An Efficient Fully Ad-Hoc Multi-Hop Broadcast Protocol for Inter-Vehicular Communication Systems

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***Abstract*— In this paper, a fully Ad-Hoc Multi-hop Broadcast protocol (AMB) is proposed for inter-vehicular networks. The AMB is an ad-hoc extension of the UMB protocol which handles broadcast in intersections with the help of repeaters. The AMB protocol eliminates the most important drawback - infrastructure dependence - of the UMB protocol by employing an efficient intersection broadcast mechanism. When there is an intersection in the path of the message dissemination, new directional broadcasts to all road segments are initiated by the vehicle closest to the intersection with a fully ad-hoc algorithm without apriori topology information. The simulation results confirm that our protocol has a very high success rate and efficient channel utilization. Consequently, it is concluded that there is no need for infrastructure support unless the the line-of-sight among different road segments incident to an intersection is blocked with obstacles.**

I. Introduction

Recently, Inter-Vehicular Communication Systems (IVC) have attracted considerable attention from the research community and the automotive industry [1]. Many automobile manufacturers started planning to build communication devices into their vehicles for the purposes of safety, comfortable driving, and entertainment. In IVC systems, broadcast is a frequently used method. Possible applications relying on broadcast include sharing emergency, traffic, weather, and road data among vehicles, and delivering advertisements and announcements.

The topology and the node movement of an IVC network is constrained by roads. The resulting communication network is a special type of Mobile Ad-Hoc Network (MANET) where the mobility rate is high but movement direction and speeds are predictable. In MANETs, flooding the network blindly is the first approach to achieve broadcasting since flooding can operate without local or global topology information. However, it has been shown in [2] that serious redundancy, contention, and collision problems occur as a result of flooding. Although [2] proposes techniques to improve blind flooding, the proposed solutions are not effective for all ranges of node densities and packet loads. Unfortunately, in IVC applications, both the node density and packet load fluctuate significantly. In [3],[4], methods to eliminate redundant packets while broadcasting is proposed using the topology information. However, in an IVC network, the large number of vehicles and high mobility make such proactive approaches impractical [5].

In [5], the IEEE 802.11 protocol is adapted for broadcasting in IVC systems by employing a distance based waiting approach before retransmissions. Although this approach distributes the highly correlated rebroadcast times, problems such as hidden nodes, collisions at high packet traffic rates, reliability, and broadcast storms still persist. Another flooding based protocol is proposed in [6] for broadcasting short packets in IVC systems. This protocol limits the channel access rate of each vehicle by defining a transmission window. To address the shortcomings of flooding based protocols, Urban Multi-hop Broadcast protocol (UMB) [7] is proposed. UMB is a broadcast protocol specifically designed for vehicular networks with infrastructure support. The UMB protocol efficiently broadcasts packets with high successful delivery rate with the help of repeaters at the road intersections. The need for an infrastructure, however, considerably decreases the deployment area of the UMB based networks because the UMB protocol fails to handle intersections without a repeater.

In this paper, we propose a fully Ad-Hoc Multi-hop Broadcast protocol (AMB) for inter-vehicular networks as a solution for the infrastructure dependence problem of the UMB protocol. AMB is an extension of the UMB protocol composed of two parts, namely *directional broadcast* and *intersection broadcast*. *Directional broadcast* adapted from the UMB protocol is a method where sender nodes attempt to select the furthest node in the broadcast direction to assign the function of forwarding and acknowledging the packet without any apriori topology information i.e., senders select the furthest node without knowing the ID or position of their neighbors. *Intersection broadcast*, as its name implies, is designed to handle the packet dissemination at intersections. Forwarding the packet to all road segments with minimum overhead is particularly important around the intersection area for the successful packet delivery. In the AMB protocol, vehicles attempt to select the closest vehicle to the intersection using a fully ad-hoc algorithm and the selected vehicle forwards the packet to all road segments except the road segment the packet is coming from. We show through simulations that the AMB protocol outperforms other flooding based broadcast protocols and it is not necessary to install repeaters at intersections

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where the line-of-sight among road segments incident to the intersection is not blocked.

II. Overview of the UMB protocol

UMB is an efficient IEEE 802.11 based Urban Multi-hop Broadcast protocol for inter-vehicular networks with infrastructure support whose details can be found in [7]. It is designed to address (i) broadcast storm, (ii) hidden node, and (iii) reliability problems of multi-hop broadcast in urban canyons. Unlike flooding based broadcast protocols, UMB assigns the function of forwarding and acknowledging the packet to only the furthest node without any apriori topology information. At the intersections where the communication among incident road segments are blocked by buildings, UMB employs repeaters installed at intersections to forward the packet to all road segments.

We assume that each vehicle is equipped with a GPS receiver and an electronic road map. Since the vehicle mobility is high and vehicles leave and enter the network frequently, the topology of this network changes fast. Therefore, the UMB protocol is designed to operate without exchanging location information among neighboring nodes.

A. Directional Broadcast

1) RTB/CTB Handshake: To mitigate the hidden node problem while minimizing the overhead, sender vehicles engage in RTS/CTS like handshake with only one of the recipients among the sender's neighbors. If we can select the furthest away node with the handshake then other nodes in between can overhear the transmission as well. To pick this vehicle, the protocol divides the road portion inside the transmission range into segments. Note that these segments are created only in the direction of dissemination. If there is more than one node in the furthest non-empty segment, this segment is divided iteratively into subsegments with smaller widths. If these segment based iterations are not sufficient to pick only one node, the nodes in the last sub-segment enter to a random phase.

We refer to RTS and CTS as *Request to Broadcast (RTB) and Clear to Broadcast (CTB)*, respectively. We cannot use the original RTS/CTS handshake because a broadcast packet has more than one destination and there is not any explicit broadcast support in IEEE 802.11 protocol. In an RTB packet, in addition to the transmission duration, the source node includes its position and intended broadcast direction. If the source wants to disseminate the message in more than one direction, a new RTB packet should be generated for each direction.

a) First RTB attempt: The source vehicle obeys all IEEE 802.11 transmission rules (CSMA/CA) while attempting to send an RTB packet. When the nodes in the direction of the dissemination receive this RTB packet, they compute their distance to the source node. Based on this distance, they send an energy burst (channel jamming signal) called *black-burst*. The black-burst method was proposed in [8] and [9] to provide guaranteed access delays to rate-limited packet traffic. In these proposals, the length of the original black-burst is proportional to the time that the node has been waiting for channel access. In our directional broadcast, we use the black-burst to select the furthest node by letting receivers sending black-burst signals proportional to their distance to the source. Since the position information of all nodes are unique, using the position information to determine the length of the black-burst gives us the capability of selecting the furthest node.

The duration of the black-burst signal in the first iteration is computed as follows:

$$L_1 = \lfloor d \cdot \frac{N_{max}}{R} \rfloor \cdot SlotTime, \tag{1}$$

where L_1 is the black-burst duration in the first iteration, d is the distance between the source and the vehicle, R is the transmission range, N_{max} is the number of segments created, and $SlotTime$ is the length of one slot. Note that $\frac{R}{N_{max}}$ is the segment width and $\lfloor d * \frac{N_{max}}{R} \rfloor$ is the number of slots the black-burst will keep busy. As a result of this computation, the furthest node sends the longest black-burst.

Nodes send their black-burst in the shortest possible time (SIFS) after they hear the RTB packet. At the end of the black-burst, nodes turn around and listen to the channel. If they find the channel empty, it means that their black-burst was the longest and they are now responsible for replying with a CTB packet after a duration called $CTBTIME$, where $SIFS < CTBTIME < DIFS$. If they find the channel busy, it means that there are some other vehicles further away and they do not try to send the CTB packet.

b) Collision among CTB packets: When there is more than one vehicle in the furthest non-empty segment, they all find the channel empty after sending their black-bursts and continue to send CTB packets. However, since all vehicles start sending the CTB packets at the same time, their CTB packets will collide. When the source node detects a transmission but cannot decode the CTB packet, it detects the collision and repeats the RTB packet after SIFS time as shown in Figure 1(a). This time, only the nodes which have sent CTB packets join the collision resolution. To pick only one node, the furthest non-empty segment is divided into N_{max} sub-segments. This process continues iteratively until a successful CTB packet is received by the source or D_{max} iterations are completed. The length of the black-burst for the i^{th} iteration (L_i) is computed as follows:

$$\begin{aligned} L_i &= \lfloor (d - L_{i-1}^{longest} * W_{i-1}) \cdot \frac{N_{max}}{W_{i-1}} \rfloor \cdot SlotTime \\ & \quad i = 2, 3, ..., D_{max} \\ W_i &= \frac{R}{N_{max}^{i}}, \end{aligned} \tag{2}$$

where $L_i^{longest}$ and W_i are the longest black-burst and the segment width in the i^{th} iteration, respectively.

Note that in an RTB packet, the source only indicates that there has been a collision: It is the receiver nodes' responsibility to choose the segment to be split. Only nodes who have sent the longest black-burst in the previous $(i-1)^{th}$

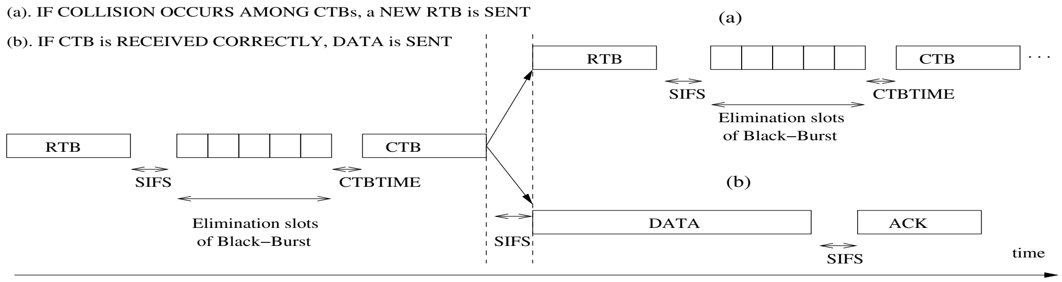

Fig. 1. Sequence of packets. (a) Second RTB/CTB handshake (b) DATA/ACK.

iteration can join to the current (i^{th}) iteration. As a result, $L_{i-1}^{longest}$ is the black-burst length of these nodes in the previous iteration and $L_{i-1}^{longest} + 1$ is the segment to be split.

If the segment based black-burst cannot resolve the collision after the D_{max}^{th} iteration, the vehicles that have sent the CTB response in the last iteration choose the black-burst length randomly. The segment based iterations decrease the segment to a very short strip and only a small number of nodes will be left at the beginning of the random phase increasing the success probability of this phase.

c) No black-burst response: Detecting a free channel after sending the RTB packet, the source node assumes that nobody has received its RTB packet. In this case, source node goes back to the first segment based iteration after a random amount of time. Details of this backoff procedure are the same as those of the IEEE 802.11 standard when no CTS is received by the sender.

2) Transmission of DATA and ACK: After receiving a successful CTB, the source node sends its broadcast packet as shown in Figure 1(b). In this broadcast packet, the source node includes the ID of the node which has successfully sent the CTB. We will refer to this node as the *corresponding node of the source*. This node is now responsible for forwarding the broadcast packet and sending an ACK to the source. This ACK packet ensures the reliability of packet dissemination in the desired direction. Although all other nodes between the source and the ACK sender receive the broadcast packet, they do not rebroadcast or acknowledge it. If the ACK packet is not received by the source before the ACK timeout, the source goes back to the first segment based iteration after a random amount of time. Details of this backoff procedure are the same as those of the IEEE 802.11 standard when ACK is not received. Note that there is a maximum number of times (RET_{max}) that the source node can go back to the first iteration.

B. Intersection Broadcast

When a node is selected to forward a packet and it is outside the transmission range of a repeater, it continues with the directional broadcast protocol as described in Section II-A. On the other hand, if the node is inside the transmission range of a repeater, the node sends the packet directly to the repeater using the point-to-point IEEE 802.11 protocol. Note that using the GPS and digital road map, each node knows the locations of itself, intersections, and repeaters. According to our protocol, the node inside the transmission range of a repeater sends RTS packet to the repeater and only the repeater replies with the CTS packet. Upon receiving the CTS packet from the repeater, the node sends the DATA packet and the transmission ends when it receives an ACK packet from the repeater. After receiving the broadcast packet, the repeater initiates new directional broadcasts in all road segments other than the road segments.

III. FULLY AD-HOC INTERSECTION HANDLING WITH THE AMB PROTOCOL

The UMB protocol is an effective protocol for urban canyons with repeaters installed at the intersections. It is, however, not necessary to install repeaters at the intersections when the line-of-sight path exists among road segments. In this paper, we propose a fully ad-hoc extension to the UMB protocol which handles intersections without infrastructure support when there is line of sight among all road segments. In the AMB protocol, the directional broadcast mechanism of the UMB protocol is employed; however, a new intersection broadcast mechanism is proposed where vehicles find the best candidate among themselves to branch the packet dissemination to other road segments. The vehicle closest to the intersection is a good candidate for this function because it is likely that vehicles closer to the intersection have a better coverage of the other road segments.

The new intersection broadcast mechanism is composed of two phases. The first phase is choosing a *HUNTER* vehicle which tries to select the closest vehicle to the intersection. For this purpose, we will define an intersection region. In the second phase, the HUNTER vehicle initiates a search to find the closest vehicle and in response to this search, vehicles reply with a black-burst according to their distance to the intersection. Once the HUNTER vehicle selects the closest vehicle to the intersection, this vehicle becomes responsible for branching the message to the other road segments.

1) Selecting the HUNTER vehicle: In the directional broadcast protocol as described in Section II-A, the dissemination of messages is controlled by a subset of vehicles in the network. These vehicles are assigned the function of forwarding the message after the RTB/CTB handshake. Since each of these vehicles choose a new vehicle in the transmission range (R) to forward the message, at least one vehicle is chosen in every R m. Keeping this fact in mind, we have defined an intersection region around each intersection starting at $R/2$ m before and extending to $R/2$ m beyond the intersection. Note that at least one vehicle is chosen inside this region during the directional broadcast when the intersection region length is at least R. The first vehicle chosen in the intersection region becomes the HUNTER vehicle.

Another reason to choose the intersection region starting at $R/2$ m before the intersection is as follows: Since the HUNTER vehicle tries to select a closer vehicle than itself, its transmission range should cover the points closer to the intersection than itself. When we use a transmission region with the proposed borders, in the worst case the HUNTER vehicle is $R/2$ away from intersection and it can cover the points up to $R/2$ away at the other side of the intersection.

2) Selecting a vehicle for branching the packet dissemination: Having being selected inside the intersection region, the HUNTER vehicle sends an RTB packet different than regular RTB defined in Section II-A.1. This new type of RTB packet which is employed to select the closest vehicle to the intersection is called *Intersection RTB* (I-RTB). The black-burst response to an I-RTB is different from the response to a regular RTB employed in the directional broadcast i.e., when vehicles receive a regular RTB, the furthest vehicle from the source sends the longest black-burst. On the other hand, when vehicles receive an I-RTB, the vehicle closest to the intersection sends the longest black-burst.

The black-burst length for the I-RTB ($\hat{L}$) is calculated using Eq. 1 and Eq. 2. Note that these equations give the L values for the regular RTB response. While determining the black-burst response length for an I-RTB, vehicles use a different d parameter ($\hat{d}$) which is the distance from the intersection instead of the distance from the source.

$$\hat{d} = \sqrt{(X_n - X_{int})^2 + (Y_n - Y_{int})^2}, \quad (3)$$

where (X_n, Y_n) is the position of the node which sends the black-burst and (X_{int}, Y_{int}) is the position of the intersection.

Once this L_i value is found by using $\hat{d}$, $\hat{L}$ is computed as follows:

$$\hat{L}_i(\hat{d}) = (N_{max} - 1) - L_i(\hat{d}) \quad (4)$$

The vehicle which sends the longest black-burst finds the channel idle and sends the CTB packet. After the transmission of DATA and ACK packets, the selection process is finished. This selected vehicle becomes responsible for initiating directional broadcasts in all road directions except the direction where it received the packet from.

An example of intersection handling is illustrated in Figure 2. In this figure, since vehicle A is outside the intersection region, it uses the directional broadcast to reach vehicle B. Vehicle B is the first selected vehicle inside the intersection region; therefore, it becomes the HUNTER and initiates a vehicle selection process by sending the I-RTB packet. Being closest to the intersection, vehicle C sends the longest black-burst and then the CTB packet. After vehicle B assigns the function of branching the packet dissemination to vehicle C, vehicle C initiates directional broadcasts to East, North and South directions.

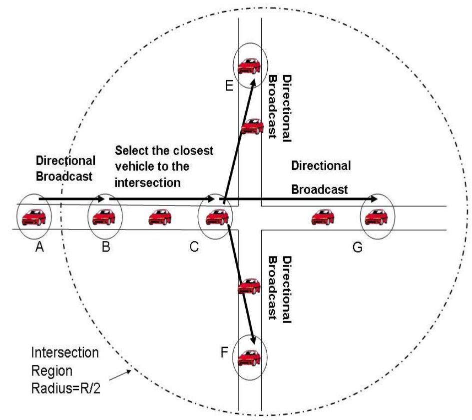

Fig. 2. Ad-hoc branching for a simple intersection

As a special case, if the HUNTER vehicle becomes unsuccessful in selecting a vehicle, HUNTER vehicle itself becomes responsible for forwarding the packet to the other road segments.

IV. Performance Evaluation

To evaluate the performance of our AMB protocol, we have developed the Wireless Simulator (WS) using the event driven simulation library CSIM [17]. WS models the physical layer, the MAC layer, and the network layer of the communication network.

In addition to AMB and UMB, we have simulated two more MAC layer protocols. In this paper, we will refer to these protocols as *802.11-distance* and *802.11-random*. They are flooding based modifications of the IEEE 802.11 standard which route packets without the network topology information or any neighborhood knowledge. They try to avoid collisions among rebroadcast packets by forcing vehicles to wait before forwarding the packets. According to these protocols, every vehicle must broadcast every distinct packet.

The first protocol, 802.11-distance, employs the idea proposed in [5], where the waiting times of the vehicles are inversely proportional to their distances from the source. The waiting time WT is computed as follows:

$$WT = (-\lfloor \frac{\hat{d}}{Range} * maxSlot \rfloor + maxSlot) * SlotTime, \quad (5)$$

where $maxSlot$ is the maximum possible number of slots a vehicle waits before forwarding the packet. As in the IEEE 802.11 standard, vehicles decrease their waiting time counters when they find the channel empty and freeze them when the channel is busy. The protocol proposed in [5] computes the waiting time continuously, however in our 802.11-distance

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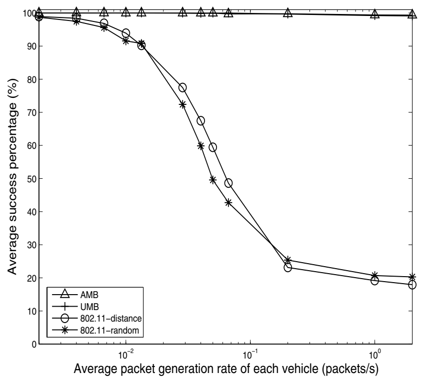

Fig. 3. Packet Delivery Percentage (100 bytes)

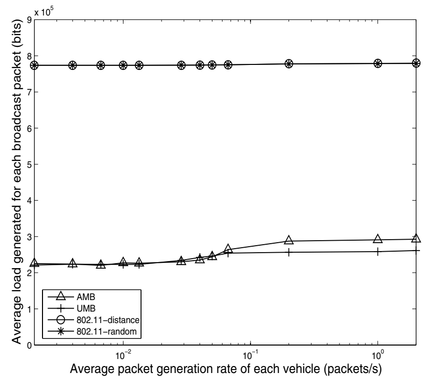

Fig. 4. Load Generated (100 bytes)

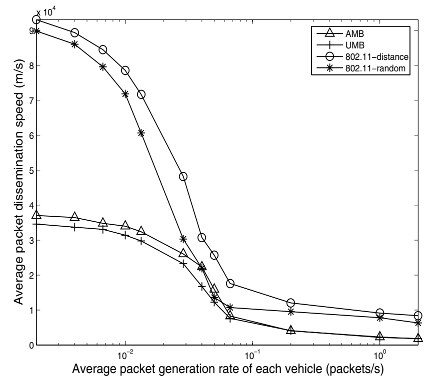

Fig. 5. Dissemination Speed (100 bytes)

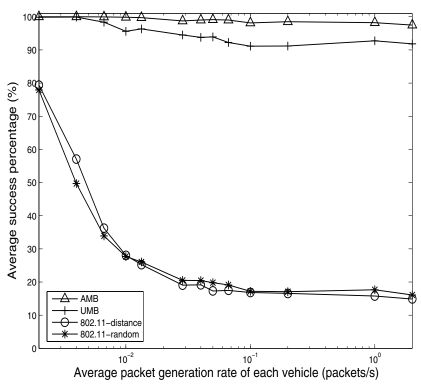

Fig. 6. Packet Delivery Percentage (2304 bytes)

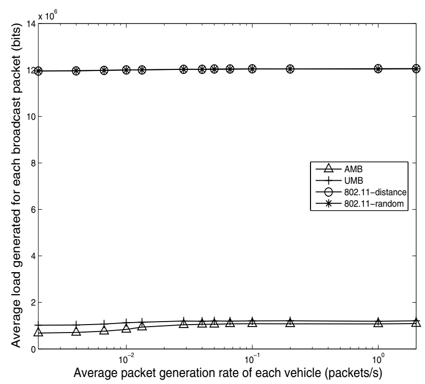

Fig. 7. Load Generated (2304 bytes)

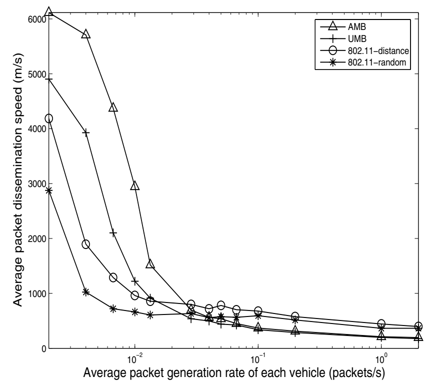

Fig. 8. Dissemination Speed (2304 bytes)

implementation, waiting times are discrete since all waiting times are computed as multiples of $SlotTime$ in the IEEE 802.11 standard.

In the second protocol, 802.11-random, when a vehicle receives a broadcast packet, it will wait for a random duration (WT) before forwarding the packet.
$WT = nSlots * SlotTime$ where $nSlot$ is a random number between [0,$maxSlot$].

Finally, the AMB and UMB protocols are simulated with the following parameters: RET_{max} =15, N_{max} =10, D_{max} =3, Ran_{max}=2.

TABLE I
PARAMETERS OF THE SIMULATOR

description	value
vehicle density	33 veh/km per lane
total number of vehicles	619
transmission range	400 m
data rate	1 Mbps
frame body	2304 bytes or 100 bytes
base protocol	802.11b
$maxSlot$	32
simulation time ($simtime$)	60 s
simulation repetitions	30

A. Common Simulation Parameters

In our road structure, two south-north and two east-west road segments intersect and create four intersections. Each road segment contains two lanes, one for each direction of traffic flow. The vehicles are randomly placed on the road segments with exponentially distributed interspaces. Lane changes, turns and overtaking is not modeled for vehicle movement. Each vehicle is assigned a speed from a Gaussian distribution with a mean of 40 km/h and a standard deviation of 5 km/h at the beginning of the simulation and this speed remains constant during the simulation.

The common parameters of the simulator are summarized in Table I. Other parameters of the MAC layer and the physical layer are taken from the IEEE 802.11b standard [10].

B. Results

1) Successful Packet Delivery Percentage: Successful Packet Delivery Percentage of a packet is the ratio of the cars that receive the broadcast packet to the total number of cars. When the average success percentage is lower than 100%, it means that the broadcast packets are not received by all vehicles. Figure 3 and Figure 6 depict the average success percentage when a payload length of 100 bytes and 2304 bytes are used respectively. Both of these figures show that our AMB protocol achieves approximately 100% successful packet delivery. When the packet generation rate is increased, we observe only a slight decrease ($\approx 2\%$) in the success rate of AMB. The AMB protocol has higher successful delivery ratio than the UMB protocol especially when the payload is

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long (Figure 6) because the UMB protocol relies on just one node, repeater, at the intersection which creates a hot spot. This single hot spot increases packet collisions and queuing delays. On the other hand, the AMB protocol chooses different vehicles at the intersection to initiate packet dissemination to other road segments. 802.11-distance and 802.11-random protocols perform poorly because of packet collisions due to hidden nodes and the lack of the acknowledgment mechanism. Moreover, 802.11-distance and 802.11-random protocols loose more packets in Figure 6 since longer packets increase the packet collision probability due to hidden nodes.

2) Normalized Load Generated per Broadcast Packet: *Load generated per broadcast packet* is the total number of bits transmitted to disseminate a packet in all retransmissions. To compute the average load, we divide the total number of bits sent by the total number of broadcast packets generated during simulation. This metric gives the total traffic generated by one broadcast packet in the network. Note that small values of this parameter correspond to efficient usage of the channel.When the dissemination of a packet stops, it can reach only a fraction of the network and it generates a smaller load compared to a packet that reaches all vehicles. For fair comparison, we divide the *load generated* by the *successful packet delivery percentage* and define a *normalized* metric for *the average load generated per broadcast packet*.

Figures 4 and 7 show the normalized average load generated per broadcast packet. For both payload lengths, we can observe that the AMB and UMB protocols generate less load while disseminating a packet with a very high successful delivery percentage than 802.11-random and 802.11-distance protocols because AMB and UMB protocols assign the function of forwarding the broadcast packet to only one vehicle while flooding based protocols assign this function to every vehicle. For the short payload, AMB and UMB generate approximately 2.5 times less load than the flooding protocols. When the length of the data packet is long, the length of the control packets (RTB, CTB, ACK and black-burst) becomes negligible compared to the length of the DATA packet. In this case, the AMB and UMB protocols perform approximately 12 times better than the flooding protocols as can be seen in Figure 7.

3) Packet Dissemination Speed (m/s): Speed of a packet at a point is computed by dividing the *distance travelled* by the packet by the *delay*. In the context of this paper, $delay$ refers to the time elapsed between the instant the packet enters the source queue and the reception time of the packet by another vehicle. Figure 5 and Figure 8 show the packet dissemination speed for short and long DATA packets. Figure 5 depicts that when the DATA packet length is short, 802.11-distance and 802.11-random disseminate the packets faster than the AMB and UMB protocols. However, recall that the successful packet delivery percentage of these protocols are extremely low as shown in Figure 6. This low packet delivery percentage decreases the queuing delays of 802.11-distance and 802.11-random. Increasing the length of DATA packet increases the speed of the AMB and UMB protocols relative to the other protocols. In Figure 8, AMB becomes the fastest one at low packet generation rates and its speed is close to the others at high packet generation rates in spite of the fact that 802.11-distance and 802.11-random protocols drop many packets.

V. Conclusions

In this paper, an efficient fully ad-hoc multi-hop broadcast protocol (AMB) for inter-vehicular communication networks is proposed without infrastructure support. AMB is an extension of the UMB protocol with a fully ad-hoc intersection broadcast mechanism. In the AMB protocol, vehicles attempt to select the closest vehicle to the intersection among themselves and the selected vehicle forwards the packet to all road segments except the road segment the packet is coming from. It is shown through simulations that when the communication among the different road segments incident to the intersection is not blocked with obstacles, our AMB protocol has a very high success percentage and efficient channel usage even at high packet loads; therefore, there is no need for an infrastructure support. It is concluded that the best solution for the broadcast problem in vehicular networks is using UMB and AMB protocols together i.e., the UMB protocol is used to handle intersections where the communication among road segments requires a repeater because of buildings and the AMB protocol is used to handle intersections without repeaters. In our future work, intersection identification without digital map will be studied.

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