MAC for ad-hoc inter-vehicle network: services and performance

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Abstract— **In this paper we analyze the performance of ADHOC MAC, a new MAC protocol proposed within CarTALK200, a European research project with the purpose to design novel solutions for inter-vehicle communications. ADHOC MAC has been devised to provide a reliable single hop broadcast channel overcoming the hidden terminal problem, and an effective multi hop broadcast service by exploiting the connectivity information provided by the protocol.**

The simulation results presented in the paper prove the effectiveness of ADHOC MAC in terms of access delay to the shared resource and resource reuse when considering a single hop broadcast service. The efficiency of the multi-hop broadcast service is compared through simulation with flooding and with a centralized greedy heuristics that gives an upper bound to the performance. Results show that the distributed ADHOC-MAC multi-hop broadcast mechanism performs closely to the centralized greedy heuristics.

I. Introduction

CarTALK 2000 [1] is a three-years project which is funded within the IST Cluster of the 5th Framework Program of the European Commission. It aims at designing an Ad Hoc wireless network for inter-vehicle communications especially devoted to enhance driving safety. Main characteristics of such kind of networks are the large and variable number of mobile terminals, extremely dynamic network topology and stringent requirements related to broadcast alarm messages [2], [3]. Existing wireless LAN protocols don't seem to be well suited to these requirements, due to both physical and MAC layer limitations. As an example, the IEEE 802.11 [4] physical layer is not devised for high speed moving terminals, nor its MAC layer can guarantee a reliable multicast/broadcast service. In order to achieve a high degree of broadcast reliability one may resort to frequent retransmissions and flooding; however this practice has devastating effect on the achievable throughput, aggravated by the broadcast storm problem [5].

In this context, we have proposed ADHOC MAC, a completely distributed MAC architecture that has the potential to overcome the problems cited above and provide a reliable broadcast service [6], [7], [8]. ADHOC-MAC uses a Dynamic TDMA mechanism that can be easily adapted to the UMTS Terrestrial Radio Access Time Division Duplex (UTRA-TDD), that has been chosen as physical target system in the CarTALK 2000 project. It is able to provide prompt access, reliable channels and support for QoS. Dynamic TDMA is achieved by the Reliable R-ALOHA protocol (RR-ALOHA), a new distributed reservation protocol capable of dynamically establishing a reliable single-hop broadcast channel, the Basic Channel (BCH). Each BCH carries signalling information used to resolve the hidden and exposed terminal problems, and to provide a valuable basis for the efficient implementation of a network broadcast service.

In this paper we present some performance figures with respect to the throughput of the BCHs and the broadcast service. The paper is organized as follows. In Section II we briefly summarize the basics of the ADHOC MAC protocol. In Section III we present and comment the simulation results obtained. Concluding remarks are given in Section IV.

II. The ADHOC-MAC protocol

To easily describe the operation of ADHOC MAC we introduce the concept of One-Hop (OH) and Two-Hop (TH) clusters. Each terminal in a OH-cluster is directly connected to, i.e. within radio range of, all other terminals of the same OH-cluster, while terminals of different OH-clusters cannot directly communicate at the physical layer. More formally, referring to the graph representing the ad-hoc network, OH-clusters are maximum-cardinality sub-graphs where all nodes are connected to all the others (clique). Obviously, terminals can belong to more than one OH-cluster, leading to the case of non disjoint OH-clusters. The union of OH-clusters having a common subset is called Two-Hop (TH) cluster.

A. RR-ALOHA

The access mechanism of ADHOC-MAC can be classified as Dynamic TDMA, where channels are assigned to the terminals according to terminal needs. However, Dynamic TDMA still needs a protocol to coordinate inter-terminal transmissions. One protocol capable of achieving dynamic channel sharing is the well known Reservation ALOHA (R-ALOHA). In R-ALOHA [9] "trial and error" transmission is used to access an available slot, e.g., slot k in a frame of N slots. If the transmission is recognized as successful the slot is reserved for that terminal in subsequent frames, and cannot be accessed by other terminals until the channel is released. The correct operation of R-ALOHA requires a central repeater through which the terminals receive all the transmitted signals and, most importantly, get the same slot status information, e.g., busy, free, or collided.

In order to implement a Dynamic TDMA in a distributed way we devised a new protocol, named Reliable R-ALOHA (RR-ALOHA)[7], that allows the same R-ALOHA procedure to be applied to the ad-hoc environment. The basic idea is that each terminal periodically transmits the perceived status of slots in the preceding period (frame), called Frame Information (FI). This information can be elaborated to get a common slot status, as in R-ALOHA, and, in particular, is used by new terminals that reach the network to get access.

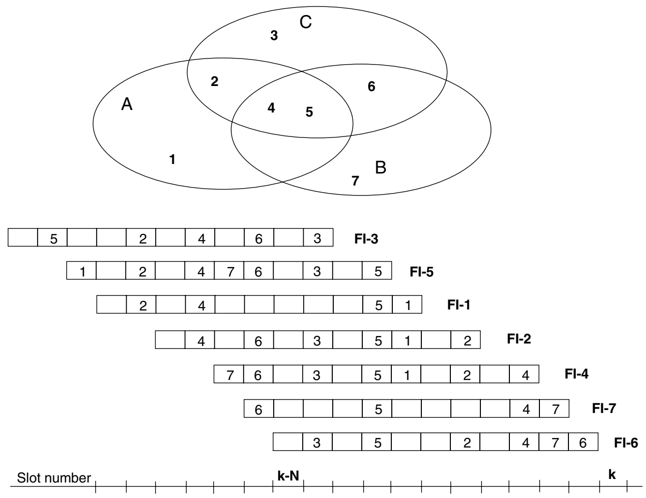

Fig. 1. *Example of the FI information propagated by the terminals 1-7 in the one-hop clusters A, B, and C represented by ellipses.*

In more detail, the FI is transmitted every N slots (frame) in slots that constitute the Basic Channel (BCH). The new terminals listen to the FI broadcast by active terminals in a frame and, in turn, acquire their BCH, in which they transmit their FI. The FI is a vector with N entries specifying the status of each of the preceding N slots as observed by the transmitting terminal itself. The slot status is marked as BUSY if a packet has been correctly received or transmitted by the station, otherwise it is FREE. In the case of a BUSY slot the FI also contains a short identifier of the transmitting terminal. Based on received FIs, each terminal marks each slot k as RESERVED if slot $(k-N)$ is coded as BUSY in at least one FI received in the slots from $(k-N)$ to $(k-1)$, or as AVAILABLE otherwise. Figure 1 reports an example of FIs transmitted by terminals of a TH-cluster.

As in R-ALOHA an available slot can be used for new access attempts. Upon accessing an AVAILBLE slot, terminal j will determine after N slots that its attempt is successful if the slot is coded as "BUSY by station j" in all of the received FIs; otherwise the transmission has failed. Note that the terminals belonging to the same OH-cluster see the same status (AVAILABLE or RESERVED) for all the slots; terminals belonging to different OH-clusters of the same TH-cluster mark as RESERVED all the slots used in the TH-cluster, while terminals belonging to disjoint OH-clusters usually see a different channel status.

As a result, slots can be reused in disjoint OH-clusters, but can not be reused in the same TH-cluster and, therefore, the hidden-terminal and exposed-terminal problems can not occur. For a wider discussion and a formal proof readers are referred to [7], [8].

The BCH gained by R-ALOHA can also be used to assure additional MAC services such as a fast and reliable single hop broadcast channel, and a signaling channel to dynamically reserve additional channels with the bandwidth and priority needed to fulfill any QoS requirement. Furthermore, the FI can be used to safely set up point-to-point channels ([7], [8]), and to implement an efficient muli-hop broadcast mechanism, as described next.

B. Multi-Hop Broadcast

The ADHOC-MAC operation can be extended to broadcast services over the whole network. This is referred to as the multi-hop broadcast service, since in the ad-hoc network environment some terminals are required to relay the broadcast packets to enable them to reach all the terminals. The relaying function is usually implemented at the network layer, but the connectivity information provided by the FI allows to efficiently provide the multi-hop broadcast service at the MAC layer. Note that an effective multi-hop broadcast support at layer 2 can ease the design of routing protocols at the network layer.

As with flooding, the broadcast packets in the ADHOC-MAC network need to be numbered and the relaying procedure is applied only once, the first time the broadcast packet is received by a terminal. Let $\mathcal{C}_i$ be the set of neighbors of terminal i, i.e. all the terminals in the same OH-cluster, and $\mathcal{C}_j^i$, for any $j \in \mathcal{C}_i$, the sets of neighbors' neighbors. Given that terminal i receives a broadcast packet from terminal z in slot k, we define the set of neighbors that have not received the packet in slot k k by $\mathcal{S}_i \subset \mathcal{C}_j^i$. All these sets are identified by terminal i through the information carried by the FIs received in the N slots following slot k.

At slot $k+N$, terminal i recognizes whether or not it needs to relay the broadcast packets. Terminal i does not relay the packet if $\mathcal{S}_i = \phi$ or if, for at least one $j \in (\mathcal{C}_j^i - \mathcal{S}_i)$ the following condition is satisfied:

$$\mathcal{S}_i \subseteq \mathcal{C}_j^i \text{ AND } \left(|\mathcal{C}_j^i| > |\mathcal{C}_i| \text{ OR } (|\mathcal{C}_j^i| = |\mathcal{C}_i| \text{ AND } \; ID_j > ID_i)\right).$$

where ID_i denotes the address of terminal i. Basically, terminal i does not relay the packet if set $\mathcal{S}_i$ is a subset of $\mathcal{C}_j^i$ and if either $\mathcal{C}_j^i$ has higher cardinality than $\mathcal{C}_i$ or, having the same cardinality, the address of j is higher than the address of i.

III. Performance evaluation

In this section we present some preliminary results on the performance of ADHOC MAC. More specifically we address the following three issues: time responsiveness of RR-ALOHA, BCHs throughput analysis, and efficiency of the broadcast service.

A. Time responsiveness

An important performance figure of the protocol is the time needed to a new active terminal to acquire the BCH. According to RR-ALOHA, a new terminal willing to set up a channel will attempt transmission with probability p in the next AVAILABLE slot. The probability that one among k contending terminals gains access, i.e., its transmission does not collided, is given by:

$$S = kp(1-p)^{k-1} \tag{1}$$

which is maximized for $kp = 1$ where it yields $S \simeq e^{-1} = 0.376$ for large values of k.

The optimal condition is easily set, as all terminals know by the FIs the number $M-k$ of terminals that have already acquired the channel, given the maximum number M of terminals that can be accommodated. So, the probability used

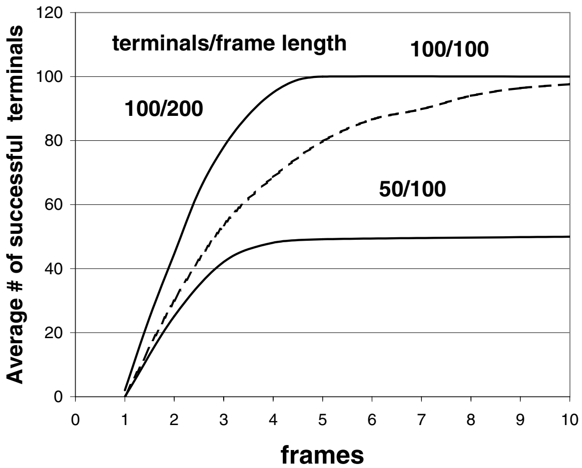

Fig. 2. *Average number of terminals that have successfully accessed their slot as function of the frame number.*

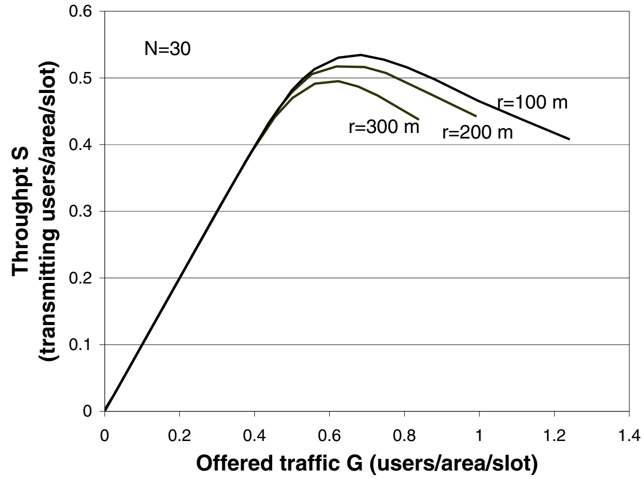

Fig. 3. *The throughput of BCH channels versus the channel load for a torus surface, different coverage radii and frame size $N = 30$.*

by the remaining k stations is set to $p = 1/k$. However, the outcome of an access attempt is known after one entire frame has elapsed, and, while awaiting the outcome, no new slots are accessed. This makes the average number of attempts per slot less than the optimal value (1), a condition that complicates the performance analysis of the access mechanism. Therefore, some preliminary figures have been obtained by simulation.

In Figure 2 we show the average number of terminals that have successfully acquired a slot at frame number shown in the abscissa when all of them turn on at the beginning of frame zero, with the assumption that all the M stations form a OH-cluster.

We have considered three cases in which the number of terminals and the number of slots in a frame are respectively $50/100$, $100/100$ and $100/200$. In the $50/100$ and $100/200$ cases, all terminals achieve their slot within 6 frames. In the case $100/100$, the period is almost doubled because more contentions exist to acquire an AVAILABLE slot.

B. The throughput of BCH channels

As it has already been explained, each new terminal in the net must acquire a BCH channel and transmit the FI. In this section we evaluate the throughput of such channels defined as the average number of terminals, among those generated, that use the BCH per slot per unit area. In general, this figure is function of the offered traffic and depends on system parameters such as the number (N) of slots in the frame and the user lifetime. It also changes with the network topology and antenna's coverage. However, if we refer to an infinite surface and measure the throughput in the antenna's coverage area the throughput does no longer depend on the size of that area. This can be verified with any finite surface by sufficiently reducing the coverage radius.

The performances have been obtained by a detailed simulation model. In this model new terminals are dynamically generated according to a Poisson process and are uniformly distributed into a square area of side length 1 Km. To get throughput uniformity we have shaped the area like a wrap-around surface. Upon generation, the new terminals try to acquire their BCHs and, after L frames have elapsed, they die, whether they have acquired the BCH or not.

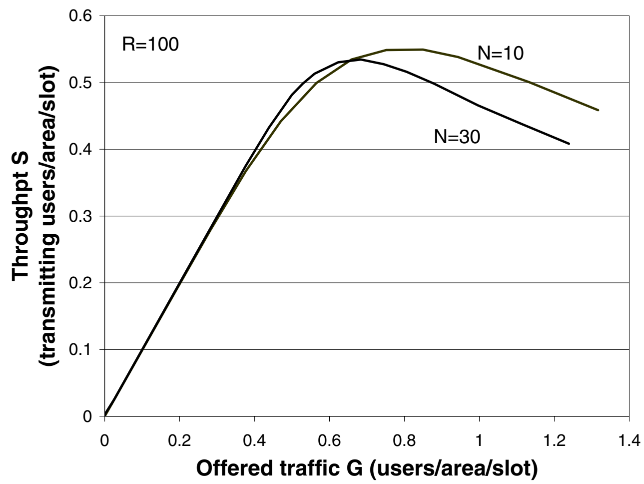

Fig. 4. *The throughput of BCH channels versus the channel load for a torus surface, for different frame sizes N.*

Figures 3 and 4 show the throughput vs the offered traffic curve for different system parameters. All the curves at first increase with the load G, reaching a maximum value $S_{\max}$ in $G_{\max}$, and then decrease because of the congestion caused by terminals. In this zone the load is greater than capacity and slots are increasingly wasted in subsequent access attempts.

We can immediately observe that the maximum throughput can not reach 1. This is due to the concurring effects of different phenomena, that can be explained by redefining the slot status, as seen by a terminal, as: INSIDE, OUTSIDE and CONTENTION. The slots in the INSIDE status carry a transmission that can be received by the terminal itself, i.e. the transmitting terminal belongs to the same OH-cluster of the receiving one. These slots are the only ones that contribute to the throughput statistics in the figures. OUTSIDE slots are those used by terminals outside the coverage area and that can not be reused inside to avoid the hidden terminal effect. The slots in the union of INSIDE and OUTSIDE slots are signaled as BUSY in the FI. CONTENTION slots are those that appear free or collided and that can be selected for access attempts.

We have always observed that, with a lifetime at least equal to 300 frames, the overhead caused by collisions is small. Therefore the main throughput limiting factor is *slot reuse*, i.e., the coexistence between INSIDE and OUTSIDE slots.

Figures 3 reports different curves that correspond to different antenna's coverage radii r when the terminals' lifetime is 300 frames. As expected, when the coverage radius is small with respect to the torus size, the throughput curves do not change with r. This is the case with $r \leq 100$ m. In fact, we have verified that the curve for $r = 50$m coincides with the one for $r = 100$m. When the coverage area becomes comparable with the torus size at first the throughput reduces, as shown in the figure. In fact, the reuse allowed by disjoint OH-cluster becomes less and less probable as the coverage area increases. However, there is a turning point in r, not shown in the figure, where a further increase makes the throughput increase again. This is due to the fact that the number of terminals that lie outside a single OH cluster, but inside the joint TH-cluster, decreases. Therefore slot conflicts due to the latter terminals are reduced and the throughput increases until it reaches 1 when all the torus is within the coverage area and reuse is no longer needed.

Figure 4 shows the effect of different frame sizes. In general, a larger frame size should favor the throughput since, in adding a new channel at a given throughput S, finding a free slot is easier. However, a larger frame means proportionally more users in the plane, which reduces reuse. In fact, adding users in the plane can transform non-overlapping OH-clusters into overlapping ones and users that originally used the same slot must use different slots when merged into the TH-cluster. Either effects prevail in different abscissa zones. When $G < G_{\max}$ the former effect is predominant, whereas the second prevails in the congested zone. A further effect, though with less impact on throughput, is the reduction of the overhead due to collisions when a large frame length is adopted.

C. Multi-Hop Broadcast efficiency

As described in section II-B, ADHOC-MAC provides a simple method to attain an effective multi-hop broadcast service, exploiting the distributed information transmitted in the FI fields. Here we evaluate the performance that the ADHOC-MAC multi-hop broadcast technique presents in bandwidth-efficiency, i.e., the number of retransmissions it needs to reach all the terminal that are connected to the net. ADHOC MAC is compared with flooding, a solution often suggested in the literature. With flooding the broadcast packets that are received for the first time are always forwarded.

Flooding is the least efficient broadcast technique and is easy to predict that ADHOC MAC offer better performance. However, to effectively evaluate ADHOC MAC we need a comparison with a most efficient technique. As benchmark we have chosen a centralized greedy procedure which gives a sub-optimal solution to the broadcast optimization problem, that has been shown to be NP-hard [10]. In the centralized greedy algorithm the choice of relaying terminals is based on a greedy heuristics. At each transmission the relaying terminal(s) among the potential ones is the one that has the higher number of neighbors still missing the broadcast packet. Each terminal is supposed to have full knowledge of the network topology.

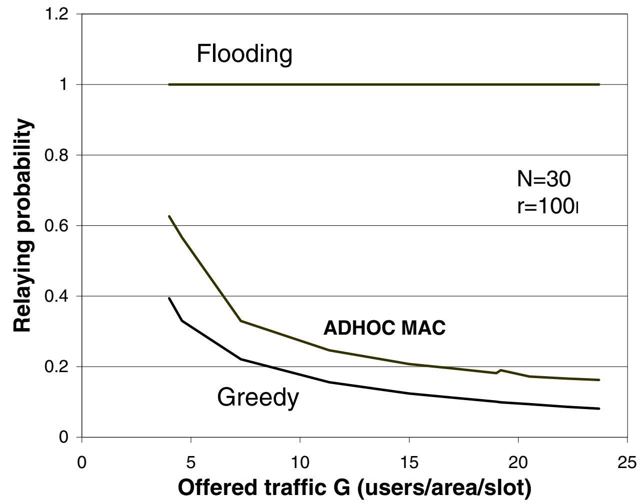

Fig. 5. Packet relaying probability versus the average number of neighbors in a square region with edge $= 1Km$ and with coverage radius $= 100m$.

The three techniques are compared using a wrap-around network topology composed by a regular square grid of nodes at a distance equal to terminal radio range, so that each node sees four grid neighbors. The grid is introduced to guarantee the complete network connectivity. Additional nodes are generated randomly on the torus surface in order to change the offered traffic.

Measures are performed simulating the three algorithms. At each run a random source for the broadcast packet is chosen, the different algorithms are applied and the number of retransmissions are measured.

Figure 5 shows the relaying probability, i.e., the average fraction of terminals involved in broadcast relaying, versus the average load G expressed as the average number of neighbors in the terminal coverage area.

When the flooding algorithm is adopted all the terminals in the network relay packets. With the greedy algorithm the relaying probability decreases as the load increases. In fact, given the grid, an increase in the load only increases the average number of terminals that do not relay packets. Furthermore, relaying terminals can be chosen in a more efficient way.

We note that ADHOC MAC performs closely to the greedy algorithm and, for a high degree of connectivity, ADHOC MAC provides a gain of 85% in terms of overhead reduction with respect to flooding. The slight difference with respect to the greedy algorithm is due to the fact that the latter implements a centralized approach where each terminal knows exactly the topology of the whole network.

In order to appreciate how accurate ADHOC MAC is with respect to the suboptimal centralized solution we have evalu-

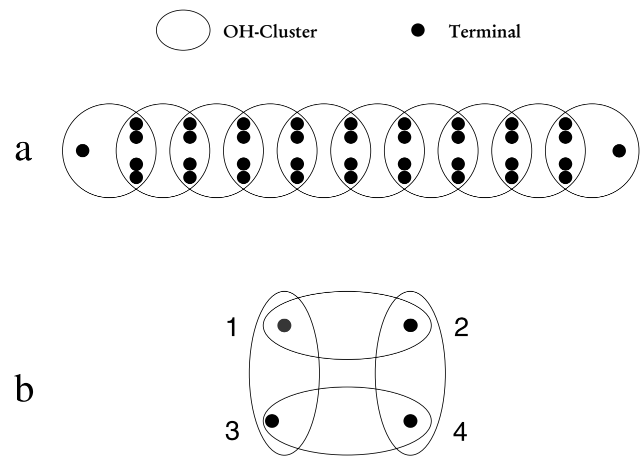

Fig. 6. *Network topologies used to test the effectiveness of the multi hop broadcast service.*

ated the broadcast service also in simple network topologies. Figure 6a shows the first case study where the network is composed by non disjoint OH-clusters disposed like a chain and covering 38 mobile terminals. The flooding procedure covers all the topology with 38 retransmissions of the packet to be broadcast, regardless of the source's position. ADHOC MAC and the centralized greedy heuristics have the same performance and provide broadcast coverage with the minimum number of retransmissions, i.e., if the source is in the middle of the net, both algorithm covers the network with 9 retransmissions; otherwise, if the packet is generated by one of the extreme nodes the number of needed retransmissions is equal to 10.

Figure 6b shows the case where the OH-clusters form a ring-like structure. Here, assuming the source is terminal 1, the optimal solution takes 2 retransmissions to cover the entire network, i.e. one transmission by either terminal 2 or terminal 3 plus the transmission of the source. If we apply ADHOC MAC we need 3 retransmissions to cover all the topology, i.e. the transmission by the source plus one transmission each by terminal 2 and 3. This is due to the fact that terminals 2 and 3 have no way to realize that they have the same common neighbor (terminal 4), so they both relay the broadcast packet.

The result obtained with the latter topology can be generalized by stating that ADHOC MAC introduces an overhead of one retransmission for each ring with respect to the optimal solution. The correctness of the above conclusion has been widely tested through simulation.

IV. Conclusions

In this paper we have presented a simulation analysis of the performance achieved by ADHOC MAC [8]. ADHOC MAC is a new MAC protocol for ad hoc networks that has been proposed and developed within the CarTALK2000 project[1] with the purpose to support inter-vehicular communications.

The present work shows the protocol feasibility and reports a detailed simulation analysis of the performance of the protocol itself when dealing with one-hop broadcast transmissions and with multi-hop ones. In details, the results shown prove that the proposed access scheme offers high performance in terms of access delay and radio resources reuse when a single hop broadcast service is considered. Furthermore, the protocol has been shown to provide a simple way to effectively implement at MAC level multi-hop broadcast services.

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