Cross-Layer Coordination for Safety Applications Enabled by Wireless Access in Vehicular Environments

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A wide range of future vehicle safety applications will rely on the wireless transmission of vehicle heartbeat messages, containing the location and kinematics of each vehicle. This paper demonstrates the impact of application level scheduling on the delivery rate of the high-volume, periodic messages. A cross-layer coordination protocol is proposed in which the heartbeat application protocol leverages knowledge about the configuration and current state of the physical and media access (MAC) layers in order to boost the message delivery rate by decreasing the number of transmission collisions. An integrated simulation system which combines a widely used microscopic vehicle simulator with a communications network simulator that this cross-layer coordination can produce improvements in the ratio of collisions to messages received of 44% to 88% for single-band radios and 18% to 92% for dual-band radios.

Keywords: *Inter-Vehicle Communication, Wireless Access in Vehicular Environments, Vehicle Heartbeat Messages*

1. Introduction

Extensive work is underway to deploy wireless network equipment in vehicles and along the roadways. Wireless Access in Vehicular Environments (WAVE) Standards are under development, and, in the United States, large-scale testbeds are currently being deployed in Michigan, California, and Florida. In addition to supporting applications using vehicle-to-roadside communications, this network will also enable a wide range of applications that use direct vehicle-to-vehicle communications. Messages supporting these applications will be transmitted in different channels in spectrum that has been dedicated to Intelligent Transportation Systems. The WAVE protocols are designed to support this range of vehicle-to-roadside and vehicle-to-vehicle messages. In particular the design of the WAVE physical and MAC layers contains specific mechanisms to support multichannel operations.

The design of the physical and MAC layers has important ramifications for the design of timing related parameters in application layer protocols. This paper explores the impact of these issues with respect to the design of vehicle heartbeat message protocols, one of the most important types of messages in vehicle-to-vehicle communication. These messages are unacknowledged, single-hop, broadcast messages, that are transmitted at a very high frequency.

This paper presents a cross-layer approach designed to minimize the message collision rate for these messages. This approach extends previous work on cross-layer scheduling in wireless networks through specific adaptations for the high velocity vehicular environment and the WAVE physical and MAC layer. The proposed cross-layer scheduling approach would require minimal changes to these protocols as currently outlined in the WAVE standards. Nonetheless, this paper uses simulation to show that this cross-layer coordination can significantly decrease the number of collision rate for the heartbeat messages, improving the ratio of collisions to messages received between 18% and 92% in a variety of traffic scenarios.

2. Literature review

Managing contention for the wireless media presents particular challenges in Mobile Ad hoc Networks (MANETs). These challenges are intensified in the vehicular environment given the density and high speeds commonly found on roadways. Moreover, the action of higher layers in the communications architecture often exacerbates the problem of contention management in mobile ad hoc networks. Consequently, much of the previous work has focused on cross-layer solutions to message scheduling.

Section 2.1 describes related research in media contention management in mobile ad hoc networks. Our approach extends this previous work by adapting and extending it for vehicle heartbeat messages with a design goal of requiring minimal changes to the WAVE architecture. The relevant aspects of the WAVE architecture are presented in Section 2.2.

2.1. Media contention management in mobile ad hoc networks

In infrastructure-based networks, the problem of timeslot allocation can be solved by base stations. Infrastructure-based algorithms can allocate resources based on complete knowledge of transmission requirements, mobile node positions, and kinematics. These algorithms can effectively be extended to the vehicular environment to ensure that throughput is maximized even under in these high speed environments [1]. In MANETs, however, the absence of an infrastructure calls for distributed algorithms, operating with limited view of the network, to manage contention for the media.

In some approaches, nodes seek to construct a complete picture of the subset of the network that includes all 2-hop neighbors through the use of additional control messages, e.g. [2]-[3]. The simplifying assumption behind these approaches is that transmission collisions are caused only by 1- and 2-hop neighbors. This assumption holds if there are at most only two simultaneous transmissions. In networks with high bandwidth utilization, the combined power by simultaneous transmissions by further nodes can also cause transmission collisions [4]. Moreover, these approaches work best under low or limited mobility scenarios, since the high relative velocities in vehicular creates a high rate of change in the set of 2-hop neighbors.

Given the difficulty of maintaining this view of the network, the 802.11 standards use a distributed contention-based algorithm – the Distributed Coordination Function (DCF) for ad hoc networking. WAVE adopts the DCF with the 802.11e model for differentiated levels of service. In the DCF, before transmitting a message, a sender chooses a random backoff in the interval from 0 to the size of the Contention Window. The sender then monitors the medium for a period of time defined by the Arbitrary InterFrame Space (AIFS). If the channel was idle during this time, the backoff timer is started. While the timer is running, for each slot where the media is detected as idle, the timer is decremented. However, if the channel is busy, the timer is frozen, and the station must wait until the media has been idle for another AIFS before restarting the timer. Eventually, when the timer reaches 0, the transmission is initiated. Once the sender initiates a transmission, if the sender detects a message collision, the size of the Contention Window is doubled, until it reaches a maximum value.

The DCF backoff mechanism can greatly decrease the likelihood of collisions between nodes within sensing range of one another. However, the hidden node problem remains, in which collisions are caused by two-hop neighbors that are outside of sensing range. For these hidden nodes, the DCF includes a RTS/CTS/DATA/ACK four-way handshake. Before sending a message, a node first sends a Request-To-Send (RTS) message in a request to reserve the media. If the media is available, the recipient will reply with a Clear-To-Send (CTS) message. A hidden node, while unable to receive the RTS message, would receive the CTS message and refrain from transmitting.

Proposals have suggested that the RTS/CTS mechanism be extended to allow nodes to infer current network demand and adjust their usage accordingly [5] or to enable more equitable round-robin scheduling for the media [6]. These approaches, however, have limited applicability to vehicle heartbeat messages since the four-way handshake is not used for multicast messages. Moreover, while it has been suggested that the use of RTS/CTS be extended to multicast messages [7], the additional control messages in such an approach would likely reduce the total throughput for the high frequency, short messages considered in this paper.

Part of the difficulty in media contention management in MANETs is the decomposition of the communications architecture into layers. Efficient approaches to transmission scheduling are often implemented at the higher layers of the architecture, but require access to metrics from the physical layer and MAC layers [8].

The need for cross-layer approaches to scheduling is especially important in wireless networks where action of higher layers can adversely affect that effectiveness of the scheduling at the MAC layer. For example, the action of TCP can unfairly, further penalize nodes delayed by the back-off mechanisms at the MAC layer [9]. Moreover, in multi-hop networks, there are unfairness problems arising due to the interaction of multiple layers based on the relative locations of nodes [10].

Cross-layer approaches for scheduling have been used extensively for the delivery of multimedia content over wireless networks. These approaches seek to maximize throughput by using techniques from multiple layers, including scheduling, power control, routing, rate control, network coding [11]-[13].

This research extends this previous research by demonstrating the adverse impact that the configuration of vehicle heartbeat messages at the application layer can have on the performance of scheduling at the MAC layer. Moreover, the research shows the benefits of a cross-layer approach in which the application layer uses knowledge of the physical and MAC layer metrics and configuration.

2.2. Wireless Access in Vehicular Environments

A key design goal in the creation of the cross layer approach to media contention management is the minimization of changes needed to the standards that are applicable to vehicle heartbeat messages transmitted in a WAVE environment. This section reviews the relevant aspects of the WAVE standards. In addition, the timing and format of heartbeat messages is elicited from industry consortium report and the emerging probe vehicle message service.

2.2.1. WAVE applications. The characteristics of the vehicle heartbeat messages are approximations based on the industry consortium report, the *SAE J2735* probe vehicle standard, and the WAVE standards. The timing of the messages are based on the application requirements described by the CAMP consortium, comprised of BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and Volkswagen, in partnership with USDOT [14]. The format of the heartbeat messages is based on the WAVE standards, while the content of these messages is based on the probe vehicle standard.

Vehicle heartbeat messages are expected to support a set of safety applications. The CAMP consortium, described seven safety applications that would be enabled by these messages: cooperative forward collision warning, lane change warning, blind spot warning, cooperative collision warning, and cooperative adaptive cruise control, highway merge assistant, and visibility enhancer [14].

The minimum frequency required for all but the visibility enhancer application would be 10 Hz, with an allowable latency of 0.1 seconds. For the visibility enhancer application a minimum frequency of 2 Hz would be sufficient. In addition, the maximum communication range needed for these applications ranges from 150 m for the first five applications to 250 m for highway merge assistant, and 300 m for the visibility enhancer.

These applications require a significant level of market penetration in order to be fully functional. On the other hand, as soon as the initial round of roadside infrastructure is deployed and some vehicles are equipped with on-board radios units, a set of day-one WAVE applications will be enabled. One of these applications is the probe vehicle message protocol, currently defined in a draft form in Annex B of the *SAE J2735 Standard* [15]. The *SAE J2735* standard specifies how vehicles should collect and distribute snapshots of a range of vehicle attribute and sensor data to be delivered to Road Side Equipment (RSE). The protocol that is currently implemented in our system, however, periodically transmits this information in order to support additional applications.

The SAE standard defines 42 vehicle data elements that can be included in each snapshot, if this data is available. In these messages, each element is represented by a two-byte element identifier, followed by a two-byte value. These fields include:

- Vehicle type, position and kinematics: vehicle type, latitude, longitude and elevation, heading, yaw rate, speed, acceleration.
- Vehicle control system measurements: steering wheel angle and rate of change, brake pressure applied, anti-lock brake status, stability control status, traction control system status.
- Environmental and roadway conditions: obstacle direction and distance, coefficient of friction, ambient air temperature and pressure, rain sensor, wiper status.

				Field Size (bytes)		
				Lower Bound	Upper Bound	Selected Value
1609.2 Signed Message			1609.2 Protocol Version			1
			Type=signed			1
	Signer Info		SignerIdentifierType (cert/cert digest)			1
			SignerIdentifier	8	125	125
	unsigned message	application	type			1
			application ID			1
			ACM	0	2^8-1	0
			Message Flags			2
		VII Probe Message	PSID			2
			PSC	0	31	0
			application data length			1
			application data (VII Probe)	0	152	152
			generation time	0	8	8
			expiry_time	0	8	0
		transmission location	latitude	0		4
			longitude	0		4
			elevation and confidence	0		3
	edcsa signature		r	28	32	28
			s	28	32	28

Figure 1: VII Probe Message Format

These data elements are very similar to the data required by the vehicle heartbeat messages and are used in this paper to approximate the content of these messages. Moreover, given the safety-critical nature of the applications that rely on these messages, the simulations make the assumption that their integrity will be protected with digital signatures.

Consequently, vehicle heartbeat messages under the WAVE standards would be structured like the message depicted in Figure 1. These messages contain an 11-125 byte header and a 56-64 byte signature. The header includes a certificate that allows for recipients of the message to verify the integrity of the message. In our simulations, the size of these certificates is set at 125 bytes, a typical value for vehicles [19]. If an RSE or OBE has already received a certificate, it can instead send an 8 or 10-byte identifier containing the lowest 8-10 bytes of the SHA-256 hash of the certificate [19]. However, our simulations assume that the entire certificate is sent with each message. In addition, our simulations assume the use of 56-byte digital signatures appended to the end of the message.

The unsigned message consists of standard 1609.2 header and trailer fields and application data with vehicle data elements defined by the SAE J2735 standard. However, only the 38 fields from the SAE J2735 standard that are not duplicated elsewhere in the message are included the application data field. The total message length with a full certificate, then, is 362 bytes.

2.2.2. The WAVE transport and network layers. The WAVE Applications will interface with the WAVE network and transport layer protocols, which are described in the IEEE Standard 1609.3 [16]. This standard specifies the use of existing protocols for the network and transport layers, as well as introducing a new Wave Short Message Protocol (WSMP) which spans both these layers.

The standard allows for the use of Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) for the transport layer. When either protocol is used, Internet Protocol version 6 (IPv6) should be used for the network layer.

Most VII applications will use UDP rather than TCP [16]. TCP transmissions require overhead to create connections between sender and receiver. With this connection, TCP provides mechanisms for error correction and packet retransmissions. However, UDP is more appropriate for the dynamic vehicular environment and the vehicle heart-beat messages, given the large overhead that would be required to create and maintain TCP connections between the sender and all nearby vehicles. Moreover, given the high rate of transmission of heart-beat messages, little utility would be provided by the retransmission of messages.

WSMP has been designed for the quick transmission of short, single-hop messages. Providing cross layer functionality, it handles both network and transport layer functions, and allows applications to specify physical layer parameters including the channel number and transmission power. WSMP also has a message prioritization function, analogous to the priority associated with different traffic classes in IP, which is used to determine the order in which messages are serviced.

2.2.3. The WAVE MAC layer. The WAVE MAC layer is a modification of the 802.11a standard that includes 802.11e extensions to support differentiated levels of service. The major differences in WAVE include the new multi-channel coordination and changes to the 802.11 Distributed Coordination Function (DCF).

One of the most significant differences between the previous 802.11 standards and the WAVE standard is the multi-channel coordination [17]. A channelization plan for the WAVE architecture calls a single control channel (CCH) and multiple service channels (SCH's). Only Roadside Equipment can transmit on the CCH.

The WAVE multi-channel coordination function provides specific rules regarding when stations should listen to the control vs. service channels, and what types of messages can be broadcast, and when [17]. Time is divided into control channel intervals (CCH intervals) and service channel intervals (SCH intervals). During the CCH interval, all vehicles must monitor the CCH for information about services offered by RSE's, safety announcements, or private service advertisements. Since vehicles must monitor the CCH during this interval, the roadside should broadcast critical announcements during the CCH interval.

In order to accommodate devices that can only monitor one channel at a time, the multi-channel coordination function provides for the suspension of transmissions on the SCH during a CCH interval. In addition, the standard defines a guard interval, which occurs at the start of each channel interval. In order to account for variations in channel interval time and timing inaccuracies among devices, no transmissions are permitted during the guard interval.

As noted earlier, WAVE adopts the 802.11 DCF with changes to support multiple channels and high relative velocities. During the guard intervals, a channel busy indication is set during the guard intervals, which freezes the back-off timer. In addition, the maximum size of the contention window is 511, instead of 1023 [17]. The slot time is increased in WAVE from 9 µs to 16 µs. The AIFS varies as a function of the AIFS number associated with a class of traffic, the slot time, and the Short InterFrame Space (SIFS). Due to an increase in both the slot time and the SIFS, the AIFS is longer in WAVE. Moreover, the AIFS number for most traffic classes have also been increased for the CCH.

2.2.4. The WAVE physical layer. The WAVE physical layer is based on the IEEE 802.11a standard. The most important modifications in WAVE include for the purposes of this research include changes to the allocated spectrum, supported data rates, and timing changes.

The WAVE physical layer operates in 5.9 GHz. The channelization plan for the communications architecture 10 MHz for the control channel, compared to 20 MHz for an 802.11a channel. The bandwidth allocated to the service channels can vary from 5 to 20 MHz. The supported data rates in the WAVE channels, ranging from 3 Mbps to 27 Mbps, are half of the ones supported by 802.11a [18].

In order to support high velocities in vehicular environments, timing-related changes have been made in WAVE. These changes lengthen the synchronization time required for the orthogonal frequency-division multiplexing (OFDM) [17].

3. Cross-layer coordination for WAVE applications

In order to avoid a large number of transmission collisions and minimize the latency of messages in high-volume message environments, WAVE applications should have both knowledge of the WAVE physical and MAC layer configuration and current delay statistics. In particular, the timing of high-volume, vehicle heartbeat messages should be a function of whether the WAVE radios are single or multi-band, the minimum 802.11 DCF Contention Window size, and the current delays experienced by the 802.11 DCF backoff mechanism.

3.1. Limitations of single-layer approaches

Application layer scheduling approaches that ignore these lower layer issues may not perform well in terms of message delivery. Note the clocks in nodes will be synchronized via GPS. Consider a situation where the length of the Periodic Broadcast Interval is 0.1 s, i.e. the nodes are transmitting the heartbeat messages at 10 Hz. The application-layer scheduling approaches for these messages could use:

- *No Offset Scheduling*: Schedule the messages to be sent at the tenth of a second boundaries, e.g. for a vehicle travelling at 1 pm, they would transmit messages at 1:00:00.0, 1:00:00.1, 1:00:00.2, etc., or
- *Random Offset Scheduling*: Choose a random offset and schedule the messages to be sent at that offset past each tenth of a second boundary, e.g. if a vehicle chose a random offset of .15 s, it would transmit the messages at 1:00:00.15, 1:00:00.25, 1:00:00.35, etc.

3.1.1. Sending messages on interval boundaries. The *No Offset Scheduling* approach suffers from two potential problems. The first issue is that if the minimum Contention Window is small, there will almost certainly be a message transmission collision given a reasonable number of vehicles within radio range. Normally, the size of the Contention Window would increase when a collision is detected. However, since vehicle heartbeat messages are unacknowledged, no collisions are detected by the sender, and the Contention Window remains at its minimum size.

An intuition into the relationship between the Contention Window size and expected number of collisions during a single interval can be developed by examining the special case for a portion of roadway in which all vehicles are within radio range of one another. In this case, the probability that another message will interfere with a given nodes message can be expressed as:

$$P(collision) = 1 - \left(\frac{CW_{min} - 1}{CW_{min}}\right)^{n-1} \qquad (1)$$

where:

- CW_{min} is the minimum size of the Contention Window, and
- n is the number of nodes.

The expected number of nodes whose transmission would collide with another transmission would be:

$$E(collisions) = (n-1)\left(1 - \left(\frac{CW_{min} - 1}{CW_{min}}\right)^{n-1}\right) \qquad (2)$$

Since each transmission would be received by n - 1 nodes, the expected number of transmission collisions at the receiver can also be calculated as:

$$E(collisions_r) = (n-1)^2\left(1 - \left(\frac{CW_{min} - 1}{CW_{min}}\right)^{n-1}\right) \qquad (3)$$

Equation 3 indicates that the expected number of collisions could be reduced by increasing the size of the Contention Window, provided that all nodes are able to transmit within a given tenth of a second Periodic Broadcast Interval.

We can derive an upper-bound for the Contention Window that would ensure that all vehicles are able to send their message during each Periodic Broadcast Interval. The worst case scenario is one in which a node must wait until the very end of the interval to transmit its message. From this worst-case scenario, we can derive an upper-bound for the minimum Contention Window size that would allow all nodes to transmit their message during each interval:

$$CW_{ideal} = T_I - n\,T_{ml} - T_{AIFS} - 2\,T_{GI} \qquad (4)$$

where:

- CW_{ideal} is the ideal size of the Contention Window in terms of collision reduction,
- T_I are the number of timeslots in each tenth of a second interval,
- T_{GI} are the number of timeslots in each Guard Interval,
- n is the number of nodes,
- T_{ml} are the timeslots required for message transmission, and
- T_{AIFS} are the timeslots required for the AIFS interval.

However, increasing the size of the Contention Window has a clear negative impact on message latency. In the worst case, the delay until transmission would be equal to $T_I - T_{ml}$. The expected value of the latency measured in timeslots (which includes the delay caused by freezing the backoff timer for n / 2 messages) would be equal to:

$$E(Delay) = \frac{n-1}{2}T_{ml} + \frac{1}{2}CW_{ideal} + T_{AIFS} + \frac{3}{2}T_{GI}$$
$$= \frac{1}{2}(T_I - T_{ml} + T_{AIFS} + T_{GI}) \qquad (5)$$

Default or typical values for these parameters include the following:

- T_I = 6,250 slots, where interval is equal 0.1 s and each time slot is 16 µs.
- T_{ml} = 88 timeslots, for the default bandwidth of 3 Mbps, 362 bytes of application layer message (see Figure 1), 92 bytes of lower layer overhead, a synchronization time of 192 µs, and a propagation time less than 3 µs.
- T_{AIFS} = 9 slots
- T_{GI} = 250 slots, with guard intervals the default length of 4 ms.

Given these typical values, increasing the Contention Window size to reduce the maximum number of collisions would create an expected latency of 3,240 timeslots or 0.052 seconds.

3.1.2. Sending messages at a random offset in each interval. Sending messages at a random offset in each interval could partially address this tradeoff between latency and collision rate. However, it also could lead to either a high rate of transmission collisions and undesirable latency, or both. These adverse consequences could occur as a direct result of application layer scheduling without regard for the configuration or current state of the lower layers of the architecture.

If the lower layers of the architecture are configured to support single-band radios, then there will be a similar backlog of messages waiting to be transmitted each interval. The multi-channel coordination function for single-band radios completely suspends the transmission of heartbeat messages during the control channel interval, until the start of the next service channel interval. By default, the control channel and service channel intervals are equivalent in length. Therefore, at the end of the control channel interval, approximately half of the nodes will simultaneously contend for the media in an attempt to send their message. For a reasonable network density, this would lead to a large number of message collisions.

As for multi-band radios, knowledge of the delays experienced by the 802.11 backoff timer could aid in the scheduling of messages. This choice of random offsets by nodes cannot produce a completely even distribution of message timings. With random selection, a portion of the interval may be unused, while in other parts of the interval, multiple nodes may be simultaneously competing for the media. An application at this node could, however, infer this condition by monitoring the delay experienced by the MAC layer in contending for the media. If this delay is significantly larger than the contention window, the application should assume that one or more other node has chosen a similar offset.

3.2. A cross-layer coordinated approach to message scheduling

The scheduling approach proposed in this paper uses knowledge of the MAC and physical layers to reduce the likelihood of collisions. This approach also does not suffer from the increase in latency associated with increasing the size of the contention window.

Like the previous approach, each node chooses an offset at random. However, as shown in Figure 4, the application uses knowledge from both the Physical and MAC Layer to choose an offset for message transmission. The Physical Layer information ensures that transmissions occur only during allowable offsets, shown, for example as the shaded region in Figure 3. Note that the only offsets that are not allowed are those that would fall during the guard intervals.

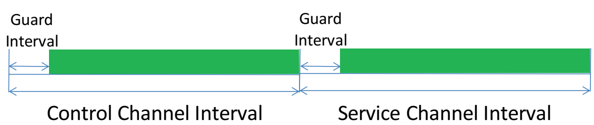

Figure 2: Offsets chosen for Multiband Radios (shaded areas depict the possible offset values)

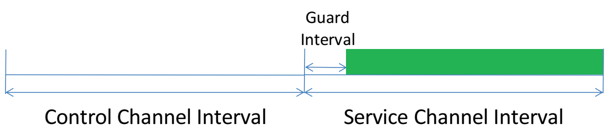

Figure 3: Offsets chosen for Single-band Radios (shaded areas depict the possible offset values)

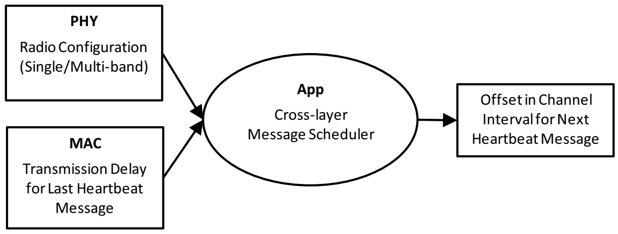

Figure 4: Data Flow Diagram for Cross-Layer Message Scheduling

The major improvement in including Physical Layer information occurs when the service has been configured for single-band radios. In this scenario, nodes may only transmit during the service channel interval, after the guard interval has elapsed. Selecting an offset from within this allowable range, shown in Figure 4, prevents the scenario in which a large number of nodes, prevented from transmitting during the control channel interval, simultaneously contend for the media at the beginning of the service channel interval.

In addition to selecting an initial offset based on the lower layers of the architecture, the scheduling approach proposed here also allows for the adjustment of this offset based on delays experienced at the MAC layer. This approach seeks to evenly distribute the different vehicles' *heart-beat* transmissions throughout each interval.

In order to minimize the changes needed at the MAC layer, this approach should minimize both the additional state data that must be recorded there and additions to its interface that must be implemented. Our scheduling approach satisfies these requirements by requiring the following two changes:

- MAC State Data: addition of $T_{Trans\ Delay}$, the delay, measured in timeslots, between the receipt of a message from the network layer and the start of transmission.
- MAC Layer Interface: addition of an accessor function that return the value of $T_{Trans\ Delay}$.

With these additions, the application layer protocol can provide a mechanism such that when two or more nodes are contending for the media at the same time, all but the node that transmitted first should choose a different offset. A node knows that its backoff timer has been frozen if the following conditions hold:

- Condition 1: $T_{Trans\ Delay} > T_{AIFS} + CW_{min}$
- Condition 2: $T_{ml} > T_{AIFS} + CW_{min}$

Condition 2 requires that the transmission time for a message be longer than the longest potential backoff time when the media is idle. However, this requirement is easily satisfied with default values for these parameters. For T_{AIFS} of 9 slots and CW_{min} of 15 slots, T_{ml} > 24 slots (384 µs). Given the need for 192 µs synchronization time and a bandwidth of 3 Mbps, this would require the transmission of at least 72 bytes. This requirement is satisfied by the lower layers alone, since the UDP, IPv6, and WAVE layers insert 92 bytes of headers and trailers.

Whenever an application sends a new heartbeat message, it uses the new MAC layer interface function to evaluate Condition 1. If this condition is true, a new offset is chosen for the next transmission (within the valid offset ranges as shown in Figures 2 and 3).

The vehicular environment presents a challenge, however, to the stability of this approach. The high relative velocities, particularly when the network consists of both directions of traffic in a highway scenario, create a volatile communications network topology. The frequent changes in the neighbors could prevent a stable, even distribution from emerging.

To address this problem, distinct regions of frequency or time are allocated to each direction of traffic. There are a variety of methods that could be employed depending on the density of traffic, whether single- or multi-band radios are used, and the need to hear heartbeat messages for vehicles travelling in the opposite direction. These methods include:

- For multi-band radios, use of the control channel interval for one direction of travel and the service channel interval for the other direction.
- Use of different service channels for different directions of travel.
- Dividing the timeslots of the service channel (or service and control channels) into two sets, with the first set of time slots for one direction of travel, and the second for the other direction.

In the last option, the size of these sets could be a function of the density of travel in each direction, with a larger set allocated to the direction with denser traffic.

4. WAVE simulation

In order to evaluate the impact of the design of the WAVE Communications architecture on the vehicle heartbeat messages, a simulation of the WAVE Communications Architecture was implemented in the commercial network simulator, Qualnet. The validated models for existing network protocols were extended to reflect the changes described in the previous section. In addition, the vehicle mobility patterns were based on simulations developed in the CORSIM microscopic vehicle simulator.

The simulation used default values for the parameterization of the WAVE Communications protocols. At the transport layer, the connectionless protocol UDP was chosen, due to its suitability for unacknowledged, connectionless broadcast messages. As called for in the WAVE standards, IPv6 was used for the network layer.

The default values for used for the parameterization of the WAVE MAC layer. The CCH interval and SCH interval durations were set to 50 μsec and the guard interval duration was set to 4 μsec [17]. The AIFS was set to the default for SCH background traffic, which is 144 μsec [17].

At the physical layer, the simulations used service channel 184, with a bandwidth of 10 MHz [18]. This channel has been chosen because it has not been reserved for a specific use, e.g. for public safety applications. The transmit power level chosen was 13.4 dBm, which with a 0.3 dBm antenna mismatch loss rate, provides the 150m radio range required for most of the vehicle heartbeat applications. This power level falls is appropriate, as it falls below the maximum transmission power of 28.8 dBm for private vehicular WAVE applications.

The vehicle mobility in the simulation was based on vehicle traces from the microscopic vehicle simulator CORSIM [20]. In CORSIM, a vehicle's mobility is determined by driver behavior, vehicle performance characteristics, and constraints imposed by the roadway geometry and surrounding vehicles.

The vehicle simulation simulates traffic on I-880 in Hayward, California [21]. Data for traffic flows on various dates in 1993 was collected by the Freeway Service Patrol Evaluation Project at the University of California, Berkeley. The author modeled the roadway geometry in CORSIM to roughly correspond to 14.8 kilometers of this roadway, varying between 6 to 8 lanes of traffic, with 22 on- and off-ramps.

Based on traffic data that was collected for March 13, 1993, two sets of scenarios were created for this roadway that models traffic without HOV lanes. Both sets of scenarios model free-flowing traffic. The first set of scenarios models traffic during peak hours, with an average vehicle density of 127 vehicles/km, while the second set of scenarios models traffic during off-peak hours, with an average vehicle density of 53 vehicles/km. As shown in Table 1, four levels of OBE deployment were created – in which vehicles had a 25%, 50%, 75%, or 100% chance of having radio units installed.

For single-band radios, the off-peak and only the 25% Rush-hour scenarios were tested, since the remaining scenarios produced traffic that was close to or exceeded the network capacity. The full deployment for rush-hour traffic exceeded the network capacity for even dual-band radios and was not tested.

Table 1: Vehicle Density

Scenario	Level of OBE Deployment	Equipped Vehicle Density (vehicles/km)
Offpeak	25%	12.92
Offpeak	50%	26.82
Offpeak	75%	39.73
Offpeak	Full	53.06
Rush hour	25%	31.73
Rush hour	50%	62.57
Rush hour	75%	94.98

5. Simulation Results

The simulations were run for to evaluate both the impact of scheduling approaches both for single-band and multi-band radios. This improvement diminished as the density of equipped vehicles increased and the amount of unused bandwidth decreases.

Thirty 30-second scenarios were generated from different portions of each traffic scenario, and different scheduling approaches were simulated for these scenarios. Simulations were run for both single- and multi-band radios. Statistics were collected only for signals received by vehicles located in the middle of the simulated highway (between the 2 km and 8 km), for the entire simulation, i.e. vehicles that entered or left the highway during the simulation were not included.

For single-band radios, scheduling the transmission offset in the service channel interval produced an improvement in the ratio of collisions to messages received of 45% to 69% over a Random Offset approach, and improvement of 72% to 88% over the No Offset approach.

The full scheduling approach described in Section 3.2 produced significant improvements in the ratio of collisions to messages received for all scenarios involving multi-band radios, except for the one with the lowest density of traffic. The improvement over the Random Offset approach ranged from 18% to 34%, and the improvements over the No Offset approach ranged from 88% to 93%.

5.1. Scheduling and single-band radios

The first round of simulations was run with single-band radios which are only allowed to transmit during the service channel interval. The results of these simulations confirm the conclusions of the analysis of Section 3.1 that application layer scheduling must take into account the allowable transmission times for these single-band radios.

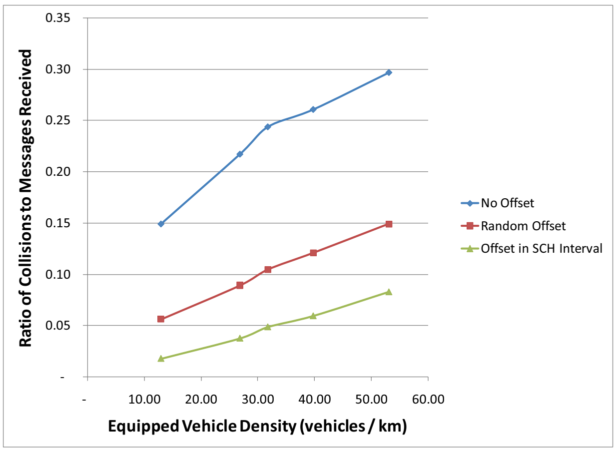

Figure 5: Impact of Scheduling Approaches on the Ratio of Collisions to Messages Received for Single-Band Radios

Table 2: Improvement in Collision to Message Received Ratio of the *SCH Offset* over the *Random Offset* and *No Offset* Scheduling Approach for Single-Band Radios

Scenario	Vehicle Density (veh/km)	Improvement over *Random Offset*	Improvement over *No Offset*
Offpeak: 25%	12.92	68.82%	88.26%
Offpeak: 50%	26.82	58.13%	82.83%
Rush hour: 25%	31.73	53.74%	80.16%
Offpeak: 75%	39.73	51.00%	77.31%
Offpeak: 100%	53.06	44.56%	72.17%

Figure 5 shows the ratio of messages received for different scheduling approaches for these radios that can only transmit during Service Channel Intervals. The *No Offset* approach, which schedules all transmissions at the beginning of the Periodic Broadcast Interval, produces a very high rate of collisions, as all nodes contend for the media at the beginning of the Service Channel Interval. The *Random Offset* approach which selects a random offset in the Periodic Broadcast Interval performed significantly better than the *No Offset* approach.

However, in the *Random Offset* approach, approximately half of the nodes simultaneously compete for the media at the beginning of the Service Channel Interval. As a result, choosing an offset in the Service Channel Interval produces fewer collisions. As shown in Table 2, the *SCH Offset* approach produces larger improvements in sparser traffic, and as traffic becomes denser and more vehicles contend for the media, the advantage of this scheduling approach diminishes. The improvement of the *Random Offset* approach range from 45% to 69%, and the improvement of *No Offset* approach ranges from 72% to 88%.

5.2. Scheduling and multi-band radios

The full *Cross-Layer Scheduling* approach, described in Section 3.2, was evaluated in the context of multi-band radios. Due to the additional bandwidth available to multi-band radios, the 50% and 75% rush-hours scenarios were also tested. In all of the scenarios, the *Cross-Layer Scheduling* approach significantly outperformed the *No Offset* scheduling approach. The *Cross-Layer Scheduling* algorithm also outperformed the *Random Offset* approach in all but the sparsest scenario.

In the simulations of the *Cross-Layer Scheduling* approach, north-bound traffic uses the Service Channel during the CCH Interval to send and monitor heartbeat messages. South-bound traffic, on the other hand, uses the Service Channel during the SCH Interval to send and monitor heartbeat messages. Over time, the number of collisions in Cross-Layer Scheduling tends to decline. Consequently, only the error rate in last 10 seconds of each 30 second scenario was considered for the *Cross-Layer Scheduling* approach.

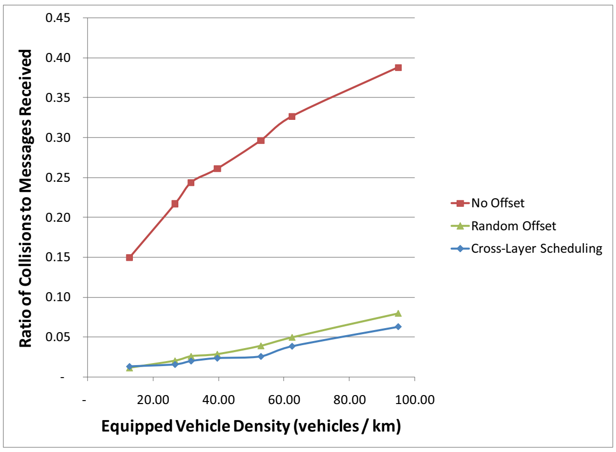

Figure 6: Impact of Scheduling Approaches on the Ratio of Collisions to Messages Received for Multi-Band Radios

Figure 6 depicts the ratio of collisions to messages received for each of the scheduling approaches under various equipped vehicle densities. This plot clearly shows the dramatic improvement of both the the *Random* and *Cross-layer* scheduling approaches over the *No Offset* approach.

Moreover, as shown in Table 3, the *No Offset* approach performed essentially identically even though it has access to twice the bandwidth in the multi-band radio scenario. The nodes simply did not make use of the additional channel interval, as they all contended for the media at the beginning of the Periodic Broadcast Interval.

As shown in Table 4, the *Cross-layer Scheduling* approach does produce an improvement over the *Random Offset* approach, in all but the sparsest of traffic scenarios. These improvements range from 18% to 34%. In addition this table shows the improvements of the *Cross-layer Scheduling* approach over the *No Offset* approach, which range from 88% to 93%.

Table 3: Comparison of *No Offset* scheduling approach with single-band and multi-band radios

Scenario	Average Vehicle Density (vehicles/km)	Ratio of Collisions to Messages Received	
		No Offset approach in a single-band radio	*No Offset* approach in a multi-band radio
Offpeak: 25%	12.92	0.1491	0.1495
Offpeak: 50%	26.82	0.2171	0.2168
Rush hour: 25%	31.73	0.2437	0.2436
Offpeak: 75%	39.73	0.2607	0.2608
Offpeak: 100%	53.06	0.2966	0.2962

Table 4: Improvement in Collision to Message Received Ratio of the *Cross-layer Scheduling* over the *Random Offset* and *No Offset* Approaches for Multi-Band Radios

Scenario	Vehicle Density (vehs/km)	Improvement over *Random Offset*	Improvement over *No Offset*
Offpeak: 25%	12.92	-15.39%	91.33%
Offpeak: 50%	26.82	23.47%	92.88%
Rush hour: 25%	31.73	23.46%	91.89%
Offpeak: 75%	39.73	17.94%	91.06%
Offpeak: 100%	53.06	34.48%	91.39%
Rush hour: 50%	62.57	22.97%	88.30%
Rush hour: 75%	94.98	21.48%	83.86%

8. Conclusions and future work

The results of these experiments show the need for cross-layer coordination when scheduling the high-volume, periodic vehicle heartbeat messages. The reliable delivery of these messages is extremely important since a range of safety critical application will rely on these messages for the regular updates of the location and kinematics of nearby vehicles.

The proposed scheduling approach uses knowledge about both the configuration and current state of the physical and MAC layers. Messages are scheduled for delivery only during times when a node is allowed to transmit, which is a function of whether the MAC layer has been configured to support single-band or multi-band radios. In addition, the time during which a vehicle transmits can be periodically adjusted based on delays experienced by the MAC layer. These adjustments help to evenly distribute the transmission times for nearby vehicles throughout the allowable transmission interval.

In order to evaluate the proposed scheduling approach, a simulation system was developed which uses vehicle traces from a widely used microscopic vehicle simulator and extensions to a communications network simulator based on the Wireless Access in Vehicular Environments (WAVE) standards. In simulations of a variety of highway traffic, this cross-layer coordination produced improvements in the ratio of collisions to messages received of 45% to 88% for single-band radios and 18% to 93% for dual-band radios.

The authors intend to extend this research to include other roadway scenarios and applications. Future simulations will include arterial roadways and additional classes of WAVE messages. Other vehicle-to-vehicle messages will include both single-hop and multi-hop messages, as well as lower volume, a-periodic messages, such as roadway hazard warning messages. In addition, future work will consider Vehicle-Infrastructure Integration applications in which vehicles communicate with roadside.

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