ADHOC MAC: a new, flexible and reliable MAC architecture for ad-hoc networks

F. Borgonovo, A. Capone, M. Cesana, L. Fratta
Dipartimento Elettronica e Informazione
Politecnico di Milano
{borgonov, capone, cesana, fratta}@elet.polimi.it

***Abstract*— Ad-hoc networking, though an attractive solution for many applications, still presents many unsolved issues, such as the hidden-terminal problem, flexible and prompt access, QoS provisioning, and efficient broadcast service. In this paper we present a MAC architecture able to solve the above issues in environments with no power consumption limitation, such as networks for inter-vehicle communications. This new architecture is based on a completely distributed access technique, RR-ALOHA, capable to dynamically establish on a slotted/framed structure a reliable single-hop broadcast channel for each active terminal on the network. Though the proposed MAC uses a slotted channel, it can be adapted to operate on the physical layer of different standards, including the UMTS Terrestrial Radio Access TDD, and the IEEE 802.11. The paper presents the mechanisms that compose the new MAC: the basic RR-ALOHA protocol, an efficient broadcast service and the reservation of point-to-point channels that exploit parallel transmissions. Some basic performance figures are discussed to prove the effectiveness of this protocol.**

I. Introduction

The design of ad hoc networks has recently attracted a lot of attention, mainly because many characteristics of such networks, especially in a highly mobile environment, make the design of a prompt, efficient, flexible, and reliable MAC very difficult.

An ad hoc network is composed of mobile terminals that communicate among each other with broadcast radio transmissions, i.e., transmissions that reach all terminals within the range allowed by the transmitting power. Due to radio range limitations, physical broadcasting does not cover all terminals and a multi-hop scenario, where packets are relayed by intermediate terminals to reach their destination, must be considered.

Applications of mobile ad hoc networks can range from military ones, where networks need to be deployed immediately without the support of base stations or fixed network infrastructures, to inter-vehicle communications, designed for both traffic safety enhancement and entertainment purposes. The inter-vehicle communications application poses the most stringent requirements, due to a highly variable topology and to the need to provide a continuous exchange of broadcast information to support traffic control applications [1].

Because of the highly variable environment, in mobile ad hoc networks all protocols and coordinating functions must be totally distributed. This constraint has impact on the implementation of several layers. At the physical layer no central station that provides a central clock, slotting or framing structure can exist. Nor a central repeater can allow terminals to hear all transmissions and their owns, to perform functions such as transmission synchronization or collision detection. Furthermore, due to the distributed nature of the environment, collisions among transmissions can occur at some receivers only, an issue known as *hidden-terminal* problem [2].

Limitations at MAC level are even more challenging. In fact, the channel access must be completely distributed, but operates on a physical channel that, unlike Ethernet, does not present broadcast characteristics with all the terminals that can potentially collide with the transmitting station (the hidden-terminal problem). Approaches such as the Carrier Sense Collision Avoidance, adopted in the Distributed Coordination Function of IEEE 802.11 [3], do not completely solve the problem (see [4] for a comprehensive review of protocols proposed to avoid the hidden-terminal problem in point-to-point communications). Furthermore, no centralized algorithm, such as the Point Coordination Function of IEEE 802.11, can be applied, making very difficult to provide services with QoS requirements, such as voice traffic.

A further challenging problem in ad hoc networks is how to provide reliable broadcast service. Most of the advanced broadcast protocols, such as the tree-based protocol in [5], do not work well for ad hoc networks due to the dynamic nature of the network topology. Hence, the flooding approach and its variants, have been proposed as the preferred means to propagate routing and broadcast service [6]. In flooding, each station that receives a broadcast packet retransmits it just once until all terminals are reached. Such a procedure is highly inefficient in networks that present an high degree of connectivity. In fact, in networks with n terminals flooding requires n transmissions of the same information, while a single transmission is sufficient to reach all terminals in fully connected networks. In addition, with random access, this procedure suffers from the broadcast storm problem [7]. In fact, neighbor nodes are likely to re-transmit a broadcast packet almost at the same time, causing massive collisions.

The above drawback is especially serious in vehicular control applications, where vehicles continuously "broadcast" some background information, such as cruise parameters [8]. This information, furthermore, is intrinsically single-hop broadcast because directed mostly to neighbor vehicle, and a flooding procedure would saturate the whole network with information of no use for most terminals.

Parallel transmissions can take place in ad hoc networks, as it happens in disjoint networks. However, in networks that use carrier sensing or the RQS/CLS mechanism of IEEE 802.11, some parallel transmissions can be impeded by the "exposed-terminal" problem [4].

In this paper we present ADHOC-MAC, a MAC architecture that has the potential to overcome all the drawbacks listed above in environments, such as inter-vehicular communications, in which power consumption is not a problem. In particular, ADHOC-MAC is based on the the Reliable R-ALOHA protocol (RR-ALOHA) [9], which is a completely distributed access technique capable of dynamically establish a reliable single-hop broadcast channel on a slotted/framed structure for each active terminal on the net. This channel is used to provide the following services:

- prompt and reliable layer two connectivity information on all the stations of the network;
- contentionless access to a reliable single-hop broadcast service;
- prompt means to reserve additional bandwidth and QoS as the applications require, in a complete distributed way;
- efficient point-to-point communications that exploit parallel transmissions
- an efficient multi-hop broadcast service

The proposed MAC protocol uses a slotted channel, and therefore it can use slotted physical layers such as the UMTS Terrestrial Radio Access TDD. In this case the slotting information can be provided by the Global Positioning System [10]. However, ADHOC MAC can be adapted to operate also with asynchronous physical layers such as the IEEE 802.11.

The paper is organized as follows. In Section II we present the basics of the new protocol and show its correct operation. In Section III we discuss the performance of the protocol in terms of overhead on practical systems and responsiveness of the access mechanism. Conclusion are given in Section IV.

II. The ADHOC-MAC protocol

ADHOC-MAC operates with a time slotted structure, where slots are grouped into virtual frames (VF) of length N, and no frame alignment is needed.

The slotting information can be explicitly provided by external sources, such as GPS. However, as slotting is a local information, it can also be implemented on asynchronous physical layers such as the one provided by the IEEE 802.11. In fact, since in ADHOC-MAC all active terminals transmit periodically a packet in any frame, the slot and frame synchronization is provided by the first terminal that turns on. Others terminals synchronize by setting counters, as in IEEE 802.11, on transmissions on the fly.

To operate, the ADHOC-MAC needs that each active terminal has assigned a basic channel (BCH), corresponding to a slot in the VF, which is a reliable broadcast channel not suffering from the hidden-terminal problem. This is obtained in a distributed way by the RR-ALOHA protocol, which is described next.

A. RR-ALOHA basic operation

The RR-ALOHA operation is much the same as R-ALOHA, where contention is used to get access to an available slot in the frame and, upon success, the same slot is reserved in the following frames and no longer accessed by other terminals until it is released. However, R-ALOHA requires a central repeater to enable all terminals to receive all the transmitted signals and, most important, to get the same slot status information, e.g., busy, free, or collided. In this way a terminal can discover collisions on access and avoid to collide with ongoing transmissions.

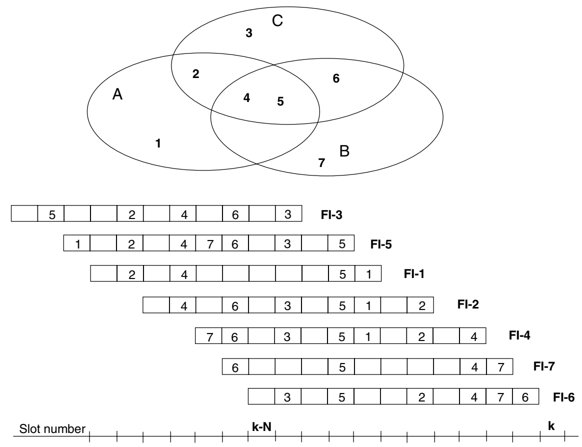

Fig. 1. *Example of the FI information propagated by the terminals in the one-hop clusters A, B, and C.*

In the application environment we are considering no central repeater is present. In these conditions a terminal is not guaranteed to hear all the transmissions because of the hidden-terminal problem, and, therefore, destructive interference can occur when trying to access a slot. Furthermore, terminals do not know the outcome of their transmissions, which might be different at different terminals. To cope with this limitation, RR-ALOHA uses the BCHs to distribute the terminal's view of the state of each slot in the frame, therefore providing slot information and acknowledgment for any transmission on the channel.

To explain the RR-ALOHA mechanism, let us consider first the case in which terminals can reach each others by at most two hops. An example is shown in Figure 1, where numbers $1-7$ denote the terminals, and elliptical areas A, B and C one-hop (OH) clusters. The terminals of each OH-cluster enjoy full connectivity within the cluster, and terminals in different clusters that do not belong to common subsets do not communicate. Terminals belonging to the subset ABC common to all clusters, hereafter denoted 1-terminals, have full connectivity with all the adjacent clusters. The union of all OH-clusters with a common subset is denoted as two-hop (TH) cluster.

The packets transmitted in the BCH contain, beside the payload, the Frame Information (FI). The FI reports the status, as perceived by the terminal, of each of the N slots of the Sliding Virtual Frame (SVF), i.e., the N slots preceding the considered slot. The status information is set as BUSY if the slot contained a successfully decoded packet or a transmission by the terminal. In these cases also the identity (ID) of the transmitting station is reported. Otherwise the slot status is set to FREE. In Figure 1 the FIs transmitted by terminals $1-7$ are shown. The FIs have been aligned so that each column refer to the same slot. FI-1 shows that terminal 1 sees, in a 11-slot frame, only the transmissions of terminals 2, 4, 5 and its own (BUSY slots), while other slots are seen as FREE. Similarly, FI-4 shows that terminal 4 sees the transmissions of all terminals because it belongs to the common subset.

The use of slots by terminals depends on the "label" attached at each slot. More precisely, at each slot, say slot k (see Figure 1), the FIs received in the SVF are used to determine the label of slot $k-N$ according to the following:
Rule 1: *the slot is labeled as RESERVED if coded as BUSY in at least one received FIs; otherwise it is labeled as AVAILABLE.*

In this way a slot used as BCH by a terminal in a cluster is seen as RESERVED by all the terminals in the TH-cluster. In fact, it is seen as BUSY by 1-terminals, which propagate the BUSY information to all other terminals in their FI.

The label of slot $k-N$ is extended to slot k which, if AVAILABLE, can be used to transmit a packet by any terminal that wish to set up the BCH. In this way the hidden-terminal problem is solved and the R-ALOHA procedure can be applied.

A terminal j that transmits in an AVAILABLE slot determines, after a time frame, the outcome of its transmission according to the following
Rule 2: *the transmission is successful if the slot is coded as BUSY for station j in all the received FIs; otherwise the transmission is failed.*

According to this rule if just one terminal is attempting access, all terminals in the same cluster will recognize the transmission and, therefore, all FIs received by the terminal will denote the slot as BUSY and the access is successful. All other terminals in the network will recognize the slot as BUSY in the FI of 1-terminals, and declare the slot as RESERVED. The RESERVED slot is then dedicated to the successful terminal until it is released.

If two or more terminals are attempting transmission on the same slot, the terminals, including 1-terminals, that can not decode the signals because of the collision, will signal the slot as FREE. It may also happen that, because of receiver capture, some terminals correctly decode either transmissions and signal the slot as BUSY. In this case the slot is assigned to terminal j if all the received FIs say so, while the contending terminals will discover their failure. Otherwise, all contending terminals have failed their access attempt.

At network start up, all slots are AVAILABLE, and terminals start transmitting according to the protocol described until all of them have acquired their own BCH. BCHs are automatically released as terminals turn off or exit the transmission range of all other terminals active in the frame.

Let us now consider the more general scenario in which OH-clusters overlap forming a multi-hop network, such as the case shown in Figure 2, where labels denote to disjoint sets. According to RR-ALOHA, terminals in A are prevented to interfere with terminals in B and vice-versa. All the terminals in A, B, and AB transmit in their own slots of a common frame, Frame 1 in Figure 2, giving rise to the TH cluster $A+B$ in which any terminal knows the status of the frame as seen by all other users in the TH-cluster.

Again terminals of set BC see the transmissions of both B and C but not those in A. Terminals in C do not receive FIs from the set AB an therefore are free to reuse the slots that are also used by terminals in A, yielding Frame 2 in figure 2 and the TH-cluster $B+C+BC$. Frame 3 represents a possible frame used by the TH clusters $C+D+CD$.

Here, we have implicitly assumed that the FI is available at the end of the slot where it has been transmitted. If this is not the case, a new access must be delayed until FI has been processed.

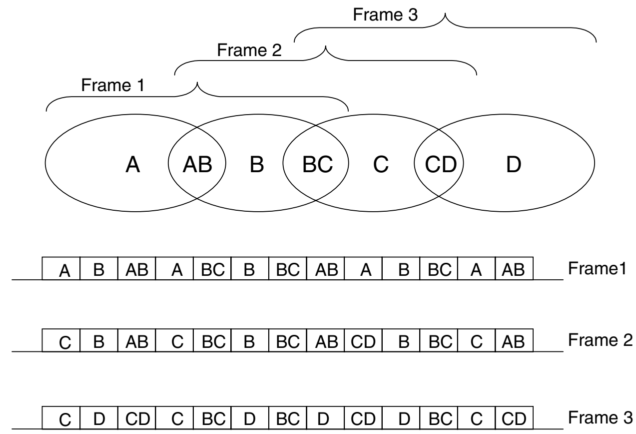

Fig. 2. *Example of how transmissions in frames become organized. Labels denote to disjoint sets.*

B. Reserving additional bandwidth

The BCH, if the payload field is long enough, can also be used to transmit application or other service information, e.g., for routing. However, if the bandwidth allowed by BCH is not enough, additional bandwidth can be provided in many forms using the slots of the frame that are still available and FIs. Here we outline two different ways.

An additional one-hop broadcast channel can be reserved using the RR-ALOHA procedure. Otherwise, the request for further slots can be signaled in the BCH together with the related priority. To face the hidden-terminal problem, the reservation, when detected by terminals, is included in the FI of subsequent transmissions as if the referred slot were occupied by a successful attempt. If more terminals try to reserve the same slot, the one signaled in the FI is determined on the basis of the priority. Nevertheless, different FIs may carry different reservations for the same slot, in which case, according to Rule 2, a collision is detected and the procedure has to be re-attempted.

If no additional slots are available, higher priority terminals can preempt lower priority transmissions by causing collisions and by signaling the new request.

Additional slots can also be used to set up point-to-point (PTP) channels that reuse slots in disjoint subsets of OH-clusters (parallel transmissions). To allow maximum reuse and solve the exposed-terminal problem, a new flag, the PTP flag, must be included in the FI for each slot. Slots are still labeled AVAILABLE or RESERVED according to Rule 1, while
Rule 3: *a terminal set the PTP flag in the FI if the received packet is a broadcast packet or if it is destined to the terminal itself.*

Available slots are accessed as in BCH. However, also RESERVED slots may be accessed depending on the following
Rule 4: *Let S be the ID of the accessing node and D the ID of its intended destination. Then a RESERVED slot can be accessed if:*

i) *the PTP flag signaled in all the received FIs is off and*

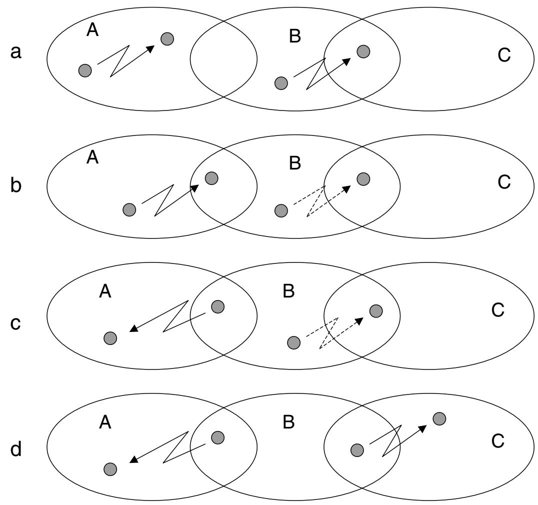

Fig. 3. *Examples of parallel transmissions. Transmissions in set A are established first. Allowed transmissions in set B are indicated by solid arrows.*

ii) *the FI received from D signals the slot as FREE.*

The conditions above assure that no collision can ever occur at both receivers. This can be seen referring to the four cases shown in Figure 3. Assuming that transmission in A has originated first, in case a all the FIs received from the terminals in AB signal the slot as BUSY with flag off. In case b the FI received from the destination terminal in AB signals the slot as BUSY with flag on. Furthermore, condition ii in Rule 4 is always met. Therefore, in case a the transmission in B can take place, while in case B can not. In cases c and d the FIs from terminals in AB signal the slot as BUSY with flag off. In case c the destination D sees the transmitter in AB, while in case d it does not. Therefore, transmission in B can take place only in case d, which is, in fact, the exposed-terminal case.

However, collisions can still occur due concurrent access attempts. The outcome of the attempt is determined, after a time frame, according to the following

Rule 5: *the transmission is successful if the slot is coded as BUSY in the FI of the destination terminal; otherwise the transmission is failed.*

C. Multi-hop broadcast service

In multi-hop broadcast service terminals must relay transmissions so that all terminals in the network are reached. With flooding, all terminals relay at least once broadcast packets, but this results in an highly inefficient use of bandwidth. In ADHOC-MAC a simple method to attain a minimal number of relaying terminals needed to cover all the network is described next.

As with flooding, broadcast packets are numbered and the relaying procedure is applied only the first time the packet is received.

Let assume that terminal i receives a broadcast packet in slot k. Let also denote by $\mathcal{C}_i$ the set of neighbors of i (OH-cluster) and by $\mathcal{S}_i \subseteq \mathcal{C}_i$ the subset of neighbors that have not received the packet in slot k. These subsets can easily be identified by i through the FIs received in the SVF following slot k. By this same information also sets $\mathcal{C}_j$, $j \in \mathcal{C}_i$, are identified.

Rule 6 : *Terminal i decides to relay the packet if $|\mathcal{S}_i| > 0$ and for all j the following condition is not satisfied*

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

To show that Rule 6 leads to a unique set of relaying terminals, let us refer first to single TH-cluster networks as the one in Figure 1, where just one 1-terminal is selected as relay.

Condition $\mathcal{S}_i \subseteq \mathcal{C}_j$, is always satisfied if j is a 1-terminal (in ABC). In this case, if i is not a 1-terminal, condition $|\mathcal{C}_j| > |\mathcal{C}_i|$ is always satisfied and terminals outside the common set ABC can not relay. If i is a 1-terminal, the whole condition is satisfied by all but the terminal with the lowest ID, which is the one that relay the broadcast packet if the packet itself has not been generated by a 1-terminal.

In the more general scenario of Figure 2, assuming that a broadcast packet is transmitted in B, condition $\mathcal{S}_i \subseteq \mathcal{C}_j$, is always satisfied if j is a 1-terminal in AB and i is a terminal in $A+B$. Proceeding as above we see that the relay terminal is a 1-terminal in set AB. Similarly, condition $\mathcal{S}_i \subseteq \mathcal{C}_j$, is also satisfied if j is a 1-terminal in BC and i is a terminal in $B+C$, and the relay terminal is a 1-terminal in set BC.

The selected terminals will relay the broadcast packet in clusters A and C respectively. As the above procedure is automatically repeated, the broadcast packet reaches all terminals in the network, with a reduced number of retransmissions with respect to the flooding approach.

It is worth noting that the above procedure, used with the knowledge of topology, as, for example, obtained by layer 3 routing mechanisms, can provide also ad-hoc multicast service.

III. Performance evaluation

In this section we present preliminary performance evaluations of RR-ALOHA. More specifically we address the following two issues: implementation overhead and time responsiveness.

A. Implementation overhead

The protocol overhead of the basic RR-ALOHA described in the previous section depends on the number N of slots in the frame and on the information needed for each slot in the FI. Since the active terminals must transmit at least once in a frame, N must be large enough to accommodate the maximum number of terminals M in any TH-cluster. In addition, if we allow any terminal to set up additional channels, N must be much larger than M.

Note that, although M is fixed, it does not limit the number of terminals that the network can support, since, within the network, slots and frames are reused, much as it happens among cells of cellular systems. As in that case, M can be reduced by reducing the terminal's transmitting power.

As an example of a large dimensioning we can assume $M = 100$ and $N = 200$. FI must specify three fields for each slot in the frame:

- the BUSY status (1 bit);
- the source temporary identifyer (ID) that serves to identify the station that has successfully captured a slot. These ID are selected at random and changed if already in use. An ID of 8 bit is sufficient for the network size assumed.

- a Priority field (2 bits)
- the PTP service flag (1 bit).

In the case considered, the overhead introduced by the FI is 2400 bit. Further fields to be transmitted in a slot are those relevant to the RR-ALOHA operation, such as the ID and the priority of the packet, the fields needed to reserve further channels, and the fields common to layer 2 packets, such as MAC addresses, sequence numbers, frame check sequence, and physical guard times. The total overall overhead can be as high as 2500 bits. The overall efficiency is a trade-off between the length of the payload and its filling degree. With a packet length of 5000 bits the payload is 2500 bits long in the BCH slots and about 5000 bits in other slots. Therefore, with the figures assumed, the maximum efficiency is 75%. The overall frame duration, assuming a 10 Mb/s channel speed, will be 100 ms, yielding a bandwidth of 25 kb/s available for applications in each BCH and a global bandwidth of 5 Mb/s available for reservations.

A further relevant overhead reduction can be obtained by inserting the ID and the Priority in the FI once every k frames, including the slots that are accessed for the first time. This information, in fact, is needed by the MAC in the access phase only, but must be repeated to let new active terminals to learn the association of busy slots with terminals. For example, if we include the ID and Priority once every 10 frames, the FI can be reduced to 400 bits the 90% of the time, yielding a maximum efficiency of 93%, still using 5000 bit packets. If a lower channel speed is used, as for instance the 3.84 Mb/s channel of UTRA-TDD, the packet length must be further reduced, at expenses of an increased overhead, to maintain the 100 ms frame duration and the related time responsiveness.

B. 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:

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

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. So, the probability used 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 can be 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 4 we show the average number of terminals that have successfully acquired a slot as function of the frame number when all of them turn on at the beginning of frame zero, with the assumption that none among the M stations in the cluster suffers from the hidden terminal effect.

We have considered three cases in which the number of terminals and the number of slots in a frame are respectively

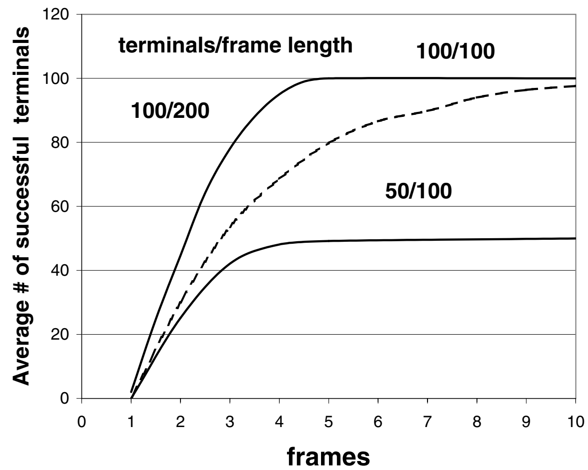

Fig. 4. *Average number of terminals that have successfully accessed their slot as function of the frame number.*

$50/100$, $100/100$ and $100/200$. In the $50/100$ and $100/200$ cases, all terminals achieve their slot within 6 frames, which, referring to the parameters given in the previous section, amount to about 600 ms. In the case $100/100$, the period is almost doubled because more contentions exist to acquire an AVAILABLE slot.

IV. CONCLUSIONS

In this paper we have presented an entirely new MAC protocol for ad hoc networks, ADHOC-MAC, which is able to deal with the hidden terminal problem and to overcome most of the problems that have been recognized in existing MAC architectures.

It is based on a framed structure in which a broadcast signaling channel is set up in a completely distributed way by the RR-ALOHA protocol, also part of ADHOC-MAC. By this channel, all terminals know the activity of their two hop neighbors and, thus, can avoid the hidden-terminal problem, coordinate to obtain prompt access to further bandwidth, and implement optimal multihop broadcast service and parallel transmissions.

Although ADHOC-MAC, as it has been described, uses a framed structure, it can be modified to operate also in asynchronous physical layers such as that of IEEE 802.11. However, as frequent periodical transmissions are needed in the broadcast signaling channel, ADHOC-MAC might not be indicated for applications that need energy saving features.

We have shown the protocol feasibility and provided basic figures on its efficiency when implemented on practical channels. Some simulation results have proven that the signaling broadcast channel set-up delay is of the order of few hundreds of ms, a value suitable for most of the applications, especially in the inter-vehicle communication scenario. Some work is in progress to define the implementation details and to obtain more accurate performance evaluations considering all the parameters of real networks scenarios.

REFERENCES

[1] "Special issue on intelligent vehicle highway systems", IEEE Trans. Veh. Technol., vol. 40, no. 1, 1991.

[2] F. A. Tobagi and L. Kleinrock, “Packet switching in radio channels: Part II-The hidden terminal problem in carrier sense multiple-access and the busy-tone solution”, IEEE Trans. Commun., vol. COM-23, pp. 1417-1433, Dec. 1975.
[3] IEEE 802.11 Working Group, “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, ANSI/IEEE Std. 802.11, Sept. 1999.
[4] Haas, Z.J., Jing Deng, “Dual busy tone multiple access (dbtma)-a multiple access control scheme for ad hoc networks”, IEEE Transactions on Comm., VOL. 50, NO. 6, June 2002.
[5] [1] I. Chlamtac, S. Kutten, “Tree-based Broadcasting in Multihop Radio Net- works,” IEEE Trans. on Communications, Oct 1987.
[6] Brad Williams, Tracy Camp, “Comparison of broadcasting techniques for mobile ad hoc networks”, Proc. ACM MobiHOC, Lausanne, Switzerland, June 2002.
[7] Y. C. Tseng , S. Y. Ni , Y. S. Chen and J. P. Sheu, “The broadcast storm problem in a mobile ad hoc network”, Wireless Networks, Volume 8, Issue 2/3, March 2002.
[8] R. Hager, R. Mathar, and J. Mattfeldt, “Intelligent cruise control and reliable communication of mobile stations”, IEEE Trans. Veh. Technol., vol. 44, no. 3, pp. 443-448, 1995.
[9] F. Borgonovo, A. Capone, M. Cesana, L. Fratta, “RR-ALOHA, a Reliable R-ALOHA broadcast channel for ad-hoc inter-vehicle communication networks”, Med-Hoc-Net 2002, Baia Chia, Italy.
[10] A. Ebner, H. Rohling, R. Halfmann, M. Lott, “Sinchronization in ad hoc networks based on UTRA TDD”, Siemens Tech. Report, 2001
[11] W. Crowther, R. Rettberg, D. Waldem, S. Ornstein, and F. Heart,“A system for broadcast communications: Reservation ALOHA”, Proc. 6th Hawaii Int. Conf. Sist. Sci., Jan. 1973.