-public safety use of the 5.9 GHz band. Accordingly, we adopt open eligibility for licensing and technical rules, most of which are embodied in the ASTM-DSRC standard, aimed at creating a framework that ensures priority for public safety communications.

The standard referred to by FCC bases DSRC on 802.11a. The IEEE 802.11 is working to formalize these modifications within a new standard: 802.11p.

Supporting safety and non-safety applications concurrently using 802.11 is challenging for the following reasons. Conventional 802.11 uses for podcasting, commercial transactions, etc., are generally sessions operating in a single-channel environment, i.e. the access point and remote station choose a single channel and perform a multitude of actions on that same channel. However, DSRC, by its design, is a multi-channel system. In its Report and Order the FCC divided the spectrum into seven 10 MHz channels—six identified as service channels and one identified as the control channel. All safety messages can be sent in the control channel but non-safety services are expected to be provided in the six service channels. The non-safety services can only send announcements in the control channel (see table I for service announcement requirements). The purpose of a six service channel bandplan is to enable the usual 802.11 hotspot model. Multiple commercial service providers with access points in the same hotpot area will co-exist by choosing different channels.

Since 802.11 radios demodulate one channel at a time, this multi-channel operational model creates the following challenge. A safety message, say one reporting sudden braking, may arise at any time on the control channel. Since this is a safety message, it is desirable that the DSRC protocols enable the vehicles behind to receive this message with high probability. However, if at the time the warning safety message is sent (in the control channel), one or more of the behind vehicles’s DSRC radios are tuned to one of the six service channels to consume non-safety services, how will the safety warning be received? This is the challenge addressed by the protocol design in this paper. One not only needs to provide QoS (Quality of Service) to safety messages, but do so while permitting the radios to consume services on the various service channels as efficiently as possible.

The literature has designs, reviewed in section II, for multi-channel networking with single channel radios. They are focused on the conventional applications. Their approaches are for the sender and receiver to use some protocol to rendezvous, negotiate a channel, and concurrently switch to the decided channel for their data transfer. However, use of these protocols for DSRC is problematic due to the broadcast nature of safety messages. The needs of vehicle safety applications are quite different. The safety messages in Table I tend to be locally broadcast with a maximum transmission range of 300 meters. This is motivated by the fact that messages sent by one vehicle contain Data Elements that are often useful to multiple vehicles in the nearby vicinity. For example, a braking message is useful to several vehicles behind the braking vehicle. Likewise, a message reporting which directions of a traffic light are red is useful to all vehicles at the intersection. Therefore it is better to broadcast such messages to all interested vehicles, rather than unicast the message one by one to all the interested parties. In a sense, these messages are geographically addressed. What matters is where the recipients are in relation to the sender. Since the different interested receivers may be spread over the six service channels, any channel negotiation would have to be an n-ary rendezvous if there are n – 1 interested receivers. Therefore the design in this paper is different from the multi-channel networking designs reviewed in the literature.

We note there may be a couple of straightforward, non-protocol design, ways to address the concurrent safety and non-safety communication challenge. One is to disable a vehicles commercial applications from using the on-board 802.11 radio unless the vehicle is parked. Here we are assuming if a vehicle is parked there is no need to receive safety messages. However, no moving vehicle would then be able to avail of DSRC services that might help with navigation, electronic payment at drive-trough restaurants, etc. This seems overly restrictive. 802.11 hotspots are proliferating and over time one would expect

<table>
<thead>
<tr>
<th>Application</th>
<th>Packet Size (Bytes)/Bandwidth</th>
<th>Allowable Latency (ms)</th>
<th>Network Traffic</th>
<th>Range (m)</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection Collision Warning/Avoidance</td>
<td>~100</td>
<td>~100</td>
<td>Event</td>
<td>250</td>
<td>Safety of Life</td>
</tr>
<tr>
<td>Emergency Braking Warning/Avoidance</td>
<td>~100</td>
<td>~100</td>
<td>Event</td>
<td>200</td>
<td>Safety of Life</td>
</tr>
<tr>
<td>Cooperative Collision Warning</td>
<td>~100</td>
<td>~100</td>
<td>Periodic</td>
<td>150</td>
<td>Safety of Life</td>
</tr>
<tr>
<td>Work Zone Warning</td>
<td>~100</td>
<td>~1000</td>
<td>Periodic</td>
<td>50-300</td>
<td>Safety</td>
</tr>
<tr>
<td>Transit Vehicle Signal Priority</td>
<td>~100</td>
<td>~1000</td>
<td>Event</td>
<td>300-1000</td>
<td>Safety</td>
</tr>
<tr>
<td>Toll Collection</td>
<td>~100</td>
<td>~50</td>
<td>Event</td>
<td>≤ 15</td>
<td>Non-Safety</td>
</tr>
<tr>
<td>Service Announcements</td>
<td>~100</td>
<td>~500</td>
<td>Periodic</td>
<td>0-90</td>
<td>Non-Safety</td>
</tr>
</tbody>
</table>

**Table I**

Examples of DSRC Applications and Requirements.
more and more services a vehicle may gainfully use while in motion. Thus our design will have value, if in the future vehicles spend non-trivial time in hotspots yet still receive safety messages. The other straightforward solution might be to equip each vehicle with two 802.11 radios, i.e., a safety radio and a non-safety radio. However, the two radios may suffer cross-channel interference. The design in this paper is to execute both safety and non-safety communications over a single 802.11 radio.

Our design seeks to maximize the bandwidth available for service communications, while meeting the Quality of Service (QoS) for the safety communications listed in table I. The bandwidth for service communication is quantified as the Available Service Transaction Time (ASTT). This is the fraction of time a vehicle in a hotspot is able to spend on the service channels. The safety message QoS measure is based on the fields of table I. The ranges and latencies in the table signify the message should be received by all vehicles within that range of the sending vehicle within that latency. We call the largest of these ranges the VSMR (Vehicle Safety Message Range). To get good QoS the VSMR needs to be adapted to vehicular traffic density as shown in [28]. Therefore our QoS measure for safety messages is the probability a safety message is received within the latency by a randomly chosen receiver within VSMR of the sender. The measure captures both range and latency requirements.

The aim is maximize ASTT while ensuring safety QoS.

The largest message range in table I is 300 meters. This can be covered in one hop by DSRC radios. FCC has permitted more than one watt (in fact 33 dBm EIRP = 2 watts). Therefore we assume safety messages are communicated in one hop. The design uses an 802.11-like access point, called coordinated access point (CAP), to coordinate channel access by all vehicles in the vicinity of the hotspot. The CAP divides time into periods and synchronizes all vehicles within range. The vehicle protocol entity has an ad-hoc mode and coordinated mode. Vehicles within range of the CAP are required to be in coordinated mode. Coordinated mode vehicles have to be on the control channel at the beginning of the period. The CAP design then ensures all vehicles seeking to consume services and others within their VSMR are polled to send their safety messages. The synchronizing role of the CAP is our way of avoiding the n-ary rendezvous problem created by the broadcast of safety messages. The polling is PCF based. After the polling is over, vehicles in the hotspot are free to depart for the service channels to consume services till the end of the period. The CAP design is PCF plus some spatial division intelligence to ensure safety message QoS and high ASTT. We also extend the PCF group management functions to handle the high mobility of vehicular traffic.

Outside the hotspot, where there are no non-safety services, vehicles remain in the common control channel and exchange safety messages using the ad-hoc protocol. Therefore the protocol modes of a moving vehicle will be as in figure 1. On nearing a hotspot it should hear the CAP and its channel access will be AP coordinated. When the vehicle is out of the CAP’s range, it will revert back to pure ad-hoc operation. We assume the ad-hoc protocol is IEEE 802.11 DCF. However, any other ad-hoc protocol will do as well. DCF is currently available making it the one most likely to be used first. Likewise, the service channel protocols used to consume the service are also flexible. Any service channel protocol compatible with periodic return to the control channel as instructed by the CAP will suffice. We have tried to minimize requirements on the service channel and ad-hoc mode protocols so these may evolve without affecting each other or the concurrent operation of both.

The design is evaluated by simulation using NS-2 based on vehicle trajectories generated by SHIFT [30]. SHIFT is an established vehicular traffic simulator. We simulate the maximum traffic flow condition on a four lane freeway. Vehicles move at non-uniform speeds and follow each other at non-uniform spacings as determined by the driver model in SHIFT. If the density of vehicles in the hotspot increases, the CAP increases the length of the polling schedule. We evaluate the safety QoS of our design relative to a baseline. The baseline is the safety QoS delivered by the ad-hoc protocol when there are no non-safety services (hotspots). In this situation all vehicles stay on the control channel all the time and we have single channel operation. Our design seeks to maintain the same QoS for safety messages even when there are non-safety services and vehicles depart to the service channels. We use single channel operation as a baseline because the safety QoS in this condition has to be acceptable. We evaluate relative to a baseline, because there is no consensus on QoS requirements for safety messages in the literature. For a more extensive discussion see [28].

The simulations show the safety message loss rate in this baseline condition to be about 3%. Therefore we seek to have the concurrent safety and non-safety communication design achieve at least the same QoS. The results in section VII show the safety QoS of our design has an interesting spatial variation. Its loss rate is better in most places, slightly worse in a certain region, and the same elsewhere. We meet the 100 millisecond latency requirement in table I by giving each vehicle an opportunity to transmit safety messages every 100 milliseconds. The ASTT is 80%, i.e., vehicles in the hotspot are able to spend 80% of their time in the service channels. By contrast, if we execute safety and non-safety communication using DCF alone, the safety message loss rate rises to 80% for the same ASTT. If we do the same using PCF alone, the loss rate
is between 35% and 40% for the same ASTT. Thus we argue, the CAP design is essential.

Our design has a vehicle transmit its safety message periodically. Table I suggests some safety messages are event-driven. Thus messages may arise in storms, with sudden motions by a vehicle, triggering the transmission of messages by other vehicles. However, our protocol design will force these messages to wait for the next opportunity to transmit. We give a vehicle the opportunity to transmit every 100 milliseconds so that the wait will not violate the latency requirement. In a storm, a vehicle can send multiple messages at its next transmission opportunity. In the simulation evaluation every vehicle has something to send every 100 milliseconds.

The contributions of this paper include the CAP protocol design, and its demonstrated superior performance over the IEEE 802.11 PCF and DCF MAC protocols used alone. Since our CAP protocol leverages PCF primitives, PCF is the natural point of comparison to CAP. However, PCF was designed only for single-channel operation, and does not directly address the issue of receiving safety and non-safety messages in different DSRC channels. Neither PCF nor DCF perform as well in this multi-channel DSRC environment as CAP.

Our proposal for consuming services while still receiving safety messages requires roadside coordination. Receiving safety message alone does not require roadside assistance. We assume commercial services usually involve APs. The role of the coordinator could be assumed by one of the service APs. However, P2P services are not excluded by our design. As long as there is a CAP, some services in its vicinity can be P2P.

An ad-hoc solution, i.e., one requiring no roadside coordinator, would have obvious advantages, but the difficulty is the \(n\)-ary rendezvous problem arising from the broadcast nature of these safety messages together with the multi-channel operation model. There are ad-hoc leader election methods in the literature to elect a vehicle as coordinator on the fly, but it is difficult to make these methods work at the volume and speed of freeway traffic. Moreover, the latency numbers in table I show any ad-hoc scheduling in time or across channels needs to work with latencies under 100 milliseconds. While there is a rich literature on this subject, including a contribution by us [3], it is difficult to make these real-time wireless medium access protocols work fast enough when the neighbors of a vehicle are so numerous and change as fast as they do on multi-lane roads carrying upwards of 2000 vehicles per hour per lane. Therefore, we have proposed and evaluated the roadside assisted design in this paper and believe it provides some ideas that might be useful for a future ad-hoc design. As this paper shows, even with roadside assistance, the design is complex.

The structure of the paper is as follows. Section II reviews the literature. Design is described in three sections with progressive levels of detail. Section III describes the design. Section IV describes the different kinds of frames and control messages used by the design. Section V presents some logical properties of the design as theorems. The theorems explain why the design is structured the way it is. Thereafter the design is evaluated by simulation using NS-2. Section VI is a brief description of simulation parameters. Section VII presents the simulation results. Since the design relies on different power levels for spatial division section VIII discusses the selection of power levels. Finally section IX concludes the paper.

II. PRIOR WORK AND TECHNOLOGY

A preliminary version of the design appeared as a conference article [2]. This paper extends the version with protocol designs, power level design, proofs of theorems about the design, and performance evaluations set in the context of 802.11 DCF and PCF. Our prior work on ad-hoc protocols for vehicle-vehicle communication appears in [3, 9].

Xu [9] and Korkmaz [10] present preliminary ad hoc protocol designs to enhance broadcast message reception for safety over a single DSRC channel. These ad-hoc approaches generally obtain reliability by increasing repetitions, handshaking, acknowledgements, i.e., trading reliability with goodput efficiency. Enhanced Distributed Coordination Function (EDCF) [11] of IEEE 802.11e is a single channel protocol that tries to reduce access delay for delay-sensitive messages. However, it does not solve the hidden terminal problem for the broadcast communication. Any of these ad-hoc protocols could potentially be used as the ad-hoc component of the design in this paper.

To adapt any of these ad-hoc protocols for the DSRC multi-channel environment, the channel coordination problem must be addressed. Our preliminary simulation shows that if each vehicle is equipped with an 802.11a radio, and the radio is allowed to switch out of the safety channel for non-safety services, the safety performance in the safety channel degrades dramatically as service time increases (see figure 7 in section VII).

Multi-channel MAC protocols in the literature try to increase the overall throughput of the network by permitting multiple disjoined communications to occur simultaneously over multiple channels. There are two classes of approaches. The first is the multi-radio multi-channel approach (e.g., [13]–[16]) and the second is the single-radio multi-channel approach (e.g., [17]–[19]).

For the multi-radio multi-channel protocols, the general approach is to have one radio, called control radio, dedicated to the control channel used to reserve data channels, and one or more radios, called data radio(s), conduct the actual data communications on any of the remaining channels. The channel reservation process is an extension to the 802.11 RTS-CTS handshake [12], where the sender first transmits a RTS to its receiver containing a list of free channels observed by it. If its receiver agrees with any one of the channels on the list, it replies with a CTS with the chosen channel; and finally before they tune their data radio to the chosen channel, the sender transmits a confirmation so that the potential interferers around the sender will not use the same channel.
Various criteria are used by the sender and its receiver to choose the “best channel” to conduct their data communication. In the DPC [13] and DCA [14] protocols, each node tracks the current usage of each channel, the criteria for “best channel” is one which is not currently being used. The criteria in the MMCCS [15] protocol is to choose a channel that maximizes the signal-to-interference-ratio (SINR) at the receiver and minimizes the interference caused to all other active receivers. Similarly, RBCS [16] tries to pick the clearest channel at the receiver (i.e. the channel that has the lowest SINR measured at the receiver). By contrast, we focus on an architecture able to deliver value even to a vehicle with one 802.11 radio.

The single-radio multi-channel protocols are as follows. In CHAT [17], time is slotted, and each node hops from one channel to the other, spending one time slot in each channel, in a known channel hopping pattern. In each time-slot, when a sender has data to transmit to its receiver, it contends for channel access using a protocol like RTS/CTS. After the sender and its receiver gain the right to access the channel, they stay in the current channel to conduct their data communication while others continue the hopping schedule. Once the data communication is finished, the sender and its receiver quickly re-synchronize to the hopping schedule. Since at any given hop, not every node is in the same channel, broadcast communication is difficult. To solve this problem, CHAT requires each node to store a list of receivers within broadcast range. When a node has a message to broadcast, it repeats the same message over different hops until all receivers on its list receive the message.

To increase parallelism, SSCH [18] removes the constraint of having every node use the same channel hopping sequence. Each node in SSCH has its own hopping sequence. To ensure each node can find its receivers, it is required to periodically announce its hopping schedule. When a node has a message to send, it either waits until its receiver eventually meets it on the same channel or the sender partially synchronizes to its receiver’s schedule. For broadcast communication, SSCH suffers the same problem as CHAT. Each node in SSCH repeatedly transmits its broadcast message over different hops/channels, and the number of repetitions is a design parameter. Obviously frequent channel switching limits the overall channel utilization for these protocols. Furthermore, safety applications such as Cooperative Collision Avoidance (CCA) require each vehicle to periodically broadcast its position information. Having each safety message be repeated for the benefit of each receiver will deteriorate efficiency.

MMAC [19] tries to reduce the overall channel switching overhead by taking advantage of the IEEE 802.11 Power Saving Mechanism [12], where ATIM windows are modified for channel reservations, and rest of the interval is used for data communication on channels. Each node is required to synchronize to the ATIM window. In each ATIM window, each node is required to return to the default channel for channel reservations. The channel reservation process is based on the RTS/CTS mechanism. At the end of each ATIM interval, a sender begins its data communication with its receiver on their chosen channel. However, the authors did not address the broadcast communication. All these single radio approaches require stringent time synchronization, which remains an open problem for Vehicle Ad-Hoc Networks (VANETs).

In the DSRC service hot-spot, the DCAP protocol configuration contributed by this paper provides broadcast communication with bounded latency. The maximum service channel utilization can be as efficient as the single-radio multi-channel protocols. Since each vehicle requires a single radio, our system would be as economical as the other single-radio multi-channel solutions discussed. The DCAP configuration protocol is feasible for VANET since it does not require every vehicle along the highway to be time synchronized. Finally, the protocol is built on top of the 802.11 DCF and PCF [12], which are widely accepted by the industry, therefore, the development time and cost can be greatly reduced. As the results in section VII show, the DCAP configuration outperforms DCF or PCF alone. Therefore we believe it constitutes a step in the right direction. However, until vehicle safety applications are better understood it will remain unclear whether even the DCAP performance levels are good enough.

### III. DESIGN

Our design for concurrent safety and non-safety communications relies on roadside access points. We distinguish between two kinds of access points as follows:

- **Service access point (SAP)** - A roadside unit (RSU) that provides non-safety services, called a service access point, should conduct these services within an access point service region. Only vehicles located within this region should avail of these services. The SAP will advertise its services in the control channel but conduct the transactions in a service channel. We will use the terms service region and hot-spot interchangeably.

- **Coordinating access point (CAP)** - An RSU that coordinates the safety and service transmissions in its proximity is called a coordinating access point.

A single access point could be both SAP and CAP.

#### A. System Configurations

We propose two configurations based on these two kinds of access points. The configurations differ in their performance and cost. In the first configuration, a coordinating AP is co-located with one or more service AP’s. Since all coordination functions are executed on the control channel, the coordinating AP dedicates its radio to the control channel. The service AP’s could dedicate their radios to the service channels. This configuration is called dedicated coordinating AP (DCAP).
In the second configuration a single RSU shares the service and coordinating AP responsibilities by cycling between the control and service channels. This configuration reduces cost but, as we shall see, also reduces service channel throughput. This configuration is called the integrated coordinating AP (ICAP).

The DCAP configuration is the basic design. Modifications required for the ICAP configuration are pointed out as necessary.

### B. Time division of the Control Channel

Figure 2 shows the basic time division in the control channel. Time is partitioned into periodic, regulated intervals, called the repetition period. The period should be of length \( T \), where \( T \) is determined by the maximum tolerable latency of safety messages. We permit vehicles to transmit a safety message once per CFP, i.e., approximately once every \( T \) seconds. Each period is divided into two sub-periods: a regulated contention-free period (CFP), and unregulated contention period (CP). During the CFP, each vehicle in a region, defined later called the access point safety exchange region, is individually polled. At this point the vehicle can transmit its safety messages while all others must remain silent. This process is similar to the point coordination function PCF [12]. The CP follows the completion of the CFP. During the CP,

- vehicles located in the service region can receive services by switching to service channels,
- the remaining vehicles can send safety messages using an ad-hoc protocol,
- the coordinating AP executes control functions in preparation for the next CFP (see section IV-B).

We define the available service transaction time (ASTT) as the largest fraction of time a vehicle within the service region is permitted to stay on the service channel. The ASTT for vehicles within the service region is approximately \( \frac{T}{T-\|\text{CFP}\|} \). This neglects the channel switching time which for 802.11a radios can be made as small as 40-80\( \mu \)s [21]. Non-safety service providers want high ASTT. Our protocol design objective is to maximize ASTT while ensuring safety message communication with acceptable latency and reliability. Latency is determined by the choice of \( T \) and reliability has to do with suppressing collisions through the spatial division described in the next subsection.

Our design resides in the CAP and vehicle protocol entities. The CAP communications will enable the vehicle to know when to leave the control channel and return again. The SAP and service channel protocols will need to be able to handle a vehicle that departs periodically to the control channel. Other than this no other design modifications are proposed for the SAP or service channel protocols.

### C. Spatial division and communication range

We propose the spatial division in figure 3. For the sake of the discussion, all communication ranges in this paper are represented as ideal circles. These are subsequently translated into transmission power levels as described in section VIII.

We use the notation \( \Re(X, R) \) to denote a circular region centered at radio \( X \) with radius of \( R \). Thus, to describe the access point service region, we use \( \Re(AP, APSR) \), where \( APSR \) is the radius of the service region. Vehicles within this region are expected to depart for the service channel during the CP.

The purpose of the spatial division is to ensure all vehicles within \( \Re(AP, APSR) \) send and receive all relevant safety messages during the CFP, i.e., before they depart to the service channels in the CP. The protocol logic is set up to provide each vehicle in \( \Re(AP, APSR) \) the opportunity to execute a full safety exchange (FSE) in the CFP. A vehicle executes an FSE when all safety messages generated by it within the last \( T \) seconds are received by all their intended recipients, and all safety messages intended for the vehicle and generated within the last \( T \) seconds are received by the vehicle. In practice, as seen from the simulation in section VII, some fraction of these messages will be lost due to fading or packet collision. It is assumed the intended recipients of a a safety message generated by vehicle \( v \) are all within the region \( \Re(v, VSMR) \), where VSMR abbreviates Vehicle Safety Message Range. This number is estimated to lie between 50 and 300 meters [6].

\(^2\)One may object to setting the repetition interval equal to the safety delay requirement. The delay jitter inherent in any protocol implementation would likely cause the violation of a strict \( T \) sec. latency guarantee. One may also argue that if the proposed arrangement only ensures that each vehicle have a transmission every repetition period, and if the safety messages are not strictly periodically generated, then achieving a \( T \) second delay requirement mandates that the repetition interval be \( T/2 \).

\(^3\)The service region is always contained in the access point safety exchange region.
Let 

\[ APSR = APSR + VSMR. \]  

(1)

\( \mathcal{R}(AP, APSR) \) is called the access point safety exchange region. Since the maximum range of a safety message is limited to VSMR, all vehicles within \( \mathcal{R}(AP, APSR) \) must be polled by the AP within the CFP to give each vehicle in \( \mathcal{R}(AP, APSR) \) the opportunity to execute a full safety exchange.

Let 

\[ APPR = APSR + \Delta \]  

(2)

where \( \Delta = v_{max} \times T \) is the maximum possible distance a vehicle can travel in one period \( T \). \( \mathcal{R}(AP, APPR) \) is called the access point poll region. We require the poll to be sent with sufficient power to reach all vehicles within \( \mathcal{R}(AP, APPR) \). The extra transmission distance \( \Delta \) is used by the AP to notify vehicles that they are about to enter \( \mathcal{R}(AP, APSR) \). These vehicles will register with the AP in the CP as described in Section IV-B1. Thus when they enter the \( \mathcal{R}(AP, APSR) \), the AP will be ready to poll them.

Let \( IR_{\text{max}} \) denote the maximum possible distance at which a safety message transmission from one vehicle can interfere with reception of a safety message at another. \( IR_{\text{max}} \) is determined by the transmission power required to cover the VSMR\(^4\).

Let 

\[ APQR = APSR + IR_{\text{max}}. \]  

(3)

For every vehicle in \( \mathcal{R}(AP, APSR) \) to receive safety messages without collision, vehicles within \( \mathcal{R}(AP, APQR) \) must be silent during the CFP unless polled by the AP.

To ensure silence we require the AP to transmit a beacon with sufficient power to reach all vehicles within \( \mathcal{R}(AP, APBR) \), where

\[ APBR = APQR + \Delta. \]  

(4)

\( \mathcal{R}(AP, APBR) \) is called the access point beacon region. We require every vehicle receiving a beacon to keep quiet unless polled by the AP. Once again, the extra distance \( \Delta \) is used to notify the vehicles about to enter \( \mathcal{R}(AP, APQR) \) to keep quiet until the CFP is over. The beacon frame in this protocol specifies the number of time slots before the next CFP starts. This makes it slightly different to the beacon frame in 802.11.

Figure 4 shows the DCAP protocol architecture. Vehicle communication is intended to be under the control of the Coordinated Protocol Entity during the CFP and the Ad-hoc Protocol Entity during the CP or when out of range of a Coordinating AP. The Protocol Controller Entity manages this transition. It does so by controlling the data path in the Multiplexer Entity. The Group Manager manages the joining and leaving of vehicles from the Coordinating AP poll list. The Queue Manager in the figure passes packets on demand to the Ad-hoc or Coordinated protocol entities. Likewise it accepts packets from the Coordinated Protocol or Ad-hoc Protocol entities on demand, demultiplexes them, and passes them on to the Group Manager or LL. The Queue Manager in our current simulator implements a FIFO queue. It could be modified to implement a priority queue as suggested in the DSRC standards. Complete state machine specifications of the NS-2 implementations of these protocols are in [34].
Control Packet Type | Range      | Functional Descriptions
---------------------|------------|--------------------------------------------------
Beacon               | APBR       | used to notify vehicles for the schedule of the contention free period (CFP)
CF_Start             | APBR       | used to notify the beginning of the CFP
CF_Poll              | APBR       | used to notify a vehicle for the right to transmit
CF_End               | APBR       | used to notify the end of the CFP
Service_release      | APSR       | used to notify vehicles within the service region for the schedule of next CFP
ServiceAnn           | APSR       | used by service providers to announce their services on the control channel
Assoc_Req            | APBR       | used by vehicles to request to be added to the poll list
Assoc_Resp           | APBR       | used by AP to respond to the add request
De-Assoc_Req         | APBR       | used by vehicle to request to be removed from the poll list
De-Assoc_Resp        | APBR       | used by AP to respond to the remove request

TABLE II
THE LIST OF CONTROL PACKET TYPES

IV. DCAP DESIGN: DATA MODEL

This section describes the different kinds of control packets and frames in the DCAP design. The various packets are summarized in table II.

A. Collision Free Period

As shown in Figure 5, each system cycle starts with a CFP. The CFP begins with a CF_{start} frame, proceeds to a safety exchange interval, and typically ends with a Service_{release} frame followed by a CF_{end} frame. Each CFP has an announced duration. However, the AP may end the CFP before this proposed CFP length after it completes polling all vehicles in its poll region. The difference between CFP duration and Proposed CFP duration in figure 5 illustrates this. To start a new CFP, the AP transmits a CF_{start} frame with enough power to reach every vehicle in the beacon region ($\mathbb{R}(AP, APBR)$). The safety exchange interval is used by vehicles within the $\mathbb{R}(serviceAP, APSR)$ to conduct their safety exchanges. The coordinating AP polls each vehicle on its poll list. To allow sufficient time for each vehicle to reset its hardware from transmit state to receive state and vice-versa, every transmission in the CFP is separated by a Short Interframe Spacing (SIFS) [12]. Since vehicles within the service region ($\mathbb{R}(AP, APSR)$) switch to the service channel during the CP, they miss all the beacons. Instead the Service_{release} frame informs them of the schedule of the next CFP. This frame is transmitted with just enough power to reach vehicles within the service region. The Coordinating AP ends a CFP by transmitting a CF_{end} frame. The CF_{end} is transmitted with the same power as the CF_{start} frame.

\[A^n\] In such scenarios, $HR_{max}$ is generally larger than VSMR.
B. Collision Period

The end of CFP is followed by the collision period (CP). Vehicles in the service channel are free to leave for the service channel during this time. The Coordinating AP performs group management functions, advertises available services, and sends beacons to inform all vehicles (including newly arriving vehicles) of the upcoming CFP schedule.

1) Group management: The group management interval is used by vehicles entering or leaving $\Re(A,P,APR)$ to notify the AP of their presence. This enables the AP to ensure its poll schedule will include all vehicles needed to complete the safety exchanges required by vehicles in the service region. Upon reception of an association or de-association request from a vehicle, the AP replies with a confirmation (e.g. association response or de-association response) to the vehicle, and adds or removes the vehicle from its poll list. In the ICAP configuration the AP will need to stay on the service channel for part of the CP to execute the group management function. This will reduce ASTT.

2) Service announcements: The service announcement interval is used by the APs to advertise the services offered in the service region on the service channels. The DCAP design is agnostic to the format of these announcements. For example, the standards in [29] are compatible with this design. In the ICAP configuration the AP will have to switch out of the service channel during the CP to make these announcements on the control channel. This will also reduce ASTT.

3) Beaconing: To create a CFP in the $i^{th}$ cycle, the AP has to transmit beacons in the $(i-1)^{th}$ cycle. Every vehicle that receives a beacon will update its network allocation vector (NAV). The vehicle will remain silent for the duration of the CFP (duration of the NAV) unless it is polled. Vehicles that do not receive any of the beacon transmissions during the CP will continue to operate using the ad-hoc protocol throughout the next CFP. They can potentially interfere with the reception of polled messages during the CFP. Since the control channel is not centrally scheduled during the CP, the beacons sent by the AP must contend for channel access just like any vehicle message, i.e. their transmission and reception is not guaranteed. They do this using the ad-hoc protocol. Clearly, the probability of beacon reception is critical to the reliability of the safety exchanges during the CFP. To increase the probability of beacon reception the AP may optionally repeat its beacon multiple times, as shown in figure 5. Vehicles that receive at least one beacon in the $(i-1)^{th}$ cycle will set their network allocation vector (NAV) to the end of the $i^{th}$ CFP, i.e. they will not interfere during the $i^{th}$ CFP.

V. DCAP Design: Logical Properties

The design in this paper has been created to have certain logical properties. These are summarized as theorems in this section. The proofs are in [34].

The logical properties are safety and efficiency properties. For safety, we have sought to enable a full safety exchange (FSE) every cycle for every vehicle. A vehicle experiences a Full Safety Exchange in a cycle if all neighboring vehicles within distance VSMR receive a safety message from the vehicle during the cycle and the vehicle receives a safety message from all the same neighbors within the cycle. Needless to say, due to collisions or fading this does not always occur. Nevertheless, the design strives to give each vehicle the opportunity for an FSE. For efficiency, we have sought to maximize the fraction of time spent on the service channel per cycle by each vehicle in the service region, subject to the constraint that each vehicle receive the opportunity for an FSE. The fraction is quantified by the ASTT (Available Service Transaction Time) as defined in section III-B.

The quantities APBR, APSR, APSER in this section are as defined by equations 1, 2, 3, and 4 in section III. Likewise the CP and CFP are also as defined in the same section. $\overline{S}$ denotes the complement of the set $S$. The following notation is also used in this section.

- $t_i$: Starting time of the $i-$th cycle.
• $T$: Duration of each cycle.
• $\delta_{max}$: Maximum duration for each CFP.
• $D_i(n,r)$: The set of nodes within a circle centered at node $n$, with radius $r$, during the time interval $[t_i, t_{i+1})$.
• $\delta_i$: Duration of the CFP in the $i^{th}$ cycle. Note $\delta_i < \delta_{max}$.
• $FSE_i(n,r)$: Full safety exchange indicator function for a node $n$ and range $r$ in $CFP_i$. It is 1 if node $n$ experiences an FSE with all vehicles in $D_i(n,r)$ in the period $CFP_i$, and is 0 otherwise.

We assume $\delta_{max} < T$. To a first order $\delta_{max}$ is

$$\delta_{max} = APBR \cdot vehicleDensity \cdot numberOfLanes \cdot 2 \cdot transmissionTime$$

(5)

$$transmissionTime = \frac{safetyMessageSizeInBits}{transmissionRate}$$

(6)


The idealizations made to establish the theorems are as follows.

**Assumptions:**

1) The proof uses a collision model. Each transmission has a specified range and each node has a location. A transmission is received if the distance between transmitter and receiver is less than the specified range and there is no collision. A collision occurs if one or more nodes within interference range ($IR_{max}$) of the receiver transmit concurrently.

2) Maximum interference range for nodes other than the AP is $IR_{max}$.

3) Each node other than the AP has only one radio, and the radio can only receive data on one channel at a time.

4) If $x$ is a poll range, then a node $n$ is polled in $CFP_i$ iff node $n$ is in $D_i(AP,x)$.

5) Each node executes the designs in section III. The state machine specifications are in [34].

6) Nodes move in discrete steps, and they change position at the $t_i$’s. The maximum distance a node can move in a time step is $\nu_{max} \times T$.

7) The number of vehicles in a given area is proportional to the size of the area.

8) The AP transmits beacons periodically in $[t_i, t_{i+1})$. There is at least one beacon transmitted in $[t_i, t_i + \delta_i)$.

The first theorem asserts the FSE safety property targeted by the DCAP design. It is achieved under the assumptions above and by hypothesizing that every vehicle in the beacon region receives a beacon in every cycle. Thus in practice, the design must be configured to ensure high beacon reception probability (see figure 12 in section VII).

**Theorem 1:** If all nodes in $D_{i-1}(AP,APBR)$ receive a beacon in period $[t_{i-1}, t_i)$, then every node in $D_i(AP,APSR)$ will complete its full safety exchange (FSE) in $CFP_i$.

The next theorem asserts our poll range is minimal assuming the FSE requirement has to hold. The minimality of the poll range is required to argue the minimality of the CFP and the maximality of the ASTT.

**Theorem 2:** Let $poll\_range$ be a poll range other than $APSR$. If poll range has the property that for any $i$ and node $n \in D_i(AP,APSR), FSE_i(n,VSMR) = 1$, under the assumption of Theorem 1, then $poll\_range \geq APSR$. If $\delta_i \propto |D_i(AP,poll\_range)|$, then when $poll\_range = APSR$, $\delta_i$ is minimized.

The next theorem asserts the minimality of the beacon range assuming the FSE property has to hold. This is important because the beacon interferes with the safety messages of vehicles that are not interested in using the service channel (see figure 9 of section VII), i.e., it deteriorates safety message reception for vehicles in the outer part of the APQR and beyond the APQR. Thus it is important it be minimized.

**Theorem 3:** Let $beacon\_range$ be a beacon range other than $APBR$. If beacon range has the property that for any $n \in D_i(AP,APSR), FSE_i(n,VSMR) = 1$, under the assumption of Theorem 1, then $beacon\_range \geq APBR$. When $beacon\_range = APBR$, number of silent nodes, i.e. $D_i(AP,APBR) \cap D_i(AP,APBR)$, in $CFP_i$ is minimized.

The following theorem establishes the latency bound on safety messages in terms of the parameters of the DCAP design.

**Theorem 4:** If every node in $D_i(AP,APBR)$ receives a beacon in both $(i-1)^{th}$ and $i^{th}$ cycles, then for every node $l$ in $D_i(AP,APSR)$, the time between consecutive polls is bounded by $T + \delta_{max}$.

The last theorem summarizes the safety and efficiency properties. It relies on theorems 1 and 2.

**Theorem 5:** If all nodes in $D_{i-1}(AP,APBR)$ receive a beacon in period $[t_{i-1}, t_i)$, then the protocol is safe and efficient for all nodes $n$ in $D_i(AP,APSR)$ in the following sense

1) $FSE_i(n,VSMR) = 1$
2) The service time, $T - \delta_i$, is maximized.

VI. SIMULATOR

We evaluate the protocol configurations of interest by simulating a 4-lane highway at capacity, i.e., with a flow of about 2200 vehicle/hour/lane at an average speed of 55 mph. The average spacing between vehicles at this flow and speed is approximately 30 meters. This is the typical maximum flow condition for U.S. freeways and therefore creates the largest number of vehicles registering and de-registering with the CAP.

Our sample size is as follows. Each simulation is 12,000 seconds long. At 2200 vehicles per hour and 4 lanes, approximately 29,300 vehicles enter each simulation. The roadway is 2 km long. At 55 mph (25 m/s) a vehicle spends about 80 seconds on
the 2 km roadway during which time it transmits about 800 messages. This gives us about 23,440,000 transmission events. Therefore each QoS point on our graphs is computed from approximately 23,440,000 samples. We kept increasing the simulation duration until we were certain the QoS estimates had converged. Therefore we are confident that longer or larger simulations will not change the performance numbers.

The CAP is installed at the midpoint of the simulated highway, with APSR = 80 meters (see figure 6). At about 80 meters the RSSI of the DSRC radio transmitting at the 27 Mbps setting moves into the -80 dBm to -70 dBm range (see figure 110, Appendix G in [6]). Thus we choose the nominal APSR to enable reliable communication at the 27 Mbps data rate. The highest supported DSRC data rate for non-safety services is 27 Mbps, since DSRC prefers non-safety service channels be 10 MHz wide, and it is based on 802.11a chipsets offering a maximum of 54 Mbps over 20 MHz channels [29]. Larger APSR values are also evaluated to provide insight into the behavior of the design.

All safety messages are exchanged in a 20 MHz channel at 6 Mbps. Though DSRC channels are usually 10 MHz, the FCC ruling permits two 10 MHz channels to be combined to form a 20 MHz channel if necessary. In our opinion, the performance results in section VII show the necessity. Field work shows 6 Mbps over a 20 MHz channel is the recommended data rate for safety message exchange (see page 107, Appendix G, in [6]).

We use vehicle trajectories generated by the SHIFT traffic simulator [30]. This has been validated with actual data from Interstate I-880 [31].

We have implemented the DCAP protocol design in NS-2 [25]. The trajectories output by SHIFT are input to NS-2 which in turn outputs the communication network performance data. The DCF and PCF implementations already exist, though DCAP requires some modification to the DCF CSMA implementation. We build on the DCF and PCF [26].

We use a collision model to capture multiple access interference. Every message has a transmission range and interference range. If a receiver node is within transmission range of the sender and no other node within interference range of the receiver transmits concurrently, the receiver node receives the transmission. We need a power attenuation model to determine the interference range corresponding to a transmission range. This is the content of sub-section VI-A. Since all message losses in our simulations occur due to collision, in reality there will be additional message losses due to shadowing and small-scale fading. These will degrade the performance of all the evaluated protocol configurations. The magnitude of these additional losses will depend on the shadow or fade margins incorporated when determining the transmit power of a message. Some data analyzed by us with rooftop antennas, indicates Nakagami fading [33]. However, no consensus exists on fading and shadowing models for vehicle-vehicle communication. Amongst other things, these would depend on the type and mounting of antennas on vehicles and these are still being debated. Thus we try to make our evaluations independent of a specific statistical model of fading by conducting them relative to baselines representing DCF and PCF without the DCAP augmentations. In practice, performance of both DCAP and the baselines will be worse due to additional losses caused by fading.

The basic simulation parameters are listed in Table III. All messages are transmitted at 6Mbps as stated above. The CAP system cycle is 100 ms, so that vehicles within \( R(\text{AP}, \text{APSER}) \) are given an opportunity to transmit a safety message once every 100 ms. GMRTimeout is chosen to be 10ms. If a vehicle does not receive an association or de-association response from the AP, it will try again 10ms later. The 150 byte packet size permits description of vehicle motion and about 80 bytes of protocol header [28]. The message format for these safety applications is now part of the Society of Automotive Safety (SAE) standard called SAE J2735. These messages typically contain the following information: the position of the sender, motion status like speed, heading, acceleration, and the control information such as brake status, steering angle, throttle position, and so on. All this information is encoded into a 32 byte payload.

The 100 ms system cycle time means a vehicle gets to transmit a safety message roughly every 100 ms. This is the fastest communication rate envisaged by the Vehicle Safety Communication Consortium (VSCC) for all but one very short range application (page 16 of [6]).

The VSMR is chosen to be 150 meters. This range is chosen to enable a vehicle stopped on the freeway to warn an oncoming vehicle. An oncoming vehicle traveling at 55 mph and decelerating at 2 m/s/s will stop in 150 meters. The stopping distance at a speed determines the largest desired message range [28]. A vehicle approaching at 65 mph will have to decelerate at 3

\[ \begin{array}{|c|c|}
\hline
\text{Data Rate} & 6\text{Mbps} \\
\text{Message Rate} & 1 \text{ message per 100ms} \\
\text{Safety Message + Header} & 150 \text{ bytes} \\
\text{AP System Cycle} & 100\text{ms} \\
\text{Transmission Opportunity per Polled Vehicle} & 1 \\
\text{GMRTimeout} & 10\text{ms} \\
\hline
\end{array} \]

**TABLE III**
**SIMULATION PARAMETERS**

\[5\text{At an 80 meter APSR a vehicle traveling 55 mph is in range of the APSR for over 6 seconds. If ASTT is 80\%, as happens in our nominal case, a vehicle could download as much as 16 MB at 27 Mbps.}\]
m/s. These are reasonable decelerations, observed during driving, and are well within the capability of almost all drivers and cars.

The 150 meter VSMR range and the 6 Mbps data rate imply \( IR_{\text{max}} \) is 300 m. This is based on the method in section VI-B. The maximum possible vehicle speed chosen for protocol design is 120 mph, i.e., \( \nu_{\text{max}} = 120 \text{ mph or 53.64 meters/sec} \). From these numbers and the equations in section III, APSER = 230 meters, APPR = 236 meters, APQR = 530 meters and APBR = 536 meters. For simplicity, communication range for association and de-association messages are chosen to have the same range as the beacons.

A. Relating Message Range to Interference Range

Message ranges are VSMR for safety messages, APSR for service announcements, and determined by equations (2) and (4) for polls and beacons respectively. All these definitions appear in section III.

The power required to cover a range depends on the data rate. We use the deterministic Friis Free-space model for short distances and the Two-ray model for longer distance [27] to determine the received power. Data rate is determined by modulation and coding. The higher data rates, i.e., larger modulation constellations and smaller code rates, require higher transmission power to cover a given range. We use a data rate of 6 Mbps. We have obtained the Signal to Noise+Interference ratio required at the receiver to receive at this data rate from an 802.11a chipset manufacturer and used it in the calculations below.

Let range be denoted by \( R \), the SINR threshold at the chosen data rate be denoted by \( \beta \) and transmission power by \( P_t \).

The procedure is:
1) Calculate the desired received power by \( P_r = N \cdot 10^\frac{\beta}{10} \) where \( N \) is the thermal noise power.
2) Calculate the desired transmission power using the following equation:
\[
P_r = P_t K \left(\frac{d_o}{R}\right)^\gamma.
\]

Here \( P_t \) is the transmit power, \( P_r \) the received power computed in the previous step, \( K \) is a dimensionless constant which depends on the antenna characteristics and average channel attenuation, \( d_o \) is a reference distance for the antenna far-field, and \( \gamma \) is the path loss exponent [22]. This is supported by empirical data for free-space path loss at a transmission distance of 100m [24]. The value of \( \gamma \) on the other hand depends on the propagation environment.

B. Calculating \( IR_{\text{max}} \)

Beacon range depends on the maximum interference range of a safety message transmission \( IR_{\text{max}} \). This section describes how to determine \( IR_{\text{max}} \). Once \( IR_{\text{max}} \) is known the beacon transmission power is calculated as in section VI-A. The \( IR_{\text{max}} \) calculation method is:
1) Calculate \( P_r \) and \( P_i \) as above for \( R = VSMR \).
2) Calculate the minimum power required to interfere (\( P_i \)) by \( P_i = 10^\frac{\beta}{10} P_r \), since if interference prevents reception of the message the of received power to interference power will be less than \( \beta \) in dB.
3) Calculate \( IR_{\text{max}} \) from
\[
P_i = P_t K \left(\frac{d_o}{IR_{\text{max}}}\right)^\gamma.
\]

Note
\[
10^\frac{-\beta}{10} P_r = P_t K \left(\frac{d_0}{IR_{\text{max}}}\right)^\gamma \Rightarrow 10^\frac{-\beta}{10} \frac{1}{R^\gamma} = \frac{1}{IR_{\text{max}}^\gamma},
\]
by substituting equation (7). Thus the relationship is independent of \( P_t, K, d_0 \) when \( \gamma \) is the same for \( R \) and \( IR_{\text{max}} \). We use a 2-ray model with \( \gamma = 2 \) before the cross-over point and \( \gamma = 4 \) after. The crossover is at about 240 meters.
VII. SIMULATION RESULTS

We evaluate the communication of safety and non-safety messages in a multi-channel environment in three protocol configurations. These are DCF only, PCF in the service hotspot only, and the DCAP configuration which is DCF combined with PCF enhanced with the spatial division in section III.

For the parameter values in section VI the CFP duration is about 21ms. This implies ASTT for vehicles within the service region \( \mathcal{R}(AP,APSR) \) is about 79%. At the maximum flow condition on a four lane highway, this is maximum service channel utilization reached by the DCAP design. On an 8-lane highway the CFP would double and the ASTT would be about 58%. The channel access delay experienced by a vehicle is 100 msec. The jitter in this delay can be 21 ms, i.e., a vehicle may wait 121 msec between transmissions. Jitter can be substantially less if new vehicles joining the poll list are added to its end. Our implementation does this. Thus we observe a delay that is almost 100 msec with very little jitter. Results in this section show that protocol message loss probabilities are small. The expected value of delay is almost 100 msec.

In addition to these QoS parameters, performance is quantified by the Sender Based Probability of Message Reception (SBPMR) and Receiver Based Probability of Message Reception (RBPMR) defined as follows.

The SBPMR of node \( x \) in the \( i^{\text{th}} \) cycle, \( SBPMR_i(x) \), is defined as,

\[
\frac{1}{K(i)} \sum_{k=1}^{K(i)} \frac{\text{num}_{-}\text{receiver}_{-}\text{recvd}(x,k)}{|D_i(x,VSMR)|},
\]

where \( K(i) \) is the number of messages transmitted by node \( x \) in the \( i^{\text{th}} \) cycle, \( \text{num}_{-}\text{receiver}_{-}\text{recvd}(x,k) \) is the number of receivers in \( D_i(x,VSMR) \) that received the \( k^{\text{th}} \) message. Similarly, the RBPMR of node \( x \) in the \( i^{\text{th}} \) cycle, \( RBPMR_i(x) \), is defined as,

\[
\frac{\text{num}_{-}\text{message}_{-}\text{recvd}(x)}{\text{num}_{-}\text{intent}_{-}\text{message}(x)},
\]

where \( \text{num}_{-}\text{message}_{-}\text{recvd}(x) \) is the number of messages received by \( x \) in the \( i^{\text{th}} \) cycle and \( \text{num}_{-}\text{intent}_{-}\text{message}(x) \) is the number of messages generated by \( D_i(x,VSMR) \). The sender based probability of message reception in a region \( R \), \( SBPMR(R) \), is defined as,

\[
\frac{1}{N} \sum_{i=1}^{N} \frac{1}{|D_i(R)|} \sum_{\forall x \in D_i(R)} SBPMR_i(x),
\]

where \( D_i(R) \) is the set of nodes in region \( R \) in the \( i^{\text{th}} \) cycle and \( N \) is total number of simulation cycles. Under suitable ergodic assumptions, it can be interpreted as the probability that a randomly chosen receiver within range VSMR of a randomly chosen sender will receive a randomly chosen message sent by it. Likewise the RBPMR defined next, can be interpreted as the probability that a randomly chosen message sent by a randomly chosen sender will be received by a randomly chosen receiver within range VSMR. The receiver based probability of message reception in a region \( R \), \( RBPMR(R) \), is defined as,

\[
\frac{1}{N} \sum_{i=1}^{N} \frac{1}{|D_i(R)|} \sum_{\forall x \in D_i(R)} RBPMR_i(x).
\]

Most results are presented in terms of RBPMR since in all but one case the two are equal. In all these cases the plots are marked with the abbreviation PMR. Where the two are distinct we use the abbreviations RBPMR and SBPMR.

We compute the probability of beacon reception to give insight into the performance of the DCAP design. This is calculated over the set of vehicles outside \( \mathcal{R}(AP,APSR) \) and within the \( \mathcal{R}(AP,APBR) \). It is defined as,

\[
\frac{1}{N} \sum_{k=1}^{N} \frac{\text{num}_{-}\text{recvd}(k)}{\text{num}_{-}\text{intent}(k)},
\]

where \( N \) is the total number of simulated system cycles, \( \text{num}_{-}\text{recvd}(k) \) is the number of vehicles in the set that received a beacon in the \( k^{\text{th}} \) cycle, and \( \text{num}_{-}\text{intent}(k) \) is the total number of vehicles in the set in the \( k^{\text{th}} \) cycle.

Figure 7 shows the performance if 802.11 DCF is used without modification. The best PMR with 802.11 DCF is 0.97. This is the baseline we seek to maintain, i.e., the PMR delivered by the DCAP design should be no worse than that delivered by 802.11 DCF. We use 802.11 DCF as our baseline because it is a widely deployed protocol available for the exchange of messages in a vehicular ad-hoc network. As expected, the PMR drops linearly with the time vehicles spend on the service channel. When the service channel time is 80% of 100 msec, the PMR is as low as 0.2. The vehicles leave for the service channel randomly, independently, and asynchronously. Clearly if service channels are to be utilized efficiently better design is required.

Figure 8 shows the performance using PCF in the service hotspot only. Since the DCAP design is an extension of PCF, PCF in the service hotspot only can be viewed as a special case of the DCAP design. It corresponds to \( APBR = APSR = APBR \). The AP polls the vehicles in the service region only. Vehicles outside the service region use 802.11DCF. Just as in normal
PCF, there is a CFP and CP. During the CFP the service region vehicles are polled to send their safety messages. They depart after the CFP to the service channel. The vehicles outside the service region stay on the service channel the entire time and use 802.11 DCF to send their messages during the CP and CFP.

In figure 8, we plot performance in terms of the sender based probability of message reception (SBPMR) and receiver based probability of message reception (RBPMR) to illustrate the problems of this design. Vehicles within the service region have an SBPMR performance similar to 802.11DCF without service. Vehicles right outside the service region have the worst SBPMR performance because as much as half of their receivers are within the service region, and these receivers are not on the control channel when they transmit in the CP. On the other hand, we see the opposite trend for the RBPMR measure. The receivers inside the service region have poor performance since they are not on the control channel 100% of the time. When their senders transmit, they miss the messages. The opposite is true for receivers outside the service region. They potentially receive each message. Performance is never better than the ad-hoc case by either measure. In a significant region it is worse. Thus PCF needs to be enhanced in some way. Our response is the spatial division added to produce DCAP.

Figure 9 shows the DCAP configuration does not suffer the problem experienced by PCF in the service hotspot. For nodes within the service region, SBPMR and RBPMR are very close to each other. This is the reason for the spatial division added to PCF.

Figures 9 and 10 show the performance of the DCAP design. Figure 10 combines figures 7, 8, and 9 in the RBPMR measure. The region in figure 10 between 230 and 530 meters is the quiet region. The safety QoS for nodes in this region is near the 97% baseline (solid line for 802.11 DCF without service). Beyond 600 meters the safety message QoS follows the baseline exactly.

Figure 10 shows performance upto about 300 meters from the AP is superior to the ad-hoc case. One can see this more clearly in figure 9. The dashed line representing DCAP merges with 1 near the vertical axis. This is so even though the service region vehicles are now spending 80 out of 100 msec on the service channel. Between 300 and 600 meters the performance
Fig. 9. Coordinated AP Performance. The SBPMR and RBPMR are very similar unlike pure PCF.

Fig. 10. 802.11 PCF versus coordinated AP. The solid line is the baseline. CAP stays close to the baseline. PCF does much worse inside the hotspot is poorer than the ad-hoc case. One can see this more clearly in figure 11. The reception probabilities drop down to between 0.95 and 0.96 in comparison to 0.97 in the ad-hoc case. The degradation is less than 2%. The degradation is a function of beacon power, poll power, and beacon rate. These are set by equations 1 through 4. These figures are based on a beacon rate of 3 beacons per cycle. We do not know how to remove this slight degradation to vehicles outside 300 meters. The high power beacon and poll messages cause additional interference reducing performance relative to the ad-hoc case.

Figure 11 shows the sensitivity of the DCAP design performance to the number of beacons per cycle. The DCF line is slightly wavy because of the variations in inter-vehicle spacing along the highway. As the number of beacons is increased performance inside the service region goes up while that in the 300 to 600 meter zone goes down. Thus the number of beacons should not be any larger than necessary. The performance difference inside the service region for 3 and 6 beacons is not significant. While the difference between the 1 and 3 beacon plots is more noticeable. Figure 12 shows the reason for the smaller difference between the 3 and 6 beacon lines. The performance improvement arising from additional beacons is related to the probability the beacons are received. This probability is almost level after 3 beacons. Thus the performance of the DCAP design, in particular the performance balance inside and outside the service region, can be adjusted by varying the number of beacons between 1 and 3.

We choose the beacon power so that the beacon range will be $APBR = APQR + \Delta$ (equation 4), where $APQR = APSER + IR$ (equation 3). Figure 13 shows the impact of choosing $APQR = APSER + \alpha IR$ where $\alpha$ varies between 0.1 and 1. The dashed line represents the worst case performance outside the service region, e.g., the lowest value on the Coordinated AP line in figure 10. As beacon power rises the performance inside the service region improves (solid line) and that outside the service region drops (dashed line). Thus the performance of the DCAP design, in particular the performance balance inside and outside the service region, can be adjusted by varying the beacon power.

Figure 14 evaluates the ability of the DCAP design to scale to larger service regions. Here as the service region size is being raised, beacon and poll powers are being raised in accordance with equations 1, 2, 3, and 4. As the service region size
Fig. 11. Coordinated AP Overhead. The amplified scale shows the safety tax is about 2%.

Fig. 12. Beacon reception

Fig. 13. Different beacon ranges
is increased performance outside the hotspot deteriorates. This is because there are more vehicles to be polled in the service region, increasing the length of the CFP. This reduces the CP and thereby also reduces the time available for other vehicles to send their safety messages. We envisage the design supporting hotspots with range 50 to 150 meter. The DCAP configuration will not scale to larger service regions.

VIII. POWER DETERMINATION

This section presents a method to choose transmission power levels assuming a shadowing model is known. This method chooses a constant power based on a statistical model of the channel. We assume the model is lognormal. For a preliminary analysis of power control based on receiver feedback see [32].

We think of received signal power as having a path loss component determining the drop in average power with distance. The total received power is determined by the path loss component superimposed with a slowly varying shadowing component caused by the environment, e.g., buildings or highway structures, and a much faster small-scale fading component. We model the shadowing component by a lognormal random process and show how to use the model to pick transmission power. We do not do the same for flat or small-scale fading because it fluctuates much more rapidly in space, i.e., on the order of half a wavelength, thereby averaging out to zero for our purposes [20].

The CAP needs to divide its surrounding region into service, poll, and beacon reception regions by transmitting its service, poll, and beacon messages with different levels of power. These are AP to vehicle communications where the AP antenna is assumed to be placed higher than the vehicles. We show how to choose the power of these messages assuming a lognormal shadowing model. We do not address vehicle to vehicle communication since we are not sure of the right form of the shadowing model. Antenna designs remain unsettled for vehicle-vehicle communication.

Our path loss model is

\[ P_r(d) = P_t K \left[ \frac{d_o}{d} \right]^{\gamma} \]  

implying that transmit and receive power in dBm are related by

\[ P_t = P_r(d) - 10 \log_{10} K + 10 \gamma \log_{10} \left[ \frac{d_o}{d} \right] \]  

Here \( P_t \) is the transmit power, \( P_r(d) \) the received power at distance \( d \) from the transmitter, \( K \) is the dimensionless constant used in equation 7 determined by antenna characteristics and average channel attenuation, \( d_o \) is a reference distance for the antenna far-field, and \( \gamma \) is the path loss exponent [22]. The value of \( \gamma \) depends on the propagation environment. Table IV summarizes typical path loss exponents [23], [24].

We model shadowing by a Gaussian random variable \( \psi \) with 0 dB mean and variance \( \sigma_\psi^2 \). Typically \( \sigma_\psi^2 = 3.65 \text{ dB} \) for a lognormal shadowing model. Hence our ratio of received to transmitted power in dB is given by:

\[ \frac{P_r(d)}{P_t}(dB) = 10 \log_{10} K - 10 \gamma \log_{10} \left[ \frac{d_o}{d} \right] - \psi \]  

We define the outage probability at a given distance \( d \) as

\[ p_{\text{out}}(d) = \text{Prob}(P_r(d) < P_{\text{min}}) = 1 - Q \left( \frac{P_{\text{min}} - (P_t + 10 \gamma \log_{10} K - 10 \gamma \log_{10} (d/d_o))}{\sigma_\psi} \right) \]
Environmental γ range
Urban macrocells 3.7-6.5
Urban microcells 2.7-3.5
Office Building (same floor) 1.6-3.5
Office Building (multiple floors) 2-6
Store 1.8-2.2
Factory 1.6-3.3
Home 3

**TABLE IV**
**TYPICAL PATH LOSS EXPONENTS**

![Graph showing cell coverage and outage probability with shadowing.](image)

Fig. 15. Cell coverage and outage probability with shadowing. $P_{\text{min}} = -120\text{dBm}$, $\gamma = mR + n$

where $P_{\text{min}}$ is the minimum received power required for message reception. The $Q$ function is the complementary error function below:

$$Q(z) = \frac{1}{2} \text{erfc} \left( \frac{z}{\sqrt{2}} \right).$$

(18)

Based on $p_{\text{out}}(d)$ we define a cell outage probability $P_{\text{out}}(R)$ for a cell of radius $R$ around the transmitter as

$$P_{\text{out}}(R) = \frac{2}{R^2} \int_0^R p_{\text{out}}(r)rdr.$$ (19)

When the aim is to reach all vehicles within some distance $R^*$ around the Coordinating AP, the transmit power is chosen so that $P_{\text{out}}(R)$ will be small when $R < R^*$ and rise rapidly when $R > R^*$.

Within the cell of radius $R^*$ the received power should be above the message reception threshold throughout the area. This is captured by defining a cell coverage measure $C(R^*)$ defined as

$$C(R^*) = E \left[ \frac{1}{\pi R^{*2}} \int_{\text{cell area}} 1[Pr(r,\theta) > P_{\text{min}}]rdrd\theta \right].$$ (20)

Combining these equations yields the following closed-form solution for $C$;

$$C = Q(a) + \exp \left( \frac{2 - 2ab}{b^2} \right) Q \left( \frac{2 - ab}{b} \right).$$ (21)

where

$$a = \frac{P_{\text{min}} - P_t - 10\log_{10}(K + 10\gamma \log_{10}(R/d_o))}{\sigma_o}$$

$$b = \frac{10\gamma \log_{10}e}{\sigma_o}$$ (22)

The aim is to choose the transmit power so that cell coverage will be sufficiently high. $\gamma$ is assumed to be between 2 and 6 and incremented linearly with the distance.

The DCAP design has three regions, i.e., beacon region, polling region, and service region. We choose the transmit power for each message using equation 21 so that $C$ is almost the same in all the regions. The figures are computed for $C = 0.8$. Thus the method is to target an outage probability and then derive the corresponding power levels. One can see that a service packet has high outage probability in the polling and beacon regions. It has low outage probability in the service region. This is desirable. Likewise the polling packet has a high outage probability in the beacon region.
IX. CONCLUSION AND FUTURE WORK

We have explored the problem of creating a wireless protocol and architecture for a vehicle-to-vehicle and vehicle-to-infrastructure communication system. The goal is ensuring that low-latency safety messages are delivered with high probability and low latency (e.g., 100 msec.). At the same time, the system should maximize the fraction of time available for vehicles to perform transactions with roadside access points on a separate service channel. Challenges imposed by DSRC include operating within a multi-channel environment with an 802.11 radio (vehicles tuned to commercial service channels cannot simultaneously receive safety messages in the control channel) and the highly dynamic network topology characterized by communication nodes moving with vehicular properties.

The solution proposed here extends the 802.11 base protocol currently specified for DSRC. It assumes that DSRC non-safety services will involve APs and requires at least one in each hotspot to regulate the timing of channel transitions for vehicles entering the service area. We refer to this AP as a coordinating access point (CAP). In areas without services we enable the exchange safety messages amongst vehicles with an ad-hoc protocol such as 802.11 DCF or any other able to obey the CAP in the vicinity of a hotspot.

Service-seeking vehicles and those proximate to them conduct a full safety exchange during a collision free period, where all safety message broadcasts are scheduled by the access point. At the completion of the collision free period, vehicles within the service area may switch to service channels to perform desired transactions. Vehicles outside of the service area will complete their safety exchange and are otherwise free to transmit non-scheduled data. Vehicles out of range of a CAP, i.e., outside its beacon range operate in ad-hoc mode, as do vehicles within beacon range during contention periods. Thus the solution builds on 802.11 PCF within range of a CAP and combines it with 802.11 DCF out of CAP range to comprehensively support safety message exchange throughout a highway.

Evaluations are conducted using NS-2. Trajectories of moving vehicles are produced by SHIFT and represent a four lane highway at maximum flow. We evaluate supporting safety and non-safety communication using DCF, PCF in the service hotspot only, i.e., without our spatial division, and the DCAP configuration. In the DCF evaluation the vehicles leave the safety message channel randomly and asynchronously since there is no signal available to synchronize their departure. Since the targeted recipients of a message are often away when the message is transmitted, safety message reception is poor. PCF restricted to the service hotspot also does poorly within about 300 meters of the AP for the same reasons. Many of the intended recipients of safety messages are away on the service channel when the message is sent.

The DCAP design delivers more consistent performance as a function of distance from the CAP. We view the performance of the ad-hoc protocol where there are no service hotspots as a desirable performance requirement. DCAP performance is significantly better within the hotspot but about 2% worse between 300 and 600 meters away from the CAP. We know how to reduce the 2% tax by making safety message reception inside the hotspot a bit worse but cannot eliminate it.

Evaluations are conducted using a collision model. Thus all power considerations are transformed into transmission ranges and corresponding interference ranges. This transformation can provide for shadow and small-scale fade margins. We use a collision model because most of the communication in the simulator is vehicle-vehicle and we do not know of established fading or shadowing values for such communication. All message losses occur due to collisions. In practice there will be some additional loss due to shadowing and small-scale fading. The amount of additional loss will depend on the margins assumed when determining the transmission power of different messages. If the shadow or fade margins have to be larger than assumed in this paper, the transmission power corresponding to VSMMR will have to rise, but \( IR_{max} \) will rise still more deteriorating the performance of the DCAP, PCF in hotspot, and DCF only configurations, i.e., the new design and the baselines used for comparison will all deteriorate.

Thus the principal finding of this paper is the relative performance of the DCAP, PCF in hotspot, and DCF only configurations. Relative to the other two, the DCAP design is able to offer consistent QoS to safety messages as vehicles travel into the hotspot, use the service channels, and travel out. QoS refers to the probability a safety message transmitted by a randomly chosen vehicle within distance VSMR, and the delay between consecutive opportunities given to a vehicle to transmit its safety messages. If adjacent hotspots overlap to create larger contiguous service regions, coordination by a single CAP is not efficient. To a rough approximation, if VSMR is 150 meters, interference range is about 300 meters. This means vehicles at opposite ends of a hotspot with radius 150 meter could transmit concurrently without interfering with each other. This suggests the path to efficient design lies in controlling service regions that are several hundred meters or more in dimension with multiple CAPs with synchronized polling schedules. These schedules should allow non-interfering vehicles to be polled concurrently to keep ASTT at a reasonable value. The poll and beacon ranges could still be derived using the equations in this paper with a small APSR value as in this paper. Then beacon and poll power would then have the order of magnitude in this paper. We think the protocol to be followed by the vehicle could also be as described in this paper.

If the CAP polling schedules are to be synchronized, CAP clocks would have to be synchronized. Given the magnitudes of 802.11 intervals like PIFS, DIFS, etc., the clocks would need to be synchronized to microsecond precision. This is difficult without using sophisticated technology that would raise cost. For example, synchronization together with centralized computation of all polling schedules for optimal operation could be realized if the CAPs were all put on an optical network like FDDI. Distributed synchronization and polling coordination using the wireless channel itself for such synchronization at vehicular traffic volumes is an unsolved problem to the best of our knowledge.
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