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ADHOC MAC: New MAC Architecture for Ad Hoc Networks Providing Efficient and Reliable Point-to-Point and Broadcast Services

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Abstract. Ad-hoc networking, though an attractive solution for many applications, still has 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 limitations, such as networks for inter-vehicle communications. This new architecture is based on a completely distributed access technique, RR-ALOHA, capable of dynamically establishing, for each active terminal in the network, a reliable single-hop broadcast channel on a slotted/framed structure. Though the proposed architecture 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 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 the protocol.

Keywords: ad hoc networks, MAC protocols, wireless access, intervehicular communications, TDMA

1. 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 one to the other through broadcast radio transmissions, i.e., transmissions that reach all the terminals within the transmission power range. However, 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 field communications, where networks must be deployed immediately without the support of base stations and 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 highly variable topology and the need to provide a continuous exchange of broadcast information to support traffic control applications [6].

Because of the highly variable environment, all protocols and coordinating functions in mobile ad hoc networks must be completely distributed. This constrains the implementation of several layers. At the physical layer no central station, providing a central clock, slotting or a framing structure, exists. Nor is there a central repeater that enables the terminals to hear all the transmissions including their own, or perform functions such as central transmission synchronization or collision detection.

The particular physical environment also poses a severe challenge at the MAC level, especially if we compare it with the well-known distributed access mechanism provided by IEEE 802.3 (Ethernet), where the terminals are attached to physical broadcast segments. Broadcast network segments are also present in ad hoc networks. However, in such networks the terminals attached to a segment change over time, because of their mobility and the changing propagation conditions. Furthermore, different segments partially overlap, causing further problems. One such problem arises when terminals belonging to different segments, that do not hear each other concurrently, transmit to a terminal in the overlapping region. Transmission collision occurs but goes undetected by the transmitting terminals. This condition is known in the literature as the *hidden terminal problem* [9].

The hidden terminal problem is mitigated by the RQS/CLS access mechanism known as Carrier Sense Collision Avoidance, that is adopted in the Distributed Coordination Function of IEEE 802.11 [7]; however, this mechanism does not solve the problem completely and many modifications, not always compatible with the existing standard, have been suggested (see [4] for a comprehensive review of these protocols).

Another unsolved problem related to segment overlapping in ad hoc networks is the *exposed-terminal* problem [4]. In this case the problem arises when the sensing mechanism prevents parallel transmission, from two or more terminals, toward receivers that would not observe collision as the receivers are located far apart.

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The hidden terminal problem not only makes point to point communications unreliable, but also undermines reliable broadcast transmission in broadcast segments, as happens in IEEE 802.11, where the Distributed Coordination Function does not make use of RQS and CLS in its broadcast procedure. In fact, an unreliable broadcast service within the broadcast segments also makes it very difficult to provide an efficient and reliable broadcast service for the entire network. Note, however, that a reliable network broadcast can be very useful in many network and application services, e.g., in vehicular control applications where vehicles continuously "broadcast" background information, like cruise parameters [5]. Also, routing protocols, both proactive or reactive, use broadcast functions to flood routing information or obtain addressing information, as in the ARP protocol.

In the absence of a reliable MAC broadcast service, "flooding" and its variants are often adopted [11]. In flooding, each terminal receiving a broadcast packet retransmits it just once until all the terminals are reached. However, this procedure is highly inefficient in networks with a high degree of connectivity. In a network with n terminals the flooding procedure requires n transmissions of the same information, while in fully connected networks one single transmission is sufficient to reach all terminals. The problem is further aggravated for random access protocols such as CSMA-CA in IEEE 802.11, where neighbor nodes are likely to re-transmit a broadcast packet almost at the same time, causing massive collisions known as the *broadcast storm* problem [10].

In this paper we present ADHOC-MAC, a MAC architecture that has the potential to overcome many of the drawbacks listed above. ADHOC-MAC implements a Dynamic TDMA mechanism that is able to provide prompt access and the variable-bandwidth, reliable channels, needed for QoS delivery. Dynamic TDMA is achieved by the Reliable R-ALOHA protocol (RR-ALOHA) [1], a new distributed reservation protocol capable of dynamically establishing a reliable single-hop broadcast channel, the Basic Channel, that provides knowledge of MAC transmissions in overlapping segments. The information conveyed by the Basic Channel resolves the hidden and exposed terminal problems, and provides a valuable basis for the efficient implementation of a network broadcast service. In fact, it is this information that leads to the dynamic election of terminals that more conveniently relay network broadcast packets.

The transmission knowledge that RR-ALOHA provides comes at the expense of continuous terminal transmission. Therefore, for environments where energy saving prevails over network topology knowledge, ADHOC MAC is not indicated. However, this is not the case for applications like inter-vehicular communication for traffic control.

The proposed MAC protocol uses a slotted channel, and can therefore 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 [8]. However, ADHOC MAC can also be adapted to operate with asynchronous physical layers such as the IEEE 802.11.

The paper is organized as follows. Section 2 presents the basics of the new protocol and its correct operation; section 3 discusses protocol performance in terms of the overhead on practical systems and responsiveness of the access mechanism. Conclusions are given in section 4.

2. The ADHOC-MAC protocol

The ADHOC-MAC protocol is devised for an environment in which the terminals can be grouped into clusters in such a way that all the terminals of a cluster are interconnected by broadcast radio communication. Such a cluster is defined as One-Hop (OH), and it is assumed that the terminals belonging to different clusters cannot communicate with each other at the physical layer. Note that terminals can belong to more than one OH-cluster, leading to the case of non disjoint clusters. The union of OH-clusters having a common subset is called a Two-Hop (TH) cluster. Such an environment is shown in figure 1 where 4 terminals are grouped into two OH-clusters and one TH-cluster. This arrangement, i.e., terminals in common subsets, generates the "hidden terminal" problem in which the transmissions of two terminals that do not see each other (hidden) collide at a common terminal. In the figure it can be seen that a transmission from terminal 1 to terminal 2 is destroyed by concurrent transmission from terminal 3 to terminal 4, as also terminal 2 receives the transmission sent out by 3.

The ADHOC-MAC protocol operates on a time slotted channel. However, this paper is not concerned with the details of time slotting implementation as many alternatives exist, such as the one that uses GPS [8]. Nevertheless, regardless of the slotting technique used in the distributed environment, the slot boundaries must take into account the maximum propagation time between terminals belonging to the same OH-cluster so that packets can be transmitted and received anywhere within the same time slot.

The access mechanism of ADHOC-MAC can be classified as Dynamic TDMA and 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), that is often referred to in ad hoc network literature [3].

In R-ALOHA, "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 is no longer able to be accessed by other terminals until the channel is released.

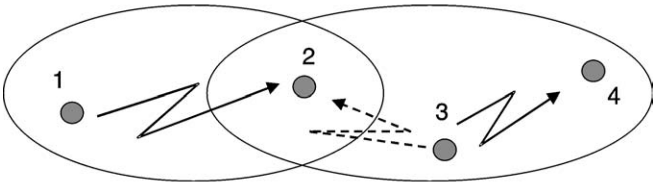


Figure 1. Example of the hidden terminal problem.

The correct operation of R-ALOHA requires a central repeater through which the terminals receive all the transmitted signals and, most importantly, obtain the same slot status information, e.g., busy, free, or collided. In this way a terminal can avoid collisions among ongoing transmissions and discover possible "on access" collisions. However, since ad hoc networks do not have a central repeater, and there is no guarantee that a terminal will hear all the transmissions (hidden terminal), destructive interference with already established channels can occur when trying to access a slot. Furthermore, the transmitting terminal does not know the outcome of its transmission, that can differ from terminal to terminal.

To implement a Dynamic TDMA, even with these limitations, we devised a new protocol, the Reliable R-ALOHA (RR-ALOHA) protocol, that, by transmitting additional information, called the Frame Information (FI), lets any terminal know the status (AVAILABLE or RESERVED) of each slot. Thus RR-ALOHA allows the same R-ALOHA procedure to be applied to the ad-hoc environment. However, with RR-ALOHA, each and every terminal must, in order to become active, acquire a channel, i.e., a slot in the frame of N slots, referred to in the sequel as the basic channel (BCH). This channel can be correctly heard by all the terminals within the same OH-cluster and is used to transmit FI, other signalling information, and also payload information.

2.1. RR-ALOHA basic operation

For each BCH slot composing a BCH, each terminal transmits a packet containing FI, that is a vector with N entries specifying the status of each of the preceding N slots, as observed by the terminal itself. The slot status can be either BUSY or FREE: if a packet has been correctly received or transmitted by the station it is BUSY, otherwise it is FREE. In the case of a BUSY slot the FI also contains the identity of the transmitting terminal.

Based on received FIs, each terminal marks a slot as RESERVED or AVAILABLE according to

Rule 1. The next slot, say slot k is labeled as RESERVED if slot $k - N$ is coded as BUSY in at least one FIs received in the slots from $k - N$ to $k - 1$; otherwise it is labeled as AVAILABLE.

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 (a time frame), the outcome of its transmission according to

Rule 2. The transmission is successful if the slot is coded as "BUSY by station j" in all the received FIs; otherwise the transmission has failed.

To be successful, rule 2 requires that the transmission be correctly received by all the terminals belonging to the OH-cluster of the transmitting terminal. This guarantees that the slot remains AVAILABLE not only if collision has occurred, but also when, because of receiver capture, the terminals decode different concurrent access attempts correctly.

To show the correctness of the above procedure in setting up a channel it must be shown that no attempt at access can be made in a slot already in use when such access would cause a collision. To do this, let us first consider a single TH-cluster network composed of three OH-clusters (see figure 2). According to the above rules we can state that:

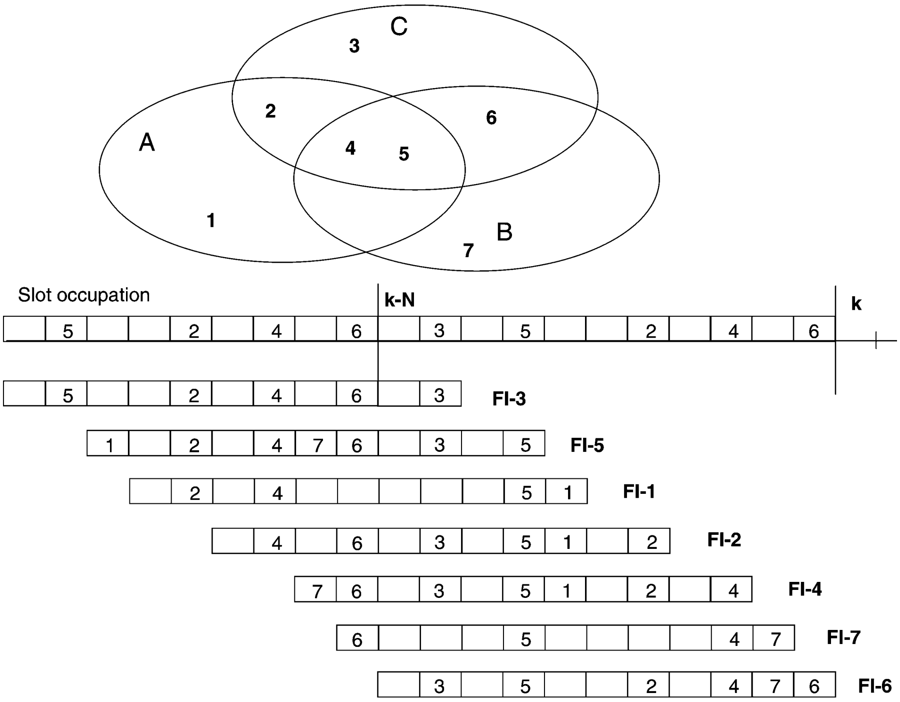


Figure 2. Example of the FI information propagated by the terminals in the one-hop clusters A, B, and C.

1. All terminals belonging to the same TH-cluster mark the slots in the same way. In fact, all the terminals receive the FI generated by the terminals belonging to the common TH-cluster set (terminals 4 and 5 in figure 2) and such FI concerns all the transmissions in the TH cluster itself. According to rule 1, one BUSY code alone is enough to force a RESERVED slot.
2. Any slot signaled as BUSY by any terminal is recognized as RESERVED by all the terminals in the TH cluster and therefore, since a reserved slot cannot be accessed, no other terminal within the TH-cluster can transmit, and no collision will occur.

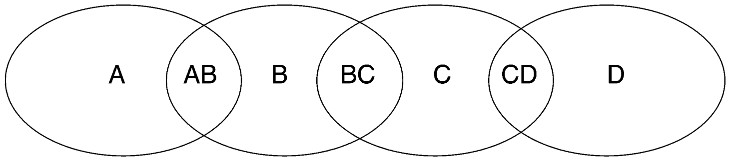
In the general case the network can be seen as being composed of several, not disjoint TH-clusters. Here it must be shown that a slot already in use in a TH-cluster cannot be accessed by terminals within the cluster itself (first step), nor can the slot be accessed by any terminal, outside the considered TH-cluster, that could collide with the transmission in the slot (second step). The first step is proven by the same arguments used for the single TH-cluster network. In fact, all the slots in use in a TH cluster are marked RESERVED by all the terminals in the same cluster. For example, let us consider the network of four OH-clusters shown in figure 3: TH-cluster 1 is composed of A, AB, B and BC areas, where the labels in the figure mark disjoint areas. The relevant FI information is propagated by the terminals in AB. The second step is demonstrated by considering overlapping TH-clusters. From step one it can be seen that collisions in each TH-cluster, e.g., $A + AB + B + BC$ and $AB + B + BC + C + CD$, are avoided; therefore no collision is guaranteed throughout the TH-clusters. Note that concurrent transmissions can take place safely if the terminals belong to disjoint clusters, e.g., those in A and $C + CD + D$. In fact, a common terminal able to propagate slot status information cannot exist.

Note that the transmission of terminals belonging to disjoint OH-clusters cannot collide at any terminal they reach, therefore the slots can be reused. However, since terminals are connected by overlapping TH-clusters, the reuse of one slot in an OH-cluster can still be constrained by the slots in use in the disjoint OH clusters. To illustrate this effect figure 3 shows an example of the slot marking, observed at different terminals, where the area labels also denote terminals in the area. For the sake of clarity the RESERVED slots are represented by the corresponding terminal identity. Note that some terminals can receive FIs denoting the same BUSY slot for different terminals. This is the case of terminal B: it receives FI from AB, denoting slot 1 BUSY to terminal A, but also receives FI from terminal BC, denoting slot 1 BUSY to terminal C (the reservation is marked as $A + C$). In fact, quite correctly, the two terminals in A and C can transmit in slot 1 because A does not detect the FI from BC and C does not detect the FI from AB. Similarly, terminals lying at least three hops apart can reuse the same slot as they can never collide with each other. This shows that the goal of avoiding collisions is achieved with an optimal use of slots.

Thus it can be seen that the procedure achieves the proposed goal of setting up channels with no interference if the cluster configuration does not change. However, when the clusters merge because of terminal migration or activation, transmission collision in established channels can still occur. In fact, transmissions in a given slot, properly reserved for different terminals belonging to disjoint clusters would, upon merging, collide at the new common terminals. The continuous checking of rule 2 by transmitting terminals makes colliding terminals become aware of any collision. When a collision is discovered, the slot is released and a new set up procedure is started.

2.2. Additional bandwidth reservation

The BCH assigned to each active terminal (see previous section) can also be used to transmit, in addition to FI, other service information, e.g., for routing, and user data. However, if the bandwidth provided by BCH is not enough to accommodate the user applications, additional bandwidth can be obtained by assigning those slots not yet reserved.



slots

1	2	3	4	5	6	7	8	9	10	11	12	13	
A	B	AB		BC	B	BC	AB	A	B		A		A
A+C	B	AB	C	BC	B	BC	AB	A+CD	B	BC	A+C	CD	AB and B
A+C	B+D	AB+D	C	BC	B+D	BC	AB	A+CD	B	BC	A+C	CD	BC
C	B+D	AB+D	C	BC	B+D	BC	AB	CD	B	BC	C	CD	C and CD
C	D	D	C	BC	D	BC		CD		BC	C	CD	D

Figure 3. Example of how terminals belonging to the labeled disjoint areas perceive reservation of slots.

A terminal can reserve one or more additional slots using either the RR-ALOHA procedure, or, more effectively, by signaling a slot reservation request in the BCH. On receiving the first slot reservation, the terminal updates its FI by marking the new reserved slot as BUSY. Further reservation requests for the same slot are ignored. Rule 2 is still valid to recognize whether a reservation has been successful or not. Instead, when a reservation is made through BCH, more sophisticated procedures, that also use priority information, can be designed. Such procedures might be desirable when applications with different QoS are considered. In fact, a high priority application can preempt a lower priority transmission, e.g., by causing collision or by appropriate signaling.

2.3. Point-to-point transmission

The procedure described provides, and guarantees, a reliable broadcast channel within an OH cluster. If the application requires a point-to-point channel, the procedure can be modified to increase the overall bandwidth efficiency by exploiting, when possible, slot reuse in adjacent OH-clusters. For this purpose a new flag, the FTP flag, is added for each slot in the FI, and is managed according to

Rule 3. A terminal sets the FTP flag in the FI if the received packet is a broadcast packet or if it is destined to the terminal itself.

To set up a point-to-point channel use can be made of both the AVAILABE slots and the RESERVED ones according to

Rule 4. A RESERVED slot can be accessed if:

(i) the FTP flag signaled in all the received FIs is off; and

(ii) the FI received from the destination terminal signals the slot as FREE.

The conditions are such that no collision can ever occur at the interested receivers if the channels are activated one at a time. Figure 4 shows correct operation. The cases a and b in the figure consider two transmitting terminals, say 1 and 2, belonging to different not disjoint clusters. Assuming that terminal 1 has already activated a FTP channel with destination 3, terminal 2 can transmit using the same slot if the conditions in rule 4 are satisfed. In case a, terminal 2 can use the same slot as terminal 1 even if it is signaled as RESERVED. In fact, the only FTP flag ON is that in the FI transmitted by terminal 3 and not received by terminal 2 (satisfying condition (i)), and the FI generated by terminal 4 marks the slot as FREE (satisfying condition (ii)). In case b the FI, generated by terminal 3 and received by terminal 2, prevents terminal 2 from transmitting (not satisfying condition (i)). In this case parallel transmission would, in fact, interefere at terminal 3, thus destroying the already activated FTP channel. In cases c and d the two transmitting terminals belong to the same cluster. In case d terminal 3 can use a RESERVED slot since both conditions (i) and (ii) are satisfed, while in case c condition (ii) is not satisfed and a collision would o ccur at terminal 4. Note that case d is the one referred to in literature as "the exposed terminal" problem [4].

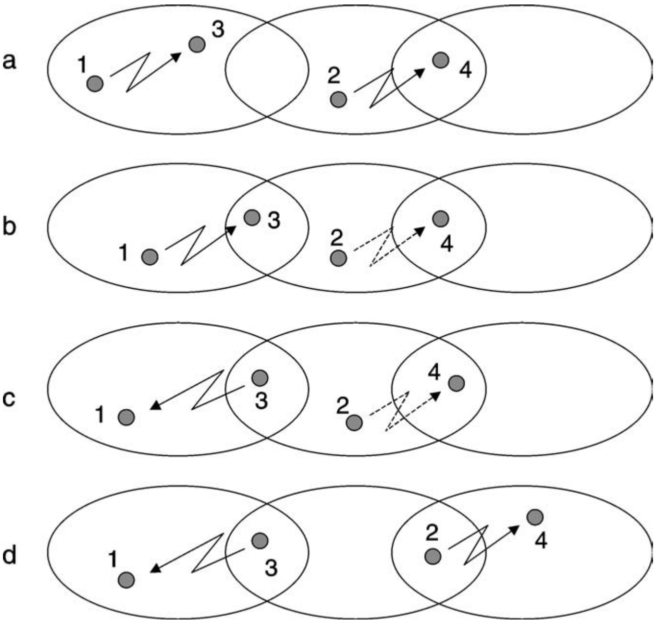


Figure 4. Examples of parallel transmissions. Transmission from terminal 1 is established first. Allowed transmissions by terminal 2 are indicated by solid arrows.

If several access attempts occur concurrently, collisions can still occur, and the transmitting terminal must then perform a further check, according to

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

2.4. Multi-hop broadcast service

So far we have considered broadcast and point-to-point transmissions among terminals in the same OH-cluster. Let us now extend the ADHOC-MAC operation to a broadcast service 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.

A possible approach to this service is the *flooding* procedure. With flooding, all the terminals relay broadcast packets at least once. The procedure is reliable, but has the drawback of generating excess retransmission, resulting in a highly inefficient use of bandwidth. ADHOC-MAC uses a small number of relaying terminals able to cover all the network.

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 i, i.e., all the terminals in the same OH-cluster, and $\mathcal{C}_j$, for any $j \in \mathcal{C}_i$, the sets of neighbors of the i 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 by $\mathcal{S}_i$ ($\subseteq \mathcal{C}_i$). All these sets are identified by terminal i through the information carried by the FIs received in the N slots following slot k. In fact, set $\mathcal{C}_i$ contains all the terminals from which terminal i has received FI, the set $\mathcal{C}_j$, for each $j \in \mathcal{C}_i$, is identified by the entries in the FIs received by the terminal j. The set $\mathcal{S}_i$ includes only those neighbors that have not marked slot k as BUSY by terminal z.

At slot $k+N$, terminal i will recognize whether or not it needs to relay the broadcast packets according to

Rule 6. Terminal i does not relay the packet if $\mathcal{S}_i = 0$ or if, for at least one $j \in \mathcal{C}_j \backslash \mathcal{S}_j$, the following condition is satisfied

$$\mathcal{S}_i \subseteq \mathcal{C}_j \text{ and } \big(|\mathcal{C}_j| > |\mathcal{C}_j| \text{ or } (|\mathcal{C}_j| = |\mathcal{C}_i| \text{ and } ID_j > ID_i)\big),$$

where ID_i denotes the address of terminal i.

Basically, terminal i does not relay the packet if its set $\mathcal{S}_i$ is a subset of $\mathcal{C}_j$ and if either $\mathcal{C}_j$ has higher cardinality than $\mathcal{C}_i$ or, having the same cardinality, the address of j is higher than the address of i. According to rule 6 only selected terminals will relay the broadcast packets, thus significantly reducing the number of retransmissions with respect to flooding. Even if the optimality of this procedure is not guaranteed in the general case, it is worthwhile noting that, in most cases, the minimum set of relaying terminals needed to cover the whole network is selected.

Let us first refer to single TH-cluster networ ks like the one in figure 2, where one terminal alone, if properly selected, is enough to guarantee the correct delivery of a broadcast packet generated by any terminal. If, for instance, the transmitting terminal is in the common area, say terminal 4, all terminals receiving the broadcast packet will have $\mathcal{S}_i = 0$, and no node will retransmit. In this case the broadcast is achieved at the physical layer. This is not the case if terminal 1 generates a broadcast packet. Terminals 2, 4 and 5, neighbors of 1, are candidates to relay the packet. Terminal 2 identifies $\mathcal{S}_2 = \{3, 6\}$ and from the FI information from terminals 4 and 5 discovers that $\mathcal{S}_2$ is a subset of $\mathcal{C}_4$ and $\mathcal{C}_5$ whose cardinalities are higher than $\mathcal{C}_2$; terminal 2 then refrains from transmitting. Terminal 4 identifies $\mathcal{S}_4 = \{3, 6, 7\}$ that is a subset of $\mathcal{C}_5$. Since $\mathcal{C}_4$ has the same cardinality as $\mathcal{C}_5$, terminal 4 refrains from transmitting because terminal 5 has a higher address. The same procedure correctly leads terminal 5 to retransmit the broadcast packet.

In the more general scenario with several nondisjoint TH-clusters as, for instance in figure 3, a broadcast packet is relayed by only one terminal per joint area. As an example let us consider a terminal in A transmitting a broadcast packet. Only terminals in AB will have $\mathcal{S}_i \neq 0$ and, according to rule 6, only the terminal with the highest address will retransmit. The retransmitted broadcast packet reaches the terminals in B and BC. Those in B have $\mathcal{S}_i = 0$ and only the highest address terminal in BC will retransmit. The procedure reiterates until all areas have been reached. Also in this case the broadcast service has been achieved with the minimum number of retransmissions. The same arguments apply to a more general network configuration where the concatenated OH-clusters do not form cycles. If this is not the case (see the simple topology in figure 5), one useless retransmission can occur per cycle. The broadcast service of a packet generated in A is guaranteed by 3 retransmissions by terminals in AB, AD and (BC or CD), while, according to rule 6, one terminal in BC and one in CD will retransmit.

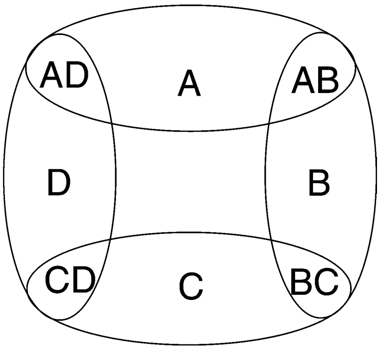


Figure 5. Example of a network where the concatenated OH-clusters form cycles.

3. Performance evaluation

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

3.1. Implementation overhead

The protocol overhead of the basic RR-ALOHA described in the previous section depends on the number of slots N 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 any terminal is to set up additional channels, N must be much larger than M.

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

As an example of 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 identifier (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 FTP 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 is needed by the MAC in the access phase only, but must be repeated to let new active terminals 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 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 the expense of increased overhead, to maintain the 100 ms frame duration and the related time responsiveness.

3.2. Time responsiveness

An important protocol performance figure is the time needed for 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 collide, is given by:

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

that 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 the terminals know, by the FI, 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 only after one entire frame, 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.

Figure 6 shows the average number of terminals that have successfully acquired a slot, as a function of the number of frames, 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.

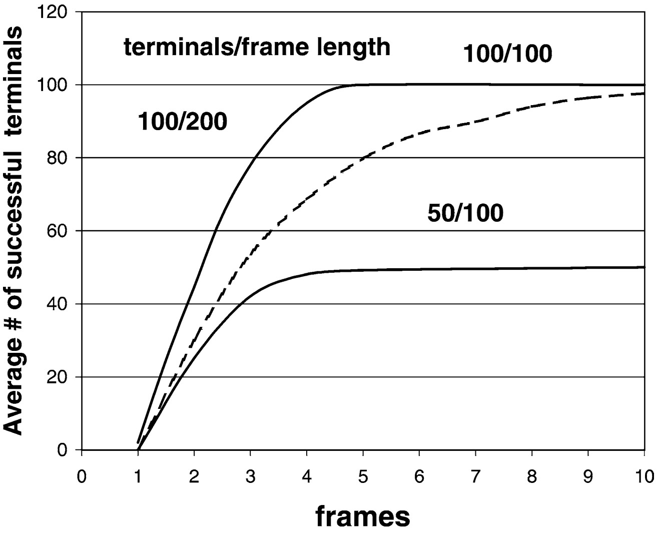


Figure 6. Average number of terminals that have successfully accessed their slot as function of the frame number.

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 the terminals achieve their slot within 6 frames, i.e., within about 600 ms, according to the parameters given in the previous section. In the case 100/100, the period is almost doubled because the acquisition of an AVAILABLE slot is more contentious.

4. Conclusions

This paper presents a new MAC protocol for ad hoc networks, ADHOC-MAC, that is able to overcome most of the problems recognized in existing MAC architectures, more specifically, "hidden" and "exposed" terminal problems and reliable broadcasting.

The protocol is based on a dynamic TDMA in which a broadcast signaling channel is set up, in a completely distributed way, by the RR-ALOHA protocol, also part of ADHOC-MAC. From this channel, all the terminals know the activity of their two hop neighbors and can thus avoid collisions with already set up connections, obtain prompt access to further bandwidth, and implement optimal multihop broadcast service and parallel transmissions.

Although ADHOC-MAC uses a slotted structure, the architecture 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 the protocol of choice for applications requiring energy saving features, but it does appear a good approach for inter-vehicle communications.

We have shown the feasibility of the protocol and provided basic figures on its efficiency when implemented on practical channels. Simulation results have proven that the broadcast channel set-up delay is in the order of few hundred ms, a value suitable for most applications, especially in the inter-vehicle communication scenario. Work is in progress to define implementation details, and to obtain more accurate performance evaluations by taking all the parameters of real network scenarios into consideration.

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