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Publication Date

2005-03-01

CALIFORNIA PATH PROGRAM
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California PATH Working Paper
UCB-ITS-PWP-2005-2

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department Transportation, Federal Highway Administration.

Report for fund 94138

March 2005

ISSN 1055-1417

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Abstract–One of the key goals of a vehicular ad-hoc network (VANET) is providing sufficient quality of service (QoS) for real-time safety applications while concurrently supporting commercial services. This paper proposes a multi-channel wireless communication architecture and protocol for the scenario where commercial services are provided by roadside infrastructure. This solution extends the IEEE 802.11 wireless LAN protocol to schedule periodic safety messages in a "safety channel". It explicitly supports concurrent non-time-critical communications in separate, non-safety "service channels". Further, it is shown that this arrangement maximizes service channel access time while maintaining the requisite QoS for safety applications. This paper concludes with simulations that confirm the attractive properties of this architecture and protocol.

1 INTRODUCTION

This paper is motivated by the growing belief that putting an 802.11-like radio into road vehicles could help the driver drive more safely. The US FCC has allocated 75 MHz of spectrum in the 5.9 GHz band for Dedicated Short Range Communications (DSRC) to enhance the safety and productivity of the nation's transportation system [7]. The FCC's December 2003 DSRC ruling has permitted both safety and non-safety/commercial applications, provided safety messages are accorded priority. The USDOT and IEEE have taken up the standardization of the associated radio technology Wireless Access for Vehicular Environments (WAVE)[1]. Industry groups such as Vehicle Safety Communication Consortium (VSCC) and DSRC Industry Consortium are working hard on safety enhancement, congestion mitigation, commercial and transit vehicle applications in partnership with the Intelligent Vehicle and Infrastructure Consortium Initiatives (IVI, IC) by USDOT. Academia and industry have come together under the auspices of the ACM, to hold the first workshop on Vehicular Ad-hoc Networks[2] (VANET) to advance the convergence of networking and automotive safety.

The United States Department of Transportation has declared that the reduction of vehicular fatalities is its top priority [2]. On an average day in the United States, vehicular collisions kill 115 and injure 8700. More health care dollars are consumed in the United States treating crash victims than any other cause of illness or injury [2]. The connection between 802.11 radios and safety provides the strongest case yet for getting such radios into cars. The case would grow stronger still, if the radio could also be used by more conventional applications like mobile infotainment, multimedia, or congestion advisories. We will call these non-safety applications. This paper explores the problem of using an 802.11-like radio in the vehicle to support both safety and non-safety applications.

Since the various players in the vehicular application space are converging on DSRC, we formulate our problem to account for the FCC rules laid down for DSRC [7] and the current industry consensus on standards [9]. Significant amongst these are a multi-channel bandplan, priority for safety applications, and compatibility with 802.11a hardware.

The contributions of the paper are as follows. Section 2 formulates our protocol design problem. Safety messages have quality of service requirements. We seek to satisfy these requirements while concurrently supporting non-safety communications with an 802.11-like radio. Section 3 reviews related work. Sections 4 and 5 describes our protocol design. Section 6 specifies the logical properties of our design. This is done as a mathematical proof of protocol correctness. Section 7 describes an implementation of the protocol in NS-2 and some preliminary simulation results. We have not yet tuned the protocol for optimal performance. Section 8 contains conclusions and future research directions.

2 PROBLEM FORMULATION

We assume the spectrum used by the safety and non-safety applications is divided into multiple channels. This makes us consistent with the FCC mandated bandplan for DSRC [7]. The DSRC spectrum is divided into seven channels, each consisting of 10 MHz. One of these seven channels is identified as a *control channel*. It can be used to send safety messages. The remaining six channels are called *service channels*. Providers of non-safety services are expected to obtain licenses to use these channels to conduct their transactions. They may use the control channel

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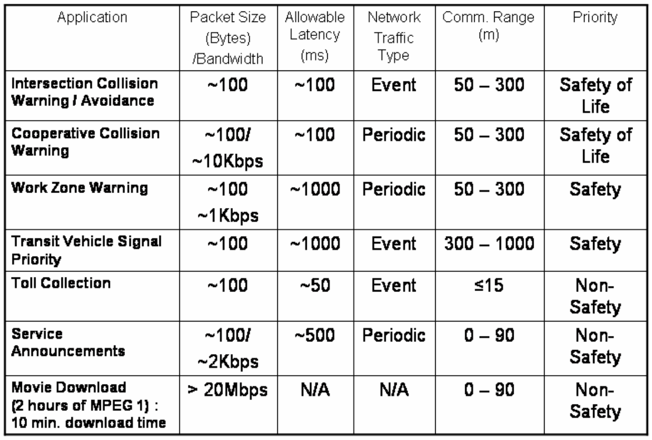
[1] http://www.standards.its.dot.gov/Documents/dsrc_advisory.htm

[2] http://www.path.berkeley.edu/vanet/

to announce services and establish the service channel communication link between responding vehicles and the service provider. Accordingly, we assume all the safety messages are sent on a single channel while all non-safety communications are to be conducted mainly on several, separate, service channels.

Safety messages, as per the deliberations of the standards bodies, have latency and range requirements (see Table 1). We lump both safety and safety of life messages into one priority class. Latency is typically between 100 and 500 msec. Ranges are between 50 and 300 meters. The stopping distance of a vehicle decelerating comfortably is about 250 meters. See Xu [5] for a more comprehensive discussion of the reasoning behind these numbers. We assume that every safety message must reach any vehicle within its specified range, in less than its specified latency with high probability. We assume there is a maximum range, called the Vehicle Safety Message Range (VSMR). The range requirements of all safety messages are assumed to be less than or equal to VSMR. Likewise we assume there is a smallest latency, denoted by T. The latency requirement of all safety messages is assumed to be greater than or equal to T. We assume all safety messages are communicated in a single hop.

We seek to permit non-safety communications while realizing a priority for safety messages. Therefore the spirit of our protocol design problem is to maximize the bandwidth available for non-safety applications, without violating the latency and range requirements of all safety messages generated by all vehicles. If a vehicle or roadside entity transmits a safety message, i.e., one whose receipt may enhance the safety of proximate vehicles, we want the proximate vehicles to receive these messages.



Application	Packet Size (Bytes) /Bandwidth	Allowable Latency (ms)	Network Traffic Type	Comm. Range (m)	Priority
Intersection Collision Warning / Avoidance	~100	~100	Event	50 – 300	Safety of Life
Cooperative Collision Warning	~100/ ~10Kbps	~100	Periodic	50 – 300	Safety of Life
Work Zone Warning	~100 ~1Kbps	~1000	Periodic	50 – 300	Safety
Transit Vehicle Signal Priority	~100	~1000	Event	300 – 1000	Safety
Toll Collection	~100	~50	Event	≤15	Non-Safety
Service Announcements	~100/ ~2Kbps	~500	Periodic	0 – 90	Non-Safety
Movie Download (2 hours of MPEG 1) : 10 min. download time	> 20Mbps	N/A	N/A	0 – 90	Non-Safety

Table 1: Examples of DSRC Applications and Requirements [11]-[13]. The data in this table is based on preliminary evaluations.

The problem is difficult because we seek to be compatible with 802.11 hardware. Standard 802.11 radios demodulate one channel at a time. (Due to cost considerations, the automotive industry has resisted adding more than one DSRC radio per vehicle.) Therefore if the vehicle radio is on a service channel when a safety message directed to the vehicle is transmitted by a neighboring vehicle or roadside entity on the control channel, the vehicle will not receive the message. We assume this is unacceptable. Our challenge is to ensure all safety messages are received by their intended recipients within the specified latencies while keeping service channel use acceptably efficient. Essentially we propose to do this by synchronizing the arrival and departure of vehicles from the control channel.

We use a roadside access point to solve the problem. We justify this by noting that many non-safety applications involve the transfer of data between vehicles and a roadside entity. We expect this roadside entity to execute certain network coordination functions. When there are no roadside entities present, we assume the only communications are safety messages generated by vehicles for vehicles. In our design, these messages are handled in an ad-hoc manner, i.e., without roadside assistance. In such a scenario, channel load may be very light. The appendix further describes a vehicle's transitions to and from areas with roadside infrastructure.

3 PREVIOUS WORK AND CURRENT TECHNOLOGY

Xu [5] and Yin [6] present preliminary protocol designs to support safety applications over wireless networks. However, they offer no insight into how the radio might concurrently support non-safety applications. These protocols are ad-hoc. Safety messages are generated by vehicles for neighboring vehicles. They are delivered through protocols overlayed on CSMA or 802.11 DCF. No roadside infrastructure is required. We adhere to this ad-hoc approach in this paper when there are no non-safety communications. We assume safety messages are communicated from vehicle to vehicle by some ad-hoc protocol when there are no non-safety communications. We do not specify the ad-hoc protocol here. Rather, the protocol for concurrent safety and non-safety communications proposed here could work with any of the ad-hoc protocols in these papers or 802.11 DCF.

The FCC [7] and standards bodies [9] have ruled on the necessity of concurrently supporting safety and non-safety communications. However, they have not proposed a design to meet this need. Hence we write this paper. They have also proposed latency and range requirements for safety messages, formats for service announcements in the control channel, and protocols to use the control channel to create the service channel link between vehicle and service provider. The design in this paper uses these proposals.

DPC [17], DCA [19], and CHAT [18] multiplex multiple applications over multiple channels. They seek to maximize throughput while preserving fairness. DPC and DCA require each node to have two radios. One radio listens to the control channel (CCH) at all times, and the other radio is used for conducting data on the data channels (DCH). The CCH is used by nodes to reserve DCH access. DCH reservation on the CCH is contention based. The mechanism is very similar to the RTS/CTS handshake. CHAT on the other hand eliminated the extra control channel, but it required each node to follow a common hopping-sequence. Channel reservation on each hop is very similar to RTS/CTS. Once channel reservation succeeds, the sender and receiver(s) remain on the reserved channel for the duration of the data exchange. When the data exchange is done, these nodes synchronize back to the common hopping sequence. Since safety messages are generally useful to vehicles proximate to the sender, the system supports broadcast communication. DPC and DCA only support unicast communication. Though CHAT supports broadcast communication, there is no bound on the latency to all broadcast receivers receiving the message.

Finally, our design builds on the 802.11 DCF and PCF protocols. [8]

4 GENERAL ARCHITECTURE 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*—A roadside unit (RSU) that provides non-safety services, called a *service access point*, may conduct these services within an *access point service region* (APSR). Only vehicles located within the APSR can avail of these services. This RSU will advertise its services in the control channel but conducts the transactions in a service channel
- *Coordinating access point*—An RSU that coordinates the transmissions in its proximity is called a *coordinating access point*. A single access point may be configured to function as both the service AP and the coordinating AP.

We have studied three 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*. The coordinating AP has a radio dedicated to the control channel. The service AP's have one or more radios dedicated to service channels. This configuration is called the *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 every T sec. This configuration reduces cost while reducing service channel throughput, and may be attractive in low traffic-density environments. This configuration is called the *integrated coordinating AP* (ICAP).

In the third configuration, a single coordinating AP (perhaps municipality-operated) shepherds several non-co-located service APs (perhaps operated by surrounding commercial providers). This may be ideal in dense, urban scenarios. This configuration is called the *shared coordinating AP* (SCAP).

The rest of this paper limits consideration to the DCAP configuration.

The *coordinating AP* divides the control channel resource in both space and time.

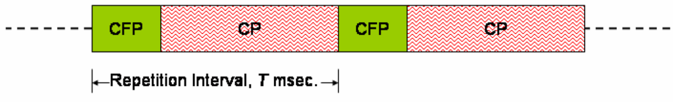


Figure 1: Basic time division in the control channel

Figure 1 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 the lower bound on the latency of safety messages[3]. The system cycle is repeated every repetition period. Each period is further divided into two sub-periods: a regulated *contention-free period* (CFP), and unregulated *contention period* (CP). During the CFP, each vehicle in a region called the *Access Point Poll Region* (APPR, defined later) 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* of [8]. The CP follows the completion of the CFP. During the CP

- vehicles located in the previously defined APSR can receive services by switching to service channels,
- the remaining vehicles can send safety messages using an ad-hoc protocol, and
- the coordinating AP executes control functions in preparation for the next CFP (see Section 5.2)

The available service transaction time (ASTT) is defined as the fraction of time a vehicle within the service region stays on the service channel. High ASTT is preferable for non-safety services. The ASTT enjoyed by vehicles within the APSR is approximately equal to $(T - CFP)/T$ (e.g. without considering the channel switching time). Channel switch times for 802.11 radios can be made as small as 1 msec.

The spatial division is shown in Figure 2. We use the notation *Region(X, R)* to denote a circular region centered at radio *X* with radius of *R*. Thus *Region (AP, APSR)* denotes the circle of radius *APSR* centered about the location of the coordinating AP radio. Since the coordinating and service AP radios are co-located we do not distinguish between the two.

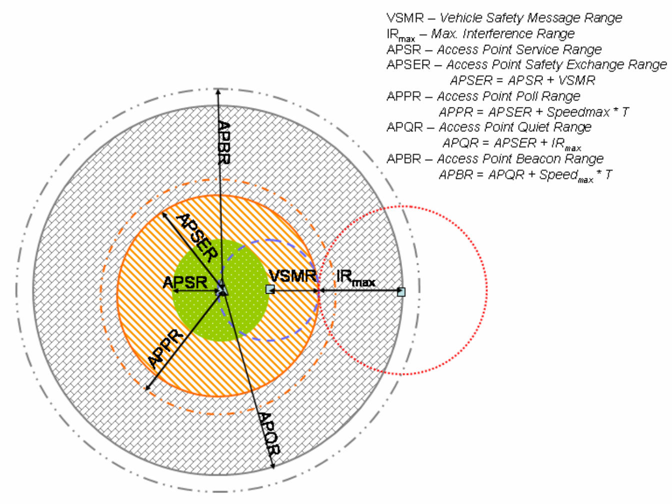


Figure 2: The spatial division around the AP

The purpose of the spatial division is to ensure that all vehicles within the APSR send and receive all relevant safety messages during the CFP, i.e., before they depart to the service channels in the CP. More formally, we require each vehicle in the APSR to execute a *full safey 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.

Let APSER = APSR + VSMR. Since the maximum specified range of a safety message is limited to VSMR, all vehicles within *Region (AP, APSER),* where APSER abbreviates access point safety exchange region, must be polled by the AP within the CFP to enable each vehicle in *Region(AP, APSR)* to execute a full safety exchange.

Let APPR = APSER + $Speed_{max} * T$. $Speed_{max}$ denotes the maximum possible speed of a vehicle. We require the poll to be sent with sufficient power to reach all vehicles within *Region(AP, APPR)*, where APPR abbreviates access point poll region. The extra transmission distance $Speed_{max} * T$ is used by the AP to notify vehicles that they are about

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[3] A careful reader 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 $T/2$. For clarity of exposition, the authors intentionally avoid this

to enter *Region(AP,APSER)*. These vehicles will register with the AP in the CP as described in Section 5.2.1. Thus when they enter the *Region(AP,APSER),* the AP will be ready to poll them.

- Let $IR_{\max}$ denote the maximum possible distance at which a transmission from one vehicle can interfere with reception at another. $IR_{\max}$ is determined by the transmission power required to cover the distance VSMR[4]. Let APQR = *APSER* + $IR_{\max}$. For every vehicle in Region (AP, APSER) to receive safety messages free of interference, vehicles within the *Region(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 *Region(AP, APBR),* where APBR = APQR + $Speed_{\max}$ *T. APBR abbreviates access point beacon range. We require any vehicles receiving a beacon keep quiet unless polled by the AP. Once again, the extra distance $Speed_{\max}$ *T is used to notify the vehicles about to enter *Region(AP, APQR)* to keep quiet until the CFP is over.

Figure 3 show the breakdown of the CP and CFP in greater detail.

5 PROTOCOL DESIGN AND CONFIGURATION

As stated above, the *dedicated coordinating AP* (DCAP) configuration co-locates a coordinating AP and one or more service APs.[5] This section provides further details of the design and configuration of this proposed system.

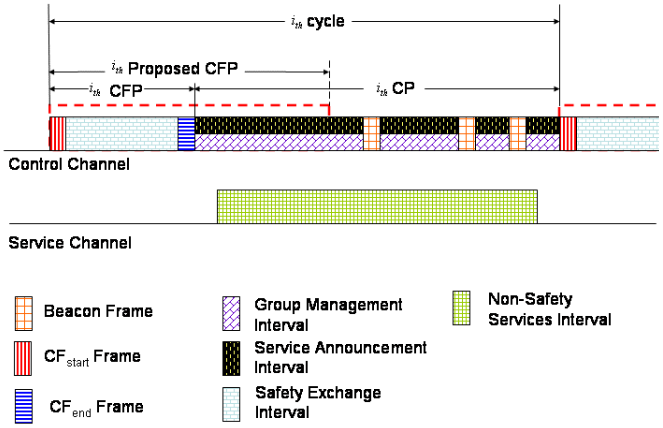

Figure 3: The timeline of control and service channel (only one service channel shown) during the i_{th} cycle.

5.1 Collision Free Period

5.1.1 Safety Exchange

As shown in Figure 3, each system cycle starts with a CFP, which begins with a CF_{start} frame, proceeds to a *safety exchange* interval, and typically ends with a CF_{end} frame[6]. The *safety exchange* interval is used for vehicles within the *Region(service AP,APSR)* to conduct their *safety exchanges*. As described in Section 4, the safety exchange period consists of the coordinating AP individually polling the vehicles on its polling list (discussed in Section 5.2.1). When a vehicle receives a poll, it broadcasts its safety message, or optionally, a shorter *null frame*. This polling method has many commonalities with the *point coordination function* proposed in [8]. To allow sufficient time for each vehicle to reset its hardware from transmit state to receive state, every transmission in the CFP is separated by a *Short Interframe Spacing* (SIFS) [6].

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precision. In practice, the authors expect vehicles to transmit a safety message once per CFP, and thus spaced by approximately *T* seconds.

[4] In such scenarios, IR_{max} is generally larger than *VSMR*.

[5] To simplify exposition, we discuss only one service AP, transmitting on one service channel. In practice, one or more service radios could provide service on one or more service channels.

[6] Each CFP has a proposed upper bound for the CFP duration. However, the AP may end the CFP before this proposed CFP length after it completes polling all vehicles in its poll region. This explains the shorter CFP duration shown in Figure 3.

5.2 *Collision Period*

The end of CFP is followed by the collision period (CP). During this CP, 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. At the same time, vehicles in the service region interact with the service AP in the service channel. Each of these functions are now described.

5.2.1 *Group management*

A reliable registration process is necessary for a proper *safety exchange*. Without a reliable de-registration process, the polling list will grow, which causes inefficiency or sub-standard performance. The *group management interval* is used for vehicles entering or leaving the *Region(AP, AP Poll Range (*APPR*))* to notify the AP their presence, so the AP schedules the appropriate vehicles to transmit for the completion of the *safety exchanges*. Vehicles within the *Region(AP, AP Safety Exchange Range (*APSER*))* must be polled during the CFP to transmit their safety message. Therefore, the AP transmits the poll frames with enough power to cover every vehicle in the *Region(AP, APPR)*, where $APPR = APSER + Speed_{max}*T$. This gives vehicles entering the *Region(AP, APSER)* at least one system cycle time to register with the AP.

During the group management interval, the vehicles entering the *Region(AP, APPR)* (those that have heard poll frames, but have not been polled) will register with the AP, and vehicles leaving the *Region(AP, APPR)* (those that have been polled, but are no longer in the *Region(AP, APPR)*) will de-register with the AP. Every time the AP receives a request, it will update its poll list.

As a vehicle enters the *Region(AP, APPR)*, it will begin to receive poll frames from the AP for other registered vehicles. This indication will cause the newly arrived vehicle to attempt to register at the next group management interval. If the AP does not poll the new vehicle in the next CFP, the vehicle attempts to register again until it succeeds.

The process of de-registering is more challenging. A vehicle should not de-register simply because it did not receive a poll in the previous CFP; the poll could have been corrupted by some other process. Vehicles leaving the *Region(AP, APPR)* are at the very edge, and departing from, the communication range of the AP. Further, vehicles leaving the *Region(AP, APPR)* would need to send an unusually powerful message to reach the AP. Because of the distance, carrier sensing may not provide much assistance. To enhance the reliability of the de-registration process, an implicit pruning algorithm, running continuously on the coordinating AP, is under evaluation. A pruning rule may incorporate some combination or variation of the following criteria: 1) the vehicle who has been on the poll list the longest is pruned; 2) the vehicle with the weakest signal strength the polled vehicle's transmissions received at the AP is pruned; 3) the vehicle with the longest response silence as determined at the AP is pruned. 4) the estimated vehicle speed which can be estimated by observing the traffic flow (e.g. number of vehicles registering per sec.).

5.2.2 *Service announcements*

The service announcement interval is used by the AP to advertise the services offered on the service channels in its *Region(AP, APSR)*. Each service can be described with the following attributes: Channel number, Service code, Locations (optional), and Radius (optional). Optional fields are used for location based service discovery, where each vehicle is expected to know its location. Multiple service entries will be combined into a service table. The service table is then put into a *service table packet*, which is broadcasted on the control channel to each vehicle within the *Region(AP, APSR)*. If the service table is too large to be placed in a single service table packet, it will be fragmented and transmitted across multiple packets.

5.2.3 *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), and remain silent during the CFP unless it is polled. Vehicles receiving none of the beacon transmissions during the CP will continue to operate in their default Ad-Hoc based protocol throughout the next CFP, and thus can potentially interfere reception of the polled messages in 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, i.e. their transmission and reception is not guaranteed. Clearly, the probability of message failure (PMF) of the beaconing is critical to the reliability of the safety exchanges in CFP.

To decrease the PMF of the beaconing, the AP may optionally repeat its beacon multiple times, as shown in Figure 3. Vehicles that received at least one beacon in the *(i-1)'th* cycle will set their network allocation vector (NAV) until the end of the *i'th* CFP, i.e. will not interfere during the *i'th* CFP.

5.2.4 Services in the service channel

During the collision period, service region vehicles may jump to the service channel to receive services. In this service channel, the service region vehicles can perform transactions with the service AP(s). Services may include map and traffic updates, electronic toll collection, multi-media up/downloads, etc. These vehicles must return to the control channel in time for the next CFP.

5.2.5 End of collision period

When the CP expires, the CFP of a new cycle will begin. The AP transmits a CF_{start} frame [8], which is very similar to a beacon frame, with enough power to be received by every vehicle in the *Region(AP*, *APBR)* to signify the beginning of a new CFP.

6 CORRECTNESS PROOF

The following proof shows that under a number of assumptions, our protocols can be summarized with the following properties:

Theorem 1: If every vehicle within *Region(AP,APBR)* receive a beacon in every cycle, then the AP provides one *Full Safety Exchange* (FSE) to every vehicle in *Region(AP,APSR)* in each cycle.
Theorem 2: APSER is the minimum poll range for the FSE, and duration of CFP is minimized
Theorem 3: APBR is the minimum beacon range for the FSE, and number of silent vehicles (i.e. vehicles are not polled in CFP, and they have to keep silent for vehicles within *Region(AP,APSR)* to complete their FSE) is minimized.
Theorem 4: The time between consecutive polls for vehicles within *Region(AP,APSER)* is bounded by $T \pm \delta_{\max}$.
Theorem 5: The protocol for vehicles within *Region(AP,APSR)* is safe and efficient (i.e.. one full safety exchange in each system cycle, and service time for each cycle is maximized)

To prove the theorem, we have used number of lemmas.

6.1 Definitions:

1. *S*: The set of all vehicles in the system
2. $\overline{A}$: is the complement of the set A.
3. t_i : Starting time of the i_{th} cycle
4. *T*: Period of the system in seconds where T = $t_{i+1} - t_i$
5. $Speed_{\max}$: Maximum speed in meter/sec. that a vehicle can move
6. *Contention-Free Period* (CFP): interval where nodes uniquely transmit according to a schedule
7. CFP_i : The CFP interval $[t_i, t_i + \delta_i)$ in the i_{th} cycle.
8. $\delta_{\max}$: Maximum duration for each CFP. Note $\delta_{\max} < T$ sec.
9. δ_i : Duration of the CFP in the i_{th} cycle. Note $\delta_i \le \delta_{\max}$.
10. τ : The duration of each time slot in $[t_i, t_i + \delta_i)$.
11. *Contention Period* (CP): Interval during which nodes transmit using a contention based MAC protocol.
12. CP_i : Duration of the contention period $[t_i + \delta_i, t_{i+1})$ in the i_{th} cycle.
13. *Vehicle Safety Message Range* (VSMR): Maximum range at which a safety message should be received without multiple access interference
14. $IR_{\max}$: The maximum distance between a receiver and an interferer. Transmitters at distance greater than $IR_{\max}$ from a receiver cannot interfere with its receptions.
15. *Access Point Service Range* (APSR): The maximum range at which the Access Point (AP) offers services.

16. *Access Point Safety Exchange Range* (APSER): The range within which the AP polls each vehicle for safety transmission. $APSER = APSR + VSMR$

17. *Access Point Poll Range* (APPR): The range within which the AP polls each vehicle for safety transmission. $APPR = APSER + Speed_{\max} \times T$.

18. *Access Point Quiet Range* (APQR): The range at which the AP requires vehicles to be silent unless polled during the CFP. $APQR = APSER + IR_{\max}$.

19. *Access Point Beacon Range* (APBR): The maximum range to which the AP transmits beacons. APBR=APQR + $Speed_{\max} \times T$.

20. $B_i(n)$: Number of beacons received by node n in $[t_i, t_{i+1})$.

21. $B_{CFPi}(n)$: Number of beacons received by node n in CFP_i.

22. $Disk(n, r)$: The set of nodes within a circle centered at node n and with radius of r.

23. $Disk_i(n, r)$: The set of nodes within a circle centered at node n and with radius of r in $[t_i, t_{i+1})$.

24. Region(n, r): A circular region centered at node n and with radius of r.

25. $Msg_i(n)$: Message indicator function of node n in CFP_i,

if node n transmits its data, $Msg_i(n) = 1$,

if node n does not transmit its data, $Msg_i(n) = 0$.

26. $R_i(n, m)$: Reception indicator function for a message from node n to node m in $[t_i, t_i + \delta_i)$, 0 if node m did not receive the message from node n, 1 if node m received the message from node n.

27. $SA_i(n)$: Allocator function (one to one) that maps node n to a non-overlapping time slot in $[t_i, t_i + \delta_i)$. $SA_i : n \in A_i \mapsto k \in \{t_i, t_i + 1\tau, ..., t_i + (|A_i| - 1)\tau\}$ where $A_i = Disk_i(AP, APPR)$. $|A_i|$ is the cardinality of set A_i.

28. $STATE(n, [t_1, t_2))$: The system state of node n in $[t_1, t_2)$. $STATE(n, [t_1, t_2)) \in$ {Ad-Hoc, AP Coordinated, Service}

29. $FSE_i(n, r)$: Full safety exchange indicator function for a node n and range r in CFP_i. It is defined to be:

For all the receivers within range *r* of node *n*, interferers of node *n* and its receivers should be in the AP Coordinated state while they are exchanging their safety messages. Moreover, if node *n* has data to send, all its receivers should receive, and if its receivers have data to send, node *n* should receive. If the above conditions are not met, FSE will be zero. More precisely,

$FSE_i(n, r) = 1$ iff:

$$\forall m \in Disk_i(n, r), \forall j \in Disk_i(n, IR_{\max}) \cup Disk_i(m, IR_{\max}),$$

$$STATE(j, [t_i, t_i + \delta_i)) = \text{AP Coordinated} \wedge Msg_i(n) \neq 0$$

$$\Rightarrow R_i(n, m) = 1 \wedge Msg_i(m) \neq 0$$

$$\Rightarrow R_i(m, n) = 1$$

$FSE_i(n, r) = 0$ otherwise.

30. *Node*: A vehicle with one radio, which can operate across multiple channels, traveling up to $Speed_{\max}$. It transmits its safety messages on the control channel with enough power to cover the VSMR, and interferes receptions at ranges no greater than $IR_{\max}$. Node is also referred as vehicle in this proof.

31. *AP*: An access point coordinating medium access by all nodes within the *Region(AP,APQR)* during the CFP or providing service to vehicles within the *Region(AP,APSR)* during the CP.

6.2 Assumptions:

1. The proof uses a collision model. Each transmission has a communication range and each node has a location. A transmission is received if the distance between transmitter and receiver is less than the communication range and there is no collision. A collision occurs if one or more transmitters with 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 $Disk_i(AP, x)$.
5. Each node executes the state machine in Figure 7 correctly.
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 $Speed_{\max} \times T$.
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 a beacon transmitted in $[t_i, t_i + \delta_i)$.

6.3 Proof of the Thereoms:

Lemma 1: If all nodes in $Disk_{i-1}(AP, APBR)$ receive a beacon in period $[t_{i-1}, t_i)$, then all nodes in $Disk_i(AP, APQR)$ will be in AP Coordinated state in CFP_i . More precisely,

$$(\forall j \in Disk_{i-1}(AP, APBR),\ B_{i-1}(j) \geq 1)$$

$$\Rightarrow (\forall k \in Disk_i(AP, APQR),\ STATE(k, [t_i, t_i + \delta_i)) = \text{AP Coordinated})$$

Proof: By Assumption 6 and Definition 19, $Disk_i(AP, APQR) \subseteq Disk_{i-1}(AP, APBR)$. Thus, by hypothesis, $B_{i-1}(j) \geq 1$ for all node j in $Disk_{i-1}(AP, APBR)$. The result follows from Assumption 5.

Lemma 2: For the following lemma see Figure 4. If all nodes in $Disk_{i-1}(AP, APBR)$ receive a beacon in period $[t_{i-1}, t_i)$, then for all nodes l in $Disk_i(AP, APSER)$, any safety messages transmitted by node l will be received by all vehicles located in $Disk_i(l, VSMR) \cap Disk_i(AP, APSER)$. More precisely,

$$\forall i,\ (\forall j \in Disk_{i-1}(AP, APBR),\ B_{i-1}(j) \geq 1)$$

$$\Rightarrow (\forall l \in Disk_i(AP, APSER),\ \forall p \in Disk_i(l, VSMR) \cap Disk_i(AP, APSER),\ Msg_i(l) \neq 0$$

$$\Leftrightarrow R_i(l, p) = 1)$$

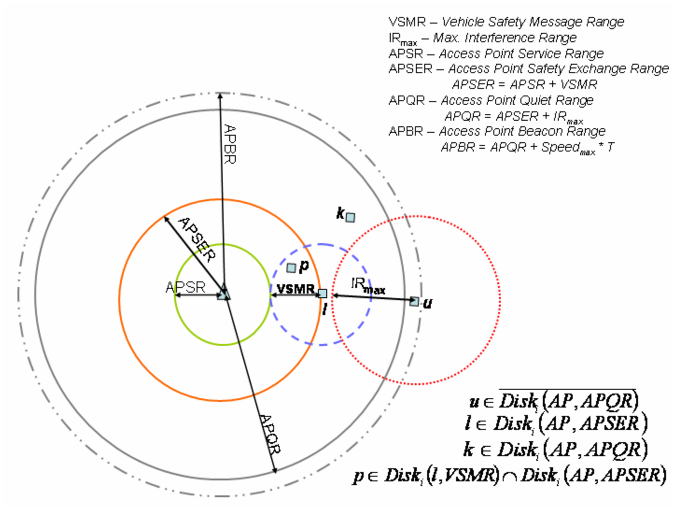

Figure 4: Supplement for Lemma 2

Proof: Pick any *i*. By Assumption 2, any node *v* only interferes with receptions in $Disk_i(v, IR_{\max})$. Thus, a node $u \in \overline{Disk(AP, APQR)}$ cannot interfere with any receptions at any node $l \in Disk(AP, APSER)$, since APQR = APSER + $IR_{\max}$. In addition, from Lemma 1, any node $k \in Disk_i(AP, APQR)$ is in AP Coordinated state during CFP_i, so it will be silent unless polled. Thus, a node *k* creates no interference to any node *l* in CFP_i. Since $\overline{Disk_i(AP, APQR)} \cup Disk_i(AP, APQR) = S$, receptions at node *l* are free of interference from any nodes in CFP_i. By Assumption 1, receivers receive only if they are within communication range of the sender. Let *l, p* be as in the hypothesis. Node *l* is within the *Region(AP,APSER),* node *p* is within the *Region(l,VSMR),* and there are no interferers. Thus, $Msg_i(l) \neq 0 \iff R_i(l, p) = 1$.

Lemma 3: $Disk_i(AP, APSER)$ contains every node in $Disk_i(AP, APSR)$ and all its receivers. More precisely,
$(Disk_i(AP, APSR) \subset Disk_i(AP, APSER)) \wedge \forall n \in Disk_i(AP, APSR)$,
$Disk_i(n, VSMR) \subset Disk_i(AP, APSER)$

Proof: By definition 16, *APSER = APSR+VSMR*. Thus, the result follows.

Theorem 1: If all nodes in $Disk_{i-1}(AP, APBR)$ receive a beacon in period $[t_{i-1}, t_i)$, then every node in $Disk_i(AP, APSR)$ will complete its full safety exchange (FSE) in CFP_i. More precisely,
$(\forall j \in Disk_{i-1}(AP, APBR), B_{i-1}(j) \geq 1) \Rightarrow (\forall n \in Disk_i(AP, APSR), FSE_i(n, VSMR) = 1)$

Proof: By Lemma 3, for all $n \in Disk_i(AP, APSR)$, node *n* and all its receivers are contained in $Disk_i(AP, APSER)$. By Lemma 2, if $Msg_i(n) \neq 0$ for node *n* in CFP_i, then for any $m \in Disk_i(n, VSMR)$, $R_i(n, m) = 1$. Similarly, if $Msg_i(m) \neq 0$ for node *m* in CFP_i, then $R_i(m, n) = 1$. By Definition 18 and 16, for all interferers $k \in Disk_i(n, IR_{\max}) \cup Disk_i(m, IR_{\max})$, *k* are contained in $Disk_i(AP, APQR)$ since *APQR = APSER + IR_{max}* and *APSER = APSR + VSMR*. By Lemma 1, every node in $Disk_i(AP, APQR)$ is in AP Coordinated state in CFP_i. Thus, node n and m will be able to receive each other's message and messages from the AP free of interference. By assumption 4, *n* and *m* will be polled once in CFP_i. The theorem follows from the definition of $FSE_i(*,*)$.

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

Proof: Suppose $poll\_range < APSER$. By Assumption 4, and since *APSER = APSR + VSMR*, there exists a node $n \in Disk_i(AP, APSR)$ and $m \in Disk_i(n, VSMR)$ such that node m is not polled in CFP_i. Thus $FSE_i(n, VSMR) \neq 1$, proving the first part. By Assumption 7,
$|Disk_i(AP, poll\_range)| \geq |Disk_i(AP, APSER)|$. Thus if $\delta_i \propto |Disk_i(AP, poll\_range)|$, when *poll_range* = APSER, δ_i is minimized.

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

Note: $\left|\overline{Disk_i(AP, APSER)} \cap Disk_i(AP, APBR)\right|$ is defined to be the silent nodes in CFP_i because they are the set of nodes which will not be polled by the AP in CFP_i. They are required to be silent for the benefit of all nodes in

$Disk_i(AP, APSR)$ to complete their *full safety exchange* (FSE). Minimizing the set of silent nodes maximizes the control channel reusability outside of the AP's coordinating area.
Proof: Suppose *beacon_range* < APBR. Since $APBR = APSR + VSMR + IR_{\max} + Speed_{\max} \times T$, there exists a node $n \in Disk_i(AP, APSR)$, $m \in Disk_i(n, VSMR)$, and $k \in Disk_i(m, IR_{\max})$ such that $B_{i-1}(k) = 0$, so the state of node k in CFP_i is not in AP Coordinated state. Thus $FSE_i(n, VSMR) \neq 1$, which contradict the hypothesis. Note that a $beacon\_range = APSR + VSMR + IR_{\max}$ is not enough since even if all vehicles in this distance receive a beacon in (i-1)-th cycle, there could be new vehicles who haven't received a beacon entering the *Region(AP,APQR)* in CFP_i. Since APBR is the minimum beacon range, by Assumption 7,
$\left|\overline{Disk_i(AP, APSER)} \cap Disk_i(AP, APBR)\right|$ is minimized.

Theorem 4: If every node in $Disk(AP, APBR)$ receives a beacon in both *(i-1)'th* and *i'th* cycles, then for every node *l* in $Disk(AP, APSER)$, the time between consecutive polls is bounded by $T \pm \delta_{\max}$. More precisely,

$$\left(\forall j \in Disk_{i-2}(AP, APBR), \forall k \in Disk_{i-1}(AP, APBR),\ B_{i-2}(j) \geq 1 \wedge B_{i-1}(k) \geq 1\right)$$
$$\Rightarrow \left(\forall l \in \{Disk_{i-1}(AP, APSER) \cap Disk_i(AP, APSER)\}, T - \delta_{\max} \leq SA_i(l) - SA_{i-1}(l) \leq T + \delta_{\max}\right)$$

Proof: By Assumption 4, AP will individually poll every node in *Region(AP.APSER).* Considering any schedule used by the nodes in CFP_i. For a node $l \in Disk_{i-1}(AP, APSER) \cap Disk_i(AP, APSER)$, the longest and the shortest wait time between two consecutive polled are the followings: If $SA_{i-1}(l) = t_{i-1}$ and $SA_i(l) = t_i + (|Disk_i(AP, APSER)| - 1)\tau$, then $SA_i(l) - SA_{i-1}(l) = T + \delta_i - \tau \leq T + \delta_{\max}$ (e.g. longest wait time). If $SA_{i-1}(l) = t_{i-1} + (|Disk_{i-1}(AP, APSER)| - 1)\tau$ and $SA_i(l) = t_i$, $SA_i(l) - SA_{i-1}(l) == T - \delta_{i-1} + \tau \geq T - \delta_{\max}$ (e.g. shortest wait time). Therefore, $T - \delta_{\max} \leq SA_i(l) - SA_{i-1}(l) \leq T + \delta_{\max}$, for all $l \in Disk_{i-1}(AP, APSER) \cap Disk_i(AP, APSER)$.

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

1) $STATE(n, [t_i + \delta_i, t_{i+1}))$ = Service
2) $FSE_i(n, VSMR) = 1$
3) The service time, e.g. $T - \delta_i$, is maximized

Proof: To show a node $n \in Disk_i(AP, APSR)$ will change to the Service state in CP_i, we need to satisfy the guard conditions in Figure 7. By Lemma 1, if all node $j \in Disk_{i-1}(AP, APBR)$ receive a beacon in period $[t_{i-1}, t_i)$, then all interferers of any node *n* in $Disk(AP, APSR)$ are in the AP Coordinated state in CFP_i. By Assumption 8, the AP will transmit a beacon in CFP_i and node n will receive it. This proves node n will transition to the Service state in CP_i. By Theorem 1, $FSE_i(n, VSMR) = 1$. By Theorem 2, δ_i is minimized. Thus, service time, $T - \delta_i$, is maximized.

7 SIMULATION EXPERIMENTS

We have implemented our protocol in NS-2 [10] and PCF implementation based on [16]. In our current implementation, Group Management, Service Announcement, and Channel Switching have not been implemented. The default protocol for each vehicle is 802.11 DCF mode [8]. To explore a worst-case scenario, in each cycle, if a vehicle doesn't receive a beacon in the previous CP, the vehicle will operate in DCF mode throughout the following CFP[7]. If the vehicle receives at least one beacon, it will switch to the protocol defined in Section 4 for the duration specified by the beacon. In the CP, the AP periodically transmits beacons. If the channel at the scheduled time is busy, the AP will skip this beacon transmission, and try again in the next scheduled time. Vehicles within the APSR will not transmit during the CP.

We use the deterministic Friis Free-space model for short distances and the Two-ray model for longer distance [15] to determine the received power. A collision model is used to model the multiple access interference. The Signal to Interference + Noise Ratio (SINR) threshold value is obtained from a commercial off-the-shelf 802.11a chipset manufacture.

7.1 Simulation Scenario

For proof of concept, we simulate a snapshot of the highway trace generated from [5]. The trace contains 4 lanes highway with average vehicle headway of 30 meters (see Figure 5). The AP is installed in the midpoint of the simulated highway, with APSR = 80 meters[8]. Since we simulate a static network, APSER = APPR and APQR = APBR. VSMR is chosen to be 150 meters, which gives drivers enough time to response to the emergency message while traveling at 55mph [5]. This VSMR range corresponds to the maximum of 300 meters interference range at 6Mbps.

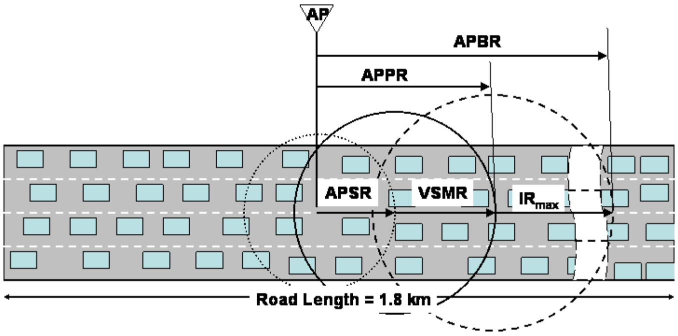

Figure 5: Network Topology and Communication Ranges. Access Point Service Range (APSR) = 80 meters, Vehicle Safety Message Range = 150 meters, Access Point Poll Range (APPR) = 230 meters, and Access Point Beacon Range (APBR) = 530 meters. Average headway between vehicles is 30 meters.

In the simulation, all messages are transmitted at 6Mbps. A set of simulation parameters is listed in Table 2. The AP repeats its system cycle every 100 ms, so that vehicles within APPR are given an opportunity to transmit once every 100 ms.

Data Rate:	6Mbps
Data Traffic Model:	Periodic (start time of each cycle is randomized)
Message Rate:	1 message per 100ms (vehicles outside of APSR repeat each message once to improve its reception)
Safety Message + Header:	150 bytes
AP System Cycle:	100ms
Transmission Opportunity per Polled Vehicle	1

Table 2: Simulation Parameters

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[7] In general, a vehicle within the beacon range can calculate the timing of the subsequent CFP's by extrapolating information in beacons received in past cycles (CP_j, $j<i-1$).

[8] For highway at capacity, if vehicles communicate with AP at the highest data range without turbo mode supported by 802.11a radio on the service channel, then each vehicle can download a 2MB file when it passes by the AP.

7.2 Simulation Result

For the described scenario, we have evaluated the average beacon reception failure and safety exchange probability of failure versus the frequency of beacon transmissions in the CP. Average beacon probability of reception failure (PRF) is calculated for nodes within the APBR, and is defined as

$$\frac{1}{N}\sum_{k=1}^{k=N}\frac{num\_fails(k)}{num\_\mathrm{intent}(k)},$$

where N is the total number of simulated system cycles, *num_fails(k)* is number of nodes within APBR that did not receive a beacon in the k'th cycle, and *num_intent(k)* is total number of nodes within APBR in the k'th cycle. If AP fails to transmit at least one beacon in the k'th cycle (e.g. the channel at the beacon scheduled transmission time is busy), PRF at the k'th cycle will be 100%. In Figure 6, for small number of beacon transmission (i.e. ~ 6 beacons per CP or 18ms per beacon transmission), the beacon PRF is about 5/10000. Fewer beacon repetitions may be required in practice.

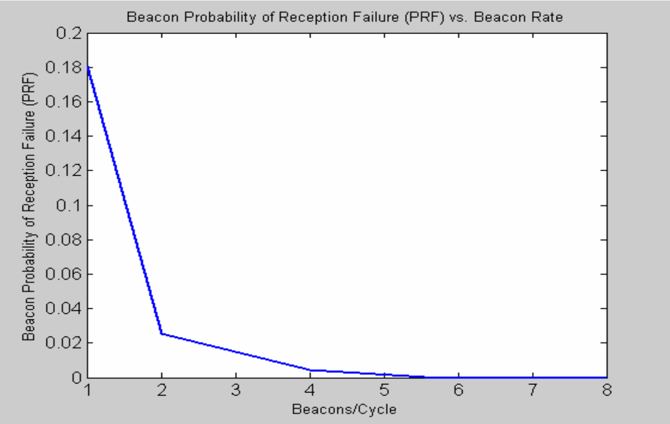

Figure 6: Beacon Probability of Reception Failure

The average safety exchange probability of failure of a node is defined as

$$\frac{1}{N}\sum_{k=1}^{N}\frac{1}{P(k)}\sum_{i=1}^{P(k)}\frac{num\_fails(k,i)}{num\_\mathrm{intent}(k,i)},$$

where N is the total number of simulated system cycles, *P(k)* is the number of polled node in the *k'*th system cycle, *num_fails(k,i)* indicates the number of nodes within $Disk_k(AP, APPR) \cap Disk_k(i, VSMR)$ that fails to receive a safety message transmitted by *i'*th poll node in the cycle *k*, and *num_intent(k,i)* is defined as the cardinality of $\left|Disk_k(AP, APPR) \cap Disk_k(i, VSMR)\right|$. If the AP polls node *i* at *k'*th cycle, and node *i* fails to broadcast its safety message (e.g. the poll is not properly received), then the probability of a failed safety exchange for this node *i* and at *k'*th cycle is 100%. In experiments reported in Table 3, one can see that if the AP transmits 2 beacons in each CP, then the average safety exchange probability is 0.0017, which satisfies the safety requirement defined in [5] and [6].

Beacons/Cycle	**Average Safety Exchange Probability of Failure**
2	0.0017
4	0.0013
8	0.0009

Table 3: Safety Exchange Probability of Failure

7.3 Discussion of Simulation Results

In Section 6, we proved a set of logical properties of our protocol under the assumption that vehicles within the APBR receive at least one beacon in each CP. Our preliminary simulation shows that even with small number of beacons transmitted in the CP, vehicles receive at least one beacon with high probability. Table 3 shows that with these low beacon reception failure probabilities, vehicles within the APSR can exchange safety message with their neighbors with high probability before they leave for the service channels.

8 CONCLUSIONS

This document explores the problem of creating a wireless protocol and architecture for a vehicle-to-vehicle and vehicle-to-infrastructure communication system. The goal of such a system is insuring 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 the given environment include operating within a multi-channel environment (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 wireless protocol currently specified for DSRC. Specifically, the timing of channel transitions for vehicles entering a service area is regulated by an access point. Vehicles within proximity of such service-seeking vehicles 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 exchanges and are otherwise free to transmit non-scheduled data.

Future work will include a further refining of this protocol within an even-more extensive and realistic simulative environment. Safety applications (e.g. collision warnings, slow-down warnings) and commercial applications (e.g. electronic toll collection, map download, video download, Internet transactions) will be developed and incorporated into the above specified communications system. Also, we shall explore extending the concepts described above to scenarios without a stationary, roadside access point.

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APPENDIX

Appendix 1 *Vehicle Top Level State Machine Specification*

In the top level, each vehicle can be any of the follow three states: Ad-Hoc, AP Coordinated, and Service (see Figure 7). Ad-Hoc state is the default state for each vehicle. Each vehicle will operate in this state when the *roadside access point* (AP) is not present or during the contention-period (CP). Under the Ad-Hoc state, each vehicle operates in the standard Ad-Hoc based protocol at which vehicles exchange safety messages in the control channel without the aid of infrastructure.

When a vehicle enters the *Region(AP, APBR)*, by receiving a beacon, the vehicle will switch from Ad-Hoc state to AP Coordinated state at the beginning of each *contention-free period* (CFP) specified in the beacons. In the AP Coordinated state, vehicles are coordinated by the AP in the control channel, and they remain silent unless polled by the AP. Vehicles will remain in the AP Coordinated state for the duration of the CFP.

When the CFP expires, vehicles outside of *Region(AP, APSR)* will switch back to the Ad-Hoc state, and vehicles inside of the *Region(AP,APSR)* will switch to Service state given they have received a beacon in the last CFP, otherwise they will remain in the AP Coordinated state. Under the Service state, vehicles with service of interest are permitted to leave the control channel until the beginning of next CFP at which they have to return to the control channel, and their system will switch back to the AP Coordinated state.

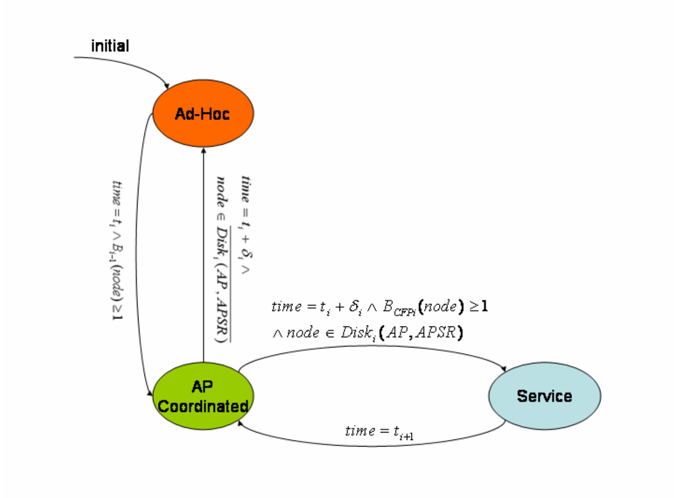

Figure 7: Vehicle Top Level State Machine Specification