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DBA-MAC: DYNAMIC BACKBONE-ASSISTED MEDIUM ACCESS CONTROL PROTOCOL FOR EFFICIENT BROADCAST IN VANETS

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Active safety systems based on dissemination of alert messages are one of the most important applications of Vehicular ad Hoc Networks (VANETs). These systems typically require to provide efficient and reliable delivery of safety information to all the vehicles travelling over a geographical area. Reducing the delivery delay is also a crucial issue due to the real-time nature of the communication. To meet these requirements, in this paper we design a cross-layered MAC and clustering solution for the fast propagation of broadcast messages in a VANET. A distributed dynamic clustering algorithm is proposed in order to create a dynamic virtual backbone inside the vehicular network. The vehicle-members of the backbone are responsible for implementing an efficient message propagation. The backbone creation and maintenance are proactively performed aiming to balance the stability of backbone connections as well as cost/efficiency trade-off and hops-reduction when forwarding the broadcast messages. A fast multi-hop MAC forwarding scheme is defined to exploit the role of backbone vehicles, under a cross-layered approach. Simulation results show that our cross-layer scheme guarantees high message delivery ratio, reduces the delivery delay and provides efficient channel utilization when compared with other dissemination schemes for VANETs.

Keywords: Design, Modeling and Simulation, Vehicular Ad Hoc Networks, Active Safety Applications, Multi-hop Broadcast, Medium Access Control, Clustering, Cross-Layering.

1. Introduction

In the last two decades, technology advances in portable devices and wireless networking have contributed to the introduction of new active safety systems assisting vehicle drivers to avoid congestion and road accidents [1,2,3,4,5,6]. Some examples of such systems include Information Warning Functions (IWF) [1,13,14], real-time traffic monitoring applications [2], advanced driver assistance systems for cooperative Adaptive Cruise Control (ACC) [3] and intersection collision avoidance [1,2,3]. Since it is not guaranteed that all roads will be covered by a wireless communication infrastructure, distributed applications based on inter-vehicle wireless communication (IVC) are investigated in the literature [1,2]. These systems foresee that neighbour vehicles will be able to communicate with each other by using dedicated short-range wireless technologies [5,6,7], thus enabling Vehicular Ad Hoc Networks (VANETs) [1].

Road-safety applications based on IVC strictly rely on the assumption of cooperation and distributed coordination among vehicles, and pose new challenges on the nature and characteristics of inter-vehicular communication [15]. Firstly, the communication involves a sender vehicle and a group of potential receivers travelling over the same geographical area, i.e. the nature of the communication is intrinsically *position-dependant*. Each time a vehicle detects a problem on the road, it will broadcast an alert message to all the receiver vehicles in the same Risk Zone (RZ) (Fig.1). Since the risk zone may be larger than the transmitting range of wireless devices, the message will be relayed by the intermediate vehicles to extend the horizon of the message advertisement (Fig. 1). Secondly, the information exchanged by safety-related applications poses strong communication requirements in terms of delivery delay: few tenths of a second delay may have a significant impact on the effectiveness of a safety application (e.g. braking assistance). Thus, the communication is also *time-dependant*. Moreover, there are several security issues, e.g. privacy, identity and trust management issues, which are fundamental for these systems and have received attention from the research community [23, 24]. We do not consider security issues in this paper. Indeed, we focus on time and delivery requirements, i.e we remark that the viability of active safety applications relies on the ability to broadcast information by guaranteeing *(i)* as fast as possible dissemination, *(ii)* highly effective message delivery ratio among the vehicles in the risk zone, *(iii)* fair and scalable resources utilization.

Vehicle-to-vehicle communication for safety related applications has been recently addressed by several international consortium and research institutes [3,4,5,6]. The Dedicated Short Range Communication (DSRC) consortium originally planned a standard technology devoted to enhance safety of the transportation systems [5]. The DSRC has de facto merged with the Wireless Access for Vehicular Environment (WAVE) initiative of IEEE 802.11 working group. A new task group P is working on

IEEE 802.11 standard amendment (IEEE 802.11p) for vehicular communication environment (5 GHz band), in cooperation with European ISO TC204/WG16 working on Continuous Air Interface for Long/Medium range communication (CALM M5) to ensure global applicability [6]. The IEEE 802.11p standard will include solutions at both PHY and MAC layers to effectively support safety-related applications based on IVC and vehicle-to-roadside communication. Due to wide technology adoption, many research works are currently based on the legacy IEEE 802.11 standard technology. The IEEE 802.11 MAC protocol [7] does not offer any specific support to the multi-hop broadcast communication, apart from the flooding scheme. However, it has been shown that flooding causes high redundancy, contention and collision problems [11]. Conversely, the main goal of multi-hop broadcast protocol is to provide fast information dissemination, limiting the number of message retransmissions. Under ideal assumptions, this goal can be achieved by allowing to relay a broadcast message only to nodes in the Minimum Connected Dominating Set [9] of vehicle-flows. As proposed in [9], the MCDS may be recursively obtained, starting from the broadcast message source, by including in the MCDS the farthest node within the covering range of the previous MCDS node, step by step. Unfortunately, building a MCDS in a vehicular environment requires that all the vehicles have a strong real-time knowledge of the vehicle positions and radio characteristics. For these reasons, most of the broadcast protocols proposed in the literature do not rely on the presence of a "pre-established" virtual structure in the VANET [10,11,12,13,14]. Each time a broadcast communication is started, the next relaying vehicle is dynamically determined, possibly as the farthest connected node with respect to the current sender. Solutions that rely on contention-based channel access differentiation have been proposed at the MAC layer to statistically get the contention winner as the farthest nodes from the sender one [10,11,12,13,14].

Cluster-based schemes may be a viable approach in supporting efficient multi-hop message propagation among vehicles [18]. In this approach, only nodes members of a cluster infrastructure are enabled to relay broadcast messages. A dynamic cluster infrastructure may be defined by providing nodes with a distributed protocol which proactively forms a backbone. We use the term *backbone* to identify a virtual chain of vehicles in a vehicular scenario (e.g. a highway). Each node of the backbone must be connected to previous and next hops of the backbone chain, as shown in Fig. 2. The backbone formation and management should be determined in a distributed way, by exploiting some unique characteristics of VANETs [17]. First of all, the vehicular mobility follows correlated mobility patterns (e.g. car following model), and physical constraints (e.g. directions defined by road borders). Secondly, vehicles travelling in the same direction typically form a "*persistent natural clustering of vehicles*" under certain mobility assumptions. Time-persistent clustering is possible, despite the high speed distribution variance characterizing some scenarios (as an example, highways), because the vehicles travelling in the same lane could maintain wireless connectivity for a relative long time interval. Under these assumptions, the overheads for dynamic and proactive cluster creation and management may be balanced by a persistent advantage in the resources saving, and in a fast and effective propagation of alert messages.

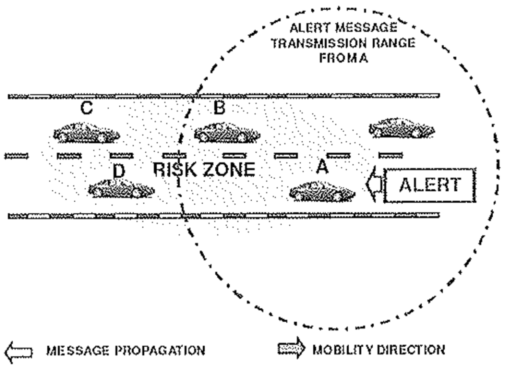

Fig. 1. Active Safety Applications in a VANET.

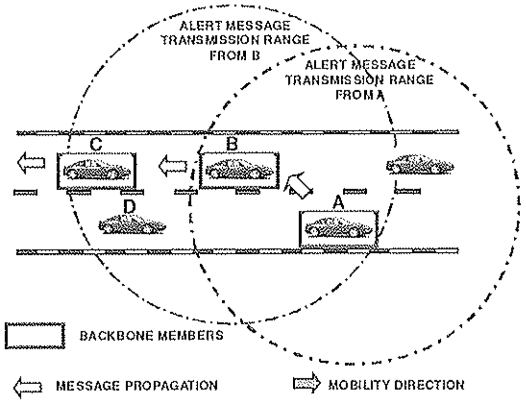

Fig. 2. Virtual Backbone Infrastructure in a VANET.

In this paper, we present a novel, cross-layered scheme which supports the fast propagation of broadcast messages in a VANET. Our cross-layer scheme is composed by a novel proactive clustering protocol and a MAC protocol inspired to IEEE 802.11 Distributed Coordination Function (DCF) basic access scheme. The proactive clustering scheme dynamically establishes a virtual backbone infrastructure in the vehicular environment. The backbone infrastructure is created by addressing robustness and lifetime of connections among backbone members. The backbone formation process works by taking into account *(i)* the current distance among candidate backbone vehicles and *(ii)* the estimated lifetime of the wireless connection among neighbour backbone members. In addition, we propose a forwarding scheme at the MAC layer which exploits the existence of the backbone infrastructure. We called it Dynamic Backbone-Assisted MAC (DBA-MAC). When an alert message is generated by a vehicle, it is relayed by the nodes of the backbone, as long as the backbone is present. The main advantages of the proposed cross-layer scheme can be summarized as follows: *(i)* broadcast message transmission among nodes of the backbone is implicitly an impulse of unicast communications, that is, reliability could be improved by means of immediate Ack notification mechanisms, and *(ii)* the effect of multi-hop MAC layer backoff delays is significantly reduced, since each backbone node receiving a message immediately broadcasts it, after a short inter-frame space (SIFS), to the next backbone node. If the transmission among vehicles of the backbone fails (e.g. due to collisions or hidden terminals), or if a backbone disruption is caused by mobility and no backbone nodes are present to relay the message, then a fast multi-hop broadcast scheme like the one proposed in [10] is used as a background (worst case) solution.

The paper is structured as follows. In section 2, we sketch the existing multi-hop broadcast protocols and clustering schemes proposed in the literature for VANETs. In section 3 we illustrate the system model and the general assumptions. In section 4, we describe the structure of the cross-layered scheme, with details of the distributed algorithm for backbone creation (section 4.1) and the solutions adopted at the MAC layer (section 4.2). Section 5 illustrates the simulation results of the DBA-MAC scheme, compared with other multi-hop broadcast schemes in a highway scenario. Conclusions and future works follow in section 6.

2. Related Works

Flooding [7] is the straight-forward approach to achieve broadcasting within a IEEE 802.11 VANET: each vehicle receiving the first occurrence of a message re-broadcasts it after a MAC backoff. The drawbacks of this approach are: the amount of potential useless retransmissions, the MAC contention caused by the *broadcast storm* problem, the high risk of message dropping due to collisions and the high average end-to-end delay. Several multi-hop broadcast protocols for VANETs have been proposed in the literature, mainly considering 802.11 variants. As an example of this approach, in [14] the authors propose to increase the reception probability of the IEEE 802.11 MAC DCF, by broadcasting a message several times within a lifetime limit. Existing multi-hop broadcast protocols for VANETs can be classified into two main classes: *location-based* broadcast protocols and *deterministic* broadcast protocols.

Location-based broadcast protocols [8] exploit local position information to decide whether a certain node should broadcast a message or not. As a result, location-based broadcast protocols can quickly adapt to topology changes in VANETs: the next hop transmitter (possibly the farthest vehicle with respect to the previous transmitter) is selected with a biased contention-phase, in a distributed way. In [11], a contention-based MAC protocol is proposed for VANETs: each time a vehicle receives an alert message from a source node, it produces a jamming signal whose duration is proportional to the distance from the source node. The vehicle producing the longest jamming signal is also the farthest vehicle within the source transmission range, and is responsible of re-broadcasting the alert message [11]. In other schemes [10,12,13], hops minimization is achieved by opportunely adjusting the parameters governing the channel access at MAC level, such as the contention window [7] in the 802.11 MAC DCF backoff scheme. Specifically, in [10] each vehicle dynamically adjusts the contention-window size upon receiving a broadcast message from the front-car. The contention window size is made inversely proportional to the distance from the sender, so that far vehicles statistically obtain the access differentiation to efficiently re-broadcast the received message, in distributed way. In addition, the authors of [10] propose a distributed scheme to allow vehicles to estimate the transmitting ranges on-the-flight. Another example of contention-based MAC protocols can be found in [12], where each vehicle adjusts its contention window (CW) based on the estimated contention of the network. The authors of [13] investigate the performance of the IEEE 802.11e Enhanced Distributed Channel Access [26] (EDCA) MAC scheme to support the propagation of alert messages in a VANET. In [13], each vehicle receiving an alert message is mapped on a different Traffic Class (TC) [26], depending on its distance from the source node. In other solutions, the multi-hop broadcast management is implemented at the application level, so that the IEEE 802.11 protocol stack of off-the-shelf devices is not modified. For example, the optimized dissemination alarm messages (ODAM) protocol [16] uses defer timers at application layer to select the next relying vehicle.

Deterministic broadcast protocols enable information propagation of alert messages in a VANET when a clustering infrastructure has been created by the vehicles [8,17,18]. The directional information propagation protocol (DPP) [18] is composed of four main components: a cluster formation and maintenance protocol, a custody transfer protocol, an inter-cluster routing protocol, and an intra-cluster routing protocol. The clustering algorithm selects a cluster-head and trailer-nodes located at the front/rear of each cluster of vehicles. The cluster head is responsible for propagating the alert messages, by communicating with the trailer vehicles of other clusters. Reliability is implemented by using acknowledged transmissions. On the other hand, cluster creation and maintenance are not explored in [18]. In [17], the authors compare the performance of four clustering algorithms in a vehicular environment, focusing on the leader election process. Although several clustering schemes have been proposed for Mobile Ad Hoc Networks (MANETs) [20], much research effort should be done to design efficient clustering schemes for VANETs.

3. System Model and Assumptions

In this work we consider the information propagation in a multi-lanes highway scenario, with vehicles travelling in both directions. The model parameters will be defined in Section 5. We assume that vehicles are equipped with sensing, wireless communication, computation and storage capabilities. IEEE 802.11 devices are considered the target wireless technology. Vehicles obtain data provided by on-board sensors (acceleration and speed) and by GPS devices (location). When a vehicle notices a critical condition on the road, it broadcasts an alarm message to inform the other vehicles in the Risk Zone (RZ). In general, the content of a message is application-dependent. We assume that each alert message contains: *i)* a *direction of propagation* (in our model, without loss of generality, we assume backward message propagation with respect to the vehicle flow direction), *ii)* a *time-to-live* (TTL) limiting the temporal validity of the message and *iii)* a *risk zone* (RZ) limiting the space horizon of the message. Only nodes in the risk zone are allowed to relay the message.

4. Cross-Layered Protocol Scheme

In a MANET, the cross-layer design of protocols enables the information exchange between protocol layers in order to have an enlarged vision of the communication [19]. As a result, joint decisions may be taken by protocols belonging to adjacent network layers [19]. In [20], we investigated the mutual support between MAC and clustering schemes in a MANET. In this paper, we show the effectiveness of the mutual support between customized clustering and MAC protocols for the real-time dissemination of broadcast messages in a VANET, extending the work presented in [25].

4.1 *Clustering scheme*

A clustering structure supporting the information dissemination of alert messages in a VANET is claimed to provide the following issues:

- *Backbone stability:* a minimum expected connectivity-duration threshold is required for a node to become part of the backbone;
- *Fairly high nodes distance*: relaying nodes needs to be as much distant as possible to achieve hop reduction;
- *Management overhead:* the backbone creation should be distributed and based on light communication. The overhead increase due to vehicle mobility and backbone disruption should be under the control of parameters, such as the periodicity of the backbone refresh procedures.

A backbone structure is not required to be monolithic. Indeed, the backbone might be composed by multiple non-overlapping chains of interconnected backbone vehicles. Each vehicle device has a unique ID (as an example, the MAC address could be used). Each chain member has at most two neighbours (i.e. previous and next hop, *prev_hop, next_hop*) and a sequence number (*chain_sequence*), defined as the vehicle hop-count in the chain itself. For example, the header vehicle of a chain will have a *chain_sequence* value equal to 1. When the backbone creation starts, we assume *prev_hop*=*next_hop*=*chain_sequence*=0. Under a clustering viewpoint, a vehicle can be in two *states*: normal vehicle (NV) or backbone member (BM).

Each backbone member has a backbone-record (BR) information with the following structure:

$$<ID, state, prev\_hop, next\_hop, chain\_sequence> \tag{4.1}$$

4.1.1 Backbone Creation

The backbone creation process starts whenever a vehicle misses to receive a backbone beacon for a time interval *RfrTim* (defined in the following). In this case, the vehicle elects itself as a backbone member, and it broadcasts a BEACON message. The BEACON message has the effect to propagate the impulse of the backbone creation process. Vehicles receiving the BEACON message and travelling in the same direction of the sender vehicle are potential next-hop candidates of the backward backbone creation process. A contention phase is performed to select the candidate that is expected to *(i)* stay connected with the sender node for at least a minimum threshold duration (*BB_REFR*), and *(ii)* be the farthest node from the sender node after a *BB_REFR* interval. When the next-hop candidate is found, the backbone creation process is propagated backward.

Without loss of generality, we assume vehicle B is following vehicle A. Under the assumption that vehicle A does not receive a BACKBONE message for a time interval *RfrTim*, the backbone creation procedure works as follows:

1. Vehicle A changes its state to BM and broadcasts a BEACON message, containing the following sender's information:

$$<ID, (x,y), R, speed, dir, horizon> \tag{4.2}$$

where *ID* is the unique sender identifier, *(x,y)* are the GPS coordinates, *R* is the transmitting range, *speed* is the average speed, *dir* is the direction of the vehicle, and *horizon* is the space limit of the risk zone, respectively.

2. Vehicle B computes the *Residual Time* RT(A,B) of the connection between the vehicles {A,B}, where RT(A,B) is defined as follows:

$$RT(A,B) = \frac{[\max(0, sign(\Delta v)] \cdot R - dist(A,B)}{\Delta v} \tag{4.3}$$

where R is the transmission range of the sender vehicle, v_A and v_B are the average speed of vehicles A and B, *dist(A,B)* is the current estimated distance, $\Delta v = v_B . v_A$ is the relative speed between nodes B and A and *sign()* is the function returning +1 if Δv is positive (that is, the distance between B and A increases) and -1 otherwise. Basically, the *Residual Time* between the nodes A and B indicates the time during which A will remain in the transmitting range of B without overtaking it.

3. If *RT(A,B)* < *BB_REFR*, then vehicle B is expected to move out of the range of vehicle A within the next BB_REFR interval. In this case, vehicle B is not a good candidate to be the next-hop of the backbone node A. For this reason, vehicle B discards the BEACON message and quits the procedure.
4. If *RT(A,B)* > *BB_REFR*, then the connectivity between A and B can be preserved within the next BB_REFR interval. In this case, vehicle B enters the contention phase (steps 5-7).
5. Vehicle B computes the *Fit Factor (FF)* as a ranking metric to become the next backbone-hop of node A. FF(B) is defined as follows:

$$FF(B) = \frac{dist(A,B) + \Delta v \cdot BB\_REFR}{R} \tag{4.4}$$

where $\Delta v = v_B - v_A$ is the relative average speed of node A with respect to backbone-node B, *dist(A,B)* is the current estimated distance and *R* is the transmission range of B. Namely, the FF is an estimation of the residual distance among vehicle B and backbone-vehicle A after a BB_REFR interval. Based on the current value of FF(B), vehicle B starts a *Defer Timer DF(B)*, defined as follows:

$$DF(B) = (1 - FF(B)) \cdot (DFMAX - DF\min) + DF\min \tag{4.5}$$

where *DFMAX* and *DFmin* are the maximum and the minimum values of the Defer Timer, respectively. When the Defer Timer DF(B) expires, vehicle B sends a CANDIDATURE message to node A.

6. When the backbone member A receives a CANDIDATURE message from candidate vehicle B, it checks the *next_hop* field in its backbone record (BR). If the *next_hop* field is zero, vehicle A sets the *next_hop* to B and sends a ACK_WINNER message to node B. If node A has already replied to the CANDIDATURE message of another node, then the CANDIDATURE message coming from B is discarded. Step 7 is not executed in this case.

7. After receiving an ACK_WINNER message from vehicle A, vehicle B changes its own state to backbone member (BM), increases the *chain_sequence* value and broadcasts a BEACON message in order to propagate the backbone creation process.

Steps 2-7 implement a distributed contention algorithm to choose the next-hop backbone member of a backbone member A. Steps 2-4 exclude from the contention all the vehicles which can not guarantee a link connectivity with node A for a minimum threshold duration (*BB_REFR*). In Step 5, the remaining vehicles rank their "goodness" to become next-hop backbone of node A. The "goodness" is defined in terms of the Fit Factor parameter (step 5). The higher is the Fit Factor, the lower is the Defer Timer (Eq. 4.5) before sending the CANDIDATURE message, and the higher is the chance to win the contention. The three-phases handshake protocol BEACON-CANDIDATURE-ACK_WINNER (steps 6-7) allows to select one single next-hop backbone member for extending the backbone. To reduce the network overhead, we assume all the vehicles perform carrier sensing while deferring the transmission of the CANDIDATURE message. If, while deferring, a vehicle C detects an early CANDIDATURE message from another vehicle A towards backbone-node B, than vehicle C aborts its candidature and remains in the NV state.

Since the backbone creation process may be initiated asynchronously by multiple vehicles, many virtual sub-chains may be created in the highway scenario. Virtual chains may remain disjoint or may be interconnected when a backbone member B with a backbone *chain_sequence* equal to 1 (that is, B is the header node of a sub-chain) receives a BEACON request from a front-head vehicle A (that is, the trailer node B of a sub-chain). In this case, vehicle B sends a CANDIDATURE message to A immediately after a *DFmin*, thus trying to realize the concatenation of two adjacent backbone sub-chains.

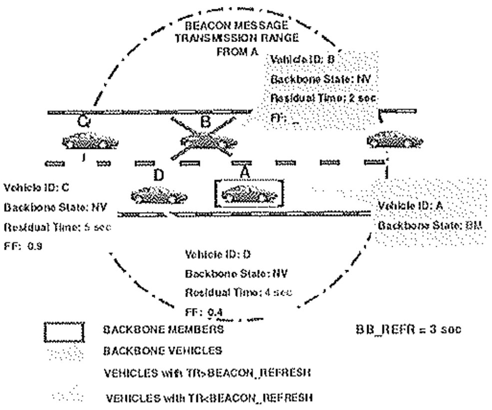

Fig. 3 Residual Time (RT) and Fit Factor (FF).

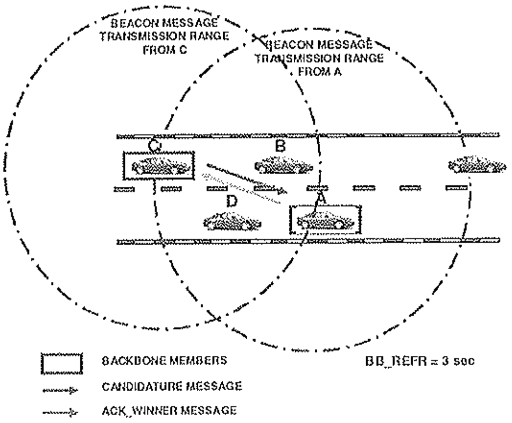

Fig. 4 BEACON-CANDIDATURE-ACK_WINNER Handshake.

Figures 3 and 4 show the process of the backbone creation after that vehicle A has broadcast a BEACON message. Vehicles C, D are potential next-hop candidates of the backward backbone creation (Fig. 3) while vehicle B will be excluded by backbone participation because it is overtaking vehicle A (to provide a numerical example, RT(A,B)=2, *BB_REFR*=3, that is, RT(A,B) < *BB_REFR*). Then, vehicle C and D compute the FF and start the DT (in the example, FF(C)=0.9, DF(C)=0.05s, FF(D)=0.4, DF(D)=0.25s). Vehicle C has the highest FF, thus it is the first to send the CANDIDATURE message to node A. Then node A replies with an ACK_MESSAGE to node C (Fig. 4). The 2-hop backbone (A-C) is now built. The backbone creation process is repeated recursively when vehicle C broadcasts the BEACON message to his neighbouring nodes (Fig. 4).

4.1.2 Backbone Maintenance

The high vehicles' mobility in a VANET may produce frequent changes in the backbone topology. For this reason: *(i)* links among vehicles of the backbone may be broken and *(ii)* the value of local connectivity factors (Residual Time) and node distance (Fit Factor) among backbone members may dynamically vary. A reactive scheme for repairing the backbone breakages would need break-detection capability and overheads, and would probably result in fragile patched backbones. To cope with these issues, our mechanism proactively refreshes the backbone, under the control of a *refresh timer*. To limit the number of vehicles re-starting the process of backbone-refresh, and to exploit the memory-effect of already existing backbone sub-chains, each backbone member (BM) maintains a refresh timer (*RfrTim*) which is a multiple of the BACKBONE_REFRESH parameter, and it is defined as:

$$RfrTim = (chain\_sequence \; \% \; Max\_chain\_size) \cdot BB\_REFR \qquad (4.6)$$

The effect of the formula above is to randomize the distribution of backbone creation/refresh events, by increasing the frequency of refreshes coming from vehicles ahead to the existing chains. This has the effect of reducing the occurrence of synchronous backbone creation processes activated by neighbouring vehicles.

4.2 MAC Layer Support

At the MAC Layer, we propose a cross-layered forwarding scheme that *(i)* exploits the presence of a backbone structure in the VANET, *(ii)* favors the fast propagation of multi-hop broadcast messages, and *(iii)* dynamically adapts to network load and cluster variations. For these reasons, we called such scheme Dynamic Backbone Assisted MAC (DBA-MAC). The DBA-MAC protocol provides differentiated channel access reflecting the vehicle role ({BM,NV}) defined in the backbone creation algorithm.

Backbone members (BM) have higher priority in accessing the channel and relaying the broadcast messages. This is supported by the MAC scheme called *Fast Multi-Hop Forwarding (FMF)*. Moreover, we introduce a recovery scheme which allows to forward the alert message when the backbone assisted FMF fails. In the recovery scheme, all the vehicles receiving the message contend for relaying it. For this reason, we called this scheme *Contention-Based Forwarding (CBF)*. To distinguish between CBF and FMF schemes, we introduced an additional bit in the header of each broadcast message, named

Contention Flag (CF). When a node receives a broadcast message, it reacts following the FMF scheme or the CBF scheme according to the current role of the vehicle ({BM,NV}) and the current value of the CF bit. We describe both FMF and CBF schemes in Sections 4.2.1 and 4.2.2, respectively. The complete algorithm of the DBA-MAC scheme is illustrated in Figure 5.

4.2.1 Fast Multi-Hop Forwarding (FMF) Scheme

The FMF scheme is implemented by backbone members (BMs) only. Let BM_i and BM_{i+1} be the backbone members with *sequence_id* equal to i and $i+1$, respectively. When BM_i receives an alert message from a vehicle S, the following steps are executed:

1. Vehicle BM_i sets CF to 1 and checks if the *next_hop* field is set in its backbone record (BR). In this case, it broadcasts the message toward vehicle BM_{i+1}. If the *next_hop* field is unset (i.e, equal to 0), then it goes to step 5;
2. After a SIFS, vehicle BM_{i+1} sends back an acknowledgment (ACK) toward vehicle BM_i ;
3. After a SIFS, vehicle BM_{i+1} immediately broadcasts the message toward vehicle BM_{i+2} (if any) without releasing the channel;
4. All the normal vehicles (NVs) receiving the broadcast message from vehicle BM_i process the message content (i.e. the safety information) but do not forward the message;
5. If vehicle BM_i does not receive the ACK after a SIFS or if *next_hop* is unset, then it sets CF to 0 and broadcasts the message. The CMF scheme is used in this case: all the vehicles receiving the broadcast message will enter the contention phase to decide the next relaying node, as explained in Section 4.2.2.

With the FMF approach, we achieve two important goals:

- *enhanced reliability:* all the backbone-assisted broadcast transmissions are acknowledged (only if messages are carried by BMs) as in the unicast IEEE 802.11 DCF protocol definition. The re-transmission will be forwarded with the help of normal vehicles (if any).
- *fast multi-hop forwarding (FMF):* as long as backbone members (BMs) receive a message, they forward it immediately after a SIFS. As a result, the medium control is inherited and propagated over pre-defined multi-hop IEEE 802.11 nodes, without introducing backoff delays, as long as the multi-hop backbone is connected and no collisions occur.

4.2.2 Contention-Based Forwarding (CBF) Scheme

The CBF scheme is used when a vehicle K receives a broadcast message form a node S with the CF bit set to 0, i.e. when the sender node is a normal vehicle (NV) or when the sender node is a backbone member (BM) performing the second attempt (Section 4.2.1, step 5). In this case, all the vehicles receiving the broadcast message are responsible for relaying the message. Let us assume vehicle K receives a broadcast message from node S. In this case vehicle K adjusts its MAC contention window (CW) [7] based on its backbone role ({BM,NV}), as follows:

$$CW(K) = \begin{cases} (1 - \frac{dist(K,S)}{R}) \cdot (CWMAX - CW\min) + CW\min & if\ role\ is\ BM \\ 4 \quad if\ role\ is\ NV \end{cases} \tag{4.7}$$

where dist(K,S) is the estimated distance between K and S, R is the transmitting range and *CWMAX*, *CWmin* are the maximum and minimum values of the contention window at MAC layer, respectively [7]. In the CBF scheme, each vehicle implements the standard IEEE MAC 802.11 DCF [7] backoff scheme and broadcasts the message. If the vehicle K is a backbone member (BM), the CW is initiated to a low value (4). In this way, a BM vehicle receiving the message gets higher priority to re-broadcast the message and to restart the FMF procedure, by riding the multi-hop backbone of vehicles. If the vehicle K is a normal vehicle (NV), the size of the contention window is inversely proportional to the distance from the sender node, like in [10]. In the worst case, the MAC-CBF scheme works like the scheme described in [10], by performing long-range broadcasts via a biased backoff scheme. A simple cancellation mechanism is introduced to limit the effect of broadcast storms: if one vehicle senses the transmission of its own alert message (with the same sequence number) from another vehicle ahead in the propagation direction, then the backoff procedure is aborted and the packet discarded.

5. Performance Evaluation

In this section, we evaluate the performance of the proposed DBA-MAC scheme under different vehicles' density, network loads and mobility factors. We consider an highway scenario of 8 Km with three uni-directional lanes. In our target application, a subset of vehicles broadcasts one alert message per second. Each alert message has a Risk Zone (horizon) spanning a distance of 1 Km. Each vehicle is assumed to be equipped with a 802.11-compliant device, with a transmission range of 240 meters.

The tool used is the ns-2 simulator [21] with the extension provided by [22] to produce realistic mobility traces of highway scenarios. The simulations parameters are shown in Table 1. Each simulation has been repeated enough times to get sizes of the 90% confidence interval always below 5% of the average values (confidence intervals not shown in the figures). We consider three different tests:

- *Vehicle Test* (Section 5.1): we vary the vehicle density (from 200 up to 600) while keeping a constant network load, i.e. considering the same number of sender vehicles in all the scenarios.
- *Load Test* (Section 5.2): we investigated the effect of the increased message-load, by varying the percentage of vehicles generating the alert messages (from 10% up to 30%).
- *Mobility Test* (Section 5.3), we evaluate the impact of the mobility factor (from 20 m/s to 40 m/s) on the protocols' performance.

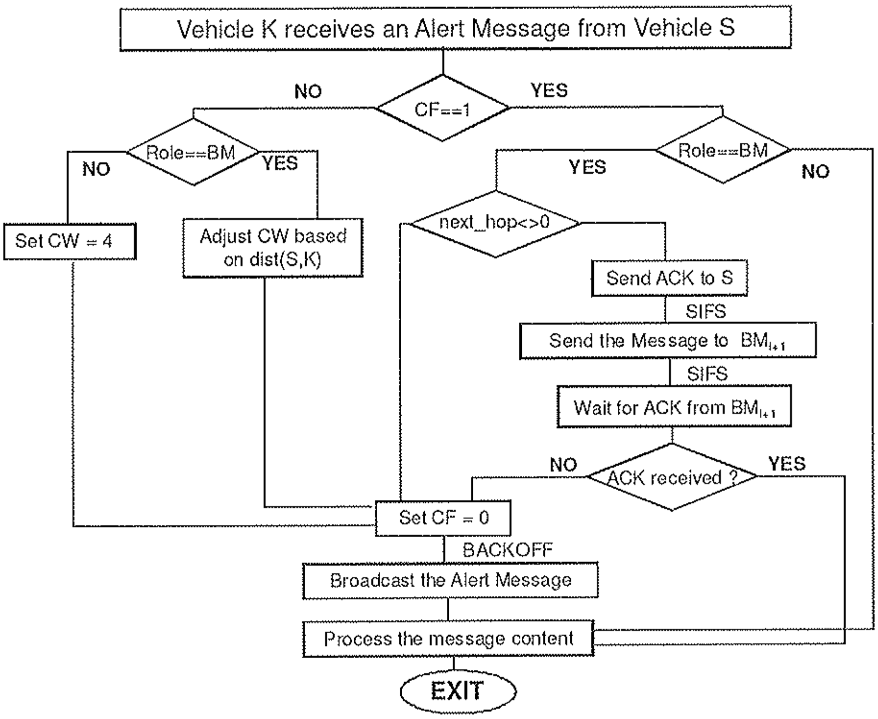

Fig. 5: flow chart of the Fast Multi-Hop Forwarding (FMF) and Contention-Basic Forwarding (CBF) schemes.

Table 1: Simulation Parameters.

Simulated Area	8 Km (3-lane highway)
Vehicles speed (max)	{20,30,40} m/s
Vehicles density	200, 400, 600 vehicles
Transmitting range	240 m
Message size	100 Byte
Message Risk Zone	1 km (horizon)
Percentage of alert generating vehicles	5%, 25%, 50% (1 alert per second)
Backbone Refresh Interval (BB_REFR)	5 sec

In the simulations, we compare the proposed DBA-MAC scheme with three similar protocols. As a basic case, we consider a flooding protocol based on the MAC 802.11 DCF: each vehicle receiving an alert message rebroadcasts it after a backoff delay. The second protocol evaluated is the Fast Broadcast MAC scheme [10]. Indeed, our DBA-MAC scheme can be considered an extension of the Fast Broadcast protocol [10]. In the DBA-MAC protocol, when the backbone fails to propagate the message, the Contention-Based Forwarding (CBF) scheme is used (Section 4.2.2). In such scheme, each vehicle dynamically adjusts its contention window based on the distance from the sender vehicle, using the same approach proposed in [10]. For this reason, the Fast Broadcast protocol can be considered the worst case behavior of our DBA-MAC scheme (when the backbone fails). As the ideal reference scenario, we consider a static backbone (like a roadside infrastructure system), composed by nodes placed at the maximum distance preserving the connectivity (240 m in our simulations). Thus, the static backbone results in a MCDS for this scenario. We call this scheme Static Backbone-Assisted MAC (SBA-MAC), to emphasize the difference with our solution (DBA-MAC) where the backbone is dynamically established in the VANET. However, both Static- and Dynamic-Assisted MAC use the MAC forwarding scheme described in Sec. 4.2.

In the performance analysis, we focus on parameters that may produce a direct impact on the communication performance, such as the delivery ratio and the average delay. In particular, we consider the following metrics: the total (average) number of retransmissions experienced by an alert message to span the risk zone (RZ), the percentage of collisions at the MAC layer, the delivery ratio among the vehicles in the risk zone (RZ), the average end-to-end delay and the percentiles of the end-to-end delay. Moreover, we investigated the overhead required for the backbone creation/maintenance and its impact on the system performance in the Mobility Test (Sec. 5.3)

5.1 Vehicle Test

In the Vehicle Test, the number of vehicles in the highway scenario varies from 200 up to 600, while the network load is constant, i.e. 80 vehicles produce an alert message every second. The mobility factor varies between 20 m/s and 30 m/s.

Fig. 6 shows the average number of retransmissions needed by an alert message to cover the horizon of the risk zone (1 km), as a function of the vehicle density. As expected, the basic 802.11-based flooding protocol requires the highest number of retransmissions to propagate the message, in all the considered scenarios: this effect is emphasized when the vehicle density increases. The average number of flooding retransmissions in the scenario with 600 vehicles is more than two times the optimal value (roughly defined as

1000m/240m = 5 hops). On the opposite side, both the backbone-assisted MAC schemes (DBA-MAC, SBA-MAC) are only partially affected by the increased vehicles' density. When the SBA-MAC is used, the alert message is often relayed by the backbone member (BM) vehicles, whose hop distance is the maximum transmission range (by construction, under our modeling choice). The performance obtained by the SBA-MAC is close to the theoretical value 5, and it obviously outperforms all other schemes since it constitutes the ideal reference scenario. Figure 6 highlights also that the performance results of our DBA-MAC scheme are only lightly worst than the static backbone results. Moreover, the performance results of the proposed DBA-MAC outperform the performance of the Fast Broadcast protocol, which is not backbone-assisted. This is due to the effect of the FMF scheme, which decreases the impact of contention during the multi-hop backbone message propagation.

Figure 7 shows the average percentage of collisions obtained at the MAC layer in the VANET, with respect to the total amount of message transmissions performed. The 802.11-based flooding scheme produces a significant 10% up to 30% collision risk, as a function of the vehicle density (that is, the MAC access contention level). The collision probability is reduced by the Fast Broadcast MAC protocol thanks to the priority-based effect of the biased backoff scheme, and it is drastically reduced when the DBA-MAC or SBA-MAC schemes are used, thanks to the reduction of contention-based accesses over the multi-hop backbones. The reduction of MAC collisions produces higher packet delivery ratio (Fig. 8) among the vehicles in the Risk Zone for both the SBA-MAC and DBA-MAC protocols.

Figure 9 shows the average end-to-end delay experienced by alert messages to cover a variable distance (x-axis, variable between 100m and 1000m) in a low-density scenario (200 vehicles over 8 km). The DBA-MAC falls in the range between the Static Backbone Assisted MAC and the 802.11-based flooding scheme. Surprisingly, the Fast Broadcast MAC protocol produces average delay worst than the flooding protocol. This problem is caused by the settings of the contention window. In the 802.11 DCF MAC protocol, the contention window size is equal to the minimum value (*CWmin*) for all the broadcast transmissions [7]. Given the low vehicle density, most flooding transmissions are successful. In the Fast Broadcast protocol, the contention window is dynamically managed, resulting equal to *CWMin* only for forwarding nodes located at the maximum transmission distance from the sender. Hence, in a low density scenario, it may frequently happen that the (farthest) forwarding vehicle uses a contention window higher than *CWMin*, for each hop, resulting in higher end-to-end delay than the 802.11-based flooding scheme. Fig. 10 shows the average end-to-end delay in a high-density scenario (600 vehicles over 8 km). The vehicle density has no effect on the backbone-assisted schemes, thus the performance results of the DBA-MAC and SBA-MAC schemes are the same of Fig. 9. Both 802.11 and Fast Broadcast MAC protocols show higher delays.

However, the Fast Broadcast MAC scheme has now better performance than the 802.11-based flooding scheme, due to the increased vehicles' density. In fact, in the high-density scenario (600 vehicles), farthest vehicles more likely exist near the transmission range border. As a result, forwarding vehicles using the Fast Broadcast scheme set their contention window (CW) close to the *CWMin* value [7]. Fig. 11 shows the MAC Delay Percentiles in the low density scenario (200 vehicles), considering the end-to-end delay of messages covering the risk zone (RZ). The distribution of delays shows small differences among the considered schemes, together with a different reliability testified by the asymptotic values of the distribution, which could be interpreted as the probability of message arrival.

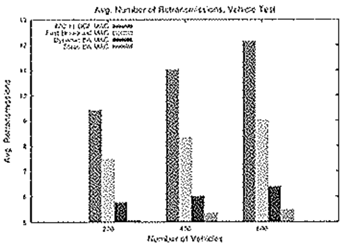

Fig. 6 Vehicle Test: Avg Retransmissions.

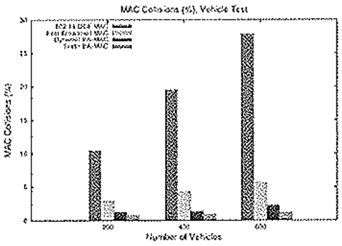

Fig. 7 Vehicle Test: Avg. % MAC Collisions.

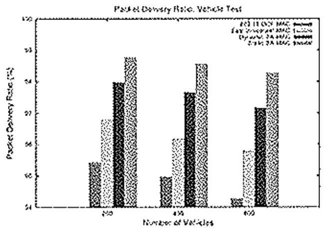

Fig. 8 Vehicle Test: Packet Delivery Ratio.

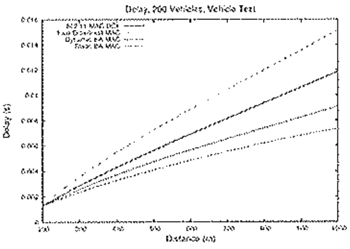

Fig. 9 Vehicle Test: End-to-End Delay, 200 Vehicles.

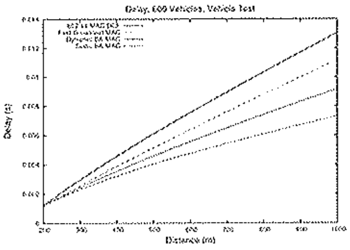

Fig. 10 Vehicle Test: End-to-End Delay, 600 Vehicles.

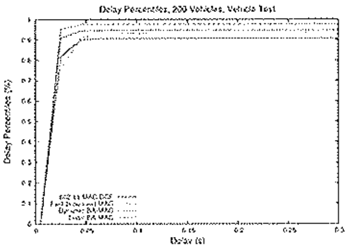

Fig. 11 Vehicle Test: MAC Delay Percentiles, 200 Vehicles.

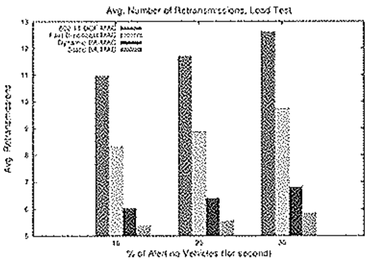

Fig. 12 Load Test: Avg Retransmissions.

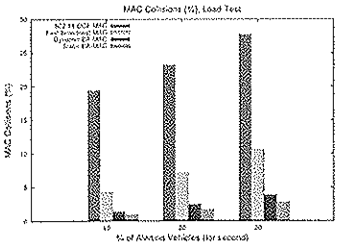

Fig. 13 Load Test: Avg. % MAC Collisions.

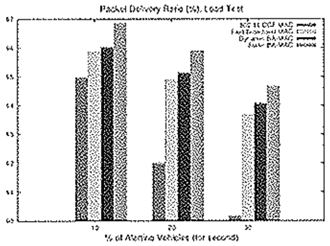

Fig. 14 Load Test: Packet Delivery Ratio.

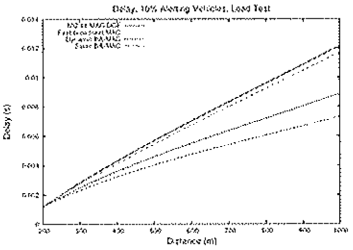

Fig. 15 Load Test: End-to-End Delay, 10% tx Vehicles.

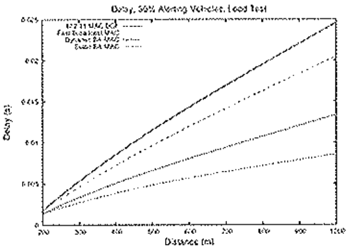

Fig. 16 Load Test: End-to-End Delay, 30% tx Vehicles.

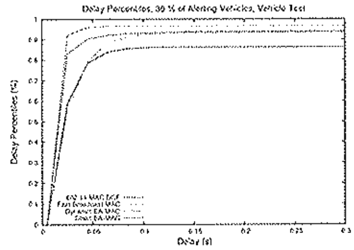

Fig. 17 Load Test: MAC Delay Percentiles, 30 tx% Vehicles.

5.2 Load Test

In the Load Test, we vary the network load by modifying the percentage of vehicles producing an alert message every second (from 10% to 30% of the overall number of nodes), while the number of vehicles is constant and equal to 400 in all the considered scenarios. As in the previous case, the mobility factor varies between 20 m/s and 30 m/s.

Figure 12 shows the average number of retransmissions needed by an alert message to cover the risk zone (RZ), as a function of the network load. In the Fast Broadcast and 802.11-based flooding schemes, the average number of retransmissions increases with the network load due to the impact of MAC collisions and hidden terminal effects. Also, the performance results of the backbone-assisted SBA-MAC and DBA-MAC schemes are affected by the increased load. This is due to the effect of the collisions between transmissions of backbone members (BMs) using the FMF forwarding scheme (Section 5.2.1) , so that the (background) CBF forwarding scheme is used more frequently (Section 5.2.2). However, even in the highest saturated scenario (i.e. 30% transmitting vehicles per second), the DBA-MAC scheme enhances the 802.11-based flooding and the

Fast Broadcast protocols, while it is close to the performance of the SBA-MAC reference scheme.

Figure 13 confirms such analysis, by showing the average percentage of collisions experimented at the MAC Layer. The 802.11-flooding approach produces a significant 20% up to 30% collision risk, as a function of the MAC access contention level. The collisions are drastically reduced when the DBA-MAC or SBA-MAC scheme are used. Moreover, Fig. 13 reveals that the overhead caused by the backbone creation and maintenance procedures in the DBA-MAC protocol has no impact on the forwarding of alert message, as shown by the low number of MAC collisions experienced by the DBA-MAC scheme. By reducing the number of re-transmissions and limiting the effect of MAC contention, the proposed DBA-MAC scheme provides higher packet delivery than the 802.11-flooding and the Fast Broadcast protocols, as shown in Fig. 14.

Figures 15 and 16 show the performance of the four protocols in terms of end-to-end delay, in a low-load scenario (i.e. 10% transmitting vehicles/second, Fig. 15) and high load scenario (i.e. 30% transmitting vehicles/second, Fig. 16), respectively. The effect of the increased message-load translates in higher end-to-end delay for all the protocols. However, the performance results of the DBA-MAC scheme are close to the performance of the SBA-MAC scheme, and still outperform the 802.11-based flooding and the Fast Broadcast schemes, in both the configurations considered (Figs. 15 and 16). Figure 17 completes the delay analysis, by showing the MAC Delay Percentiles in the high-load scenario (i.e. 30% transmitting vehicles/second). In Fig. 17, the most relevant effect is the different slope of the curves, which demonstrates the "resistance" of the system to message forwarding. As expected, the flooding approach produces the worst performance. Both Fast Broadcast and DBA-MAC protocols deliver an high percentage of messages (90%). However, the backbone assisted schemes (SBA-MAC, DBA-MAC) outperform the Fast Broadcast protocol in terms of delay bound (Fig. 17).

5.3 Mobility Test

In this section, we evaluate the impact of the vehicles' mobility on the protocols' performance. In particular, we vary the maximum speed (v_{MAX}) from 20 m/s up to 40 m/s, while the minimum speed (v_{min}) is equal to 15 m/s. We consider a scenario with 400 vehicles, where 80 vehicles produce an alert message per second.

Figure 18 shows the average number of retransmissions needed by an alert message to cover the risk zone (RZ), as a function of the maximum vehicles' speed. The performance of the 802.11-based flooding protocol and Fast Broadcast protocols are not affected by the vehicles' speed, because they do not make any assumptions about the mobility factor in the VANET. In the same way, the SBA-MAC protocol experiences the same number of retransmissions with different values of vehicles' speed (20 m/s, 30 m/s, 40 m/s), because of the presence of the static backbone, composed by static nodes. Also, the DBA-MAC protocol does not make any assumption about the maximum vehicles' speed. However, the performance of the DBA-MAC scheme may be affected by the *range of speed* (Δv), defined as the difference between the maximum and minimum speed (i.e. $\Delta v = v_{MAX} - v_{min}$), for the reasons explained below:

- The larger is the *range of speed* (Δv), the higher is the probability that the backbone propagation fails because a backbone member BM_i moves out of range of backone member BM_{i+1}, or viceversa.
- The larger is the *range of speed* (Δv), the lower is the probability to find the next-hop of a backbone member BM_i during the backbone creation process, because none of the vehicles receiving the BEACON from BM_i (e.g. vehicle K) can guarantee that the link connectivity between vehicle BM_i and vehicle K will last more than a BB_REFR interval (i.e. $RT(BM_i,K) < BB\_REFR$, according to equation 4.3).

As a consequence, the average number of retransmissions produced by the our DBA-MAC protocol increases with the maximum vehicles' speed (the minimum speed is constant in all the scenarios). However, such increase is very low, so that the performance results of our DBA-MAC scheme are still between the SBA-MAC scheme and the Fast Broadcast MAC scheme. The same considerations can be done for Fig. 19, which shows the average percentage of MAC collisions obtained by the MAC layer.

Fig. 18 Mobility Test: Avg Retransmissions.

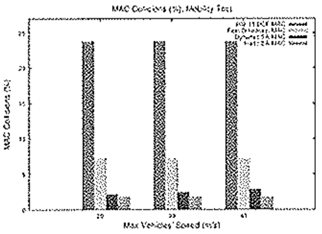

Fig. 19 Mobility Test: Avg. MAC Collisions (%).

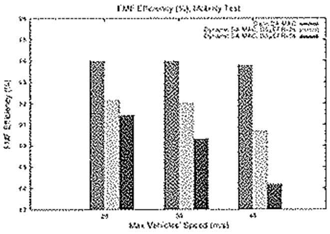

Fig. 20 Mobility Test: FMF Efficiency.

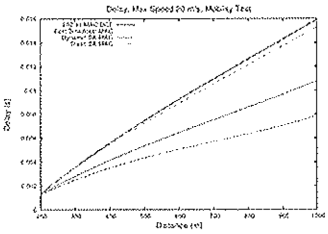

Fig. 21 Mobility Test: End-to-End Delay, Max Speed 20m/s.

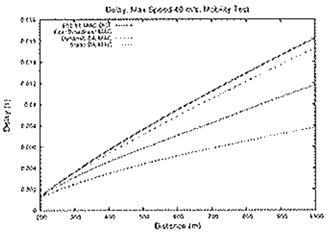

Fig. 22 Mobility Test: End-to-End Delay, Max Speed 40m/s.

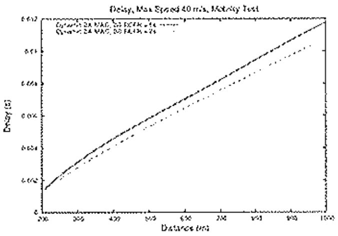

Fig. 23 Mobility Test: End-to-End Delay, Varying BB_REFR interval.

Figures 21 and 22 show the average end-to-delay experienced by an alert-message to cover a variable distance (x) in a low-mobility scenario (Fig. 21) and high-mobility scenario (Fig. 22), respectively. By the comparison between Fig. 21 and Fig. 22, we can see that the performance results of the 802.11-based flooding, Fast Broadcast and SBA-MAC protocols are not affected by the mobility factor increase. The end-to-end delay of the DBA-MAC protocol increases in the high-mobility scenario (Fig. 21). In this case, more link breakages occur in the dynamic backbone, causing the failure of the FMF propagation scheme and involving message-retransmissions performed by the CBF propagation scheme (Section 5.2). However, the DBA-MAC scheme still outperforms the performance of the Fast-Broadcast and 802.11-based flooding schemes.

We conclude the Mobility Test by investigating the tradeoff between the overhead for backbone creation and maintenance and the effectiveness of DBA-MAC protocol in providing fast multi-hop propagation of alert messages, as a function of the vehicles' speed in the VANET. Figure 20 shows the *Fast MultiHop Forwarding (FMF) Efficiency* metric for the backbone-assisted MAC protocols (SBA-MAC and DBA-MAC). The FMF Efficiency is defined as the probability that an alert message will be re-transmitted by a backbone member (BM) using the FMF propagation scheme, rather than by a normal vehicle (NV) using the CBF propagation scheme. Basically, the FMF Efficiency gives an estimation of the amount of time the backbone is working and actively supporting the alert messages propagation. Figure 20 shows the FMF Efficiency of the reference SBA-MAC scheme, and of the DBA-MAC scheme with two different values of the parameter BB_REFR, which governs the frequency of backbone refresh (Section 4.1.1). In the configuration with BB_REFR=2s, the backbone maintenance procedure (Section 4.1.2) is performed every 2 seconds. In the configuration with BB_REFR=5s, the backbone maintenance procedure is performed every 5 seconds. Both the SBA-MAC and DBA-MAC schemes do not reach the maximum efficiency (100%) due to the effects of MAC collisions and hidden terminal problems. The FMF Efficiency of the SBA-MAC scheme is not affected by the mobility factor, as expected, since the backbone members (BMs) are static for construction. When the mobility factor increases, the FMF Efficiency of the DBA-MAC protocol (slightly) decreases, due to the link breakages occurring between consecutive backbone members (BMs) of the dynamic backbone. However, such effect can be under the control of the BB_REFR parameter. Reducing the interval of the backbone creation/maintenance (BB_REFR=2) also reduces the risk of link breakages caused by vehicles' mobility, and enhances the FMF efficiency metric (Fig. 20) as well as the end-to-delay (Fig. 23).

Clearly, lower BB_REFR values result in higher overhead for backbone creation and maintenance. However, we can show that such overhead is moderate compared to the message-load. In Table 2, we show the *message-load*, computed as the amount of bits/second sent by each vehicle for the propagation of alert messages, compared to the *backbone-load*, computed as the amount of bits/second sent by each vehicle for the backbone creation/maintenance. All the data refer to a configuration with high vehicles' speed (40 m/s). As shown in Table 2, the backbone-load is just 7.7 % of the message-load even in the configuration with high frequency of backbone refresh (BB_REFR=2).

Table 2. Message vs Backbone Load, Max Vehicles' Speed = 40 m/s.

Protocol	**Message Load (b/s)**	**Backbone Load (b/s)**	**Overhead (%)**
DBA-MAC, BB_REFR=2sec	14432.23	1117.02	7.7%
DBA-MAC, BB_REFR=5sec	15357.43	502.628	3.3%

6. Conclusions

In this paper, we have illustrated the design and analysis of a cross-layered scheme for the efficient broadcast of alert messages in VANETs. Our cross-layered solution is composed by a proactive clustering scheme and a 802.11-based MAC protocol. The clustering algorithm creates a dynamic virtual backbone of vehicles inside the VANET, in a distributed way. The vehicles which are members of the backbone are responsible for implementing an efficient message propagation. The proposed MAC scheme, called Dynamic Backbone-Assisted MAC scheme, exploits the existence of the backbone infrastructure, favoring the fast propagation of alert message by the nodes of the backbone. Moreover, we propose a background forwarding scheme that guarantees the message delivery when the backbone propagation fails. The proposed scheme is compliant with IEEE 802.11 DCF systems, under the MAC layer viewpoint. The performance of the DBA-MAC has been compared to other schemes, by showing general advantages in performance, reliability, and overhead reduction. Future works will include: the extension of the DBA-MAC protocol to urban scenarios, the investigation of multi-radio multi-channel MAC technologies to support the fast propagation of alert message in a VANET, the analytical modeling and validation of the proposed DBA-MAC protocol.

Acknowledgments

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