RR-ALOHA, a Reliable R-ALOHA broadcast channel for ad-hoc inter-vehicle communication networks

Flaminio Borgonovo, Antonio Capone, Matteo Cesana, Luigi Fratta
Dipartimento Elettronica e Informazione
Politecnico di Milano
{borgonov, capone, cesana, fratta}@elet.polimi.it

Abstract— Ad-hoc networking is under evaluation for inter-vehicle communication architectures. In spite of the large existing literature, many problems generated by the peculiarity of this specific scenario are still unsolved. In this paper we present a novel MAC protocol, RR-ALOHA, able to guarantee a reliable single-hop broadcast communication in an ad-hoc network environment where the hidden terminals problem exists. This protocol is designed for the inter-vehicle communication architecture based on UTRA-TDD slotted physical channel, but can be easily modified to operate on other standard physical layers. According to this protocol any active terminal can reserve a channel by capturing a slot in the frame. Reliable communication is guaranteed, after access, even in presence of hidden terminals thanks to the information exchanged by the active terminals. The operation of the protocol is completely distributed and enables also to install channels of different speeds to satisfy QoS of different services. The protocol feasibility and some basic performance figures are discussed to prove the effectiveness of the protocol itself in the inter-vehicle communication scenario.

I. INTRODUCTION

Recently, ad-hoc networking has been proposed for inter-vehicle communication architecture both for traffic safety enhancement and for entertainment purposes [1], [2], [3]. In such an environment, data exchange between cars has great local relevance and communications take place in traffic platoons that move at considerable speed; for these characteristics of the system, the ad-hoc solution can provide a more stable configuration than a solution using fixed infrastructure such as cellular systems. However, the traffic-control application poses a severe challenge to the design of an effective communication system, since it requires contemporary exchange of information among many vehicles that may change very frequently in their number and identity. Although the routing mechanism play a relevant role in ad-hoc networks [4], [5], a correct MAC layer design, with broadcast capabilities, is fundamental in providing feasible and efficient communications.

Layer-two connectivity with neighbors nodes, as they move in and out the vehicle platoon, can be easily assured by the broadcast nature of the radio medium, and layer two point-to-point channels can be set up with protocols that use the RTS/CTS (Request To Send/Clear To Send) mechanism with real time ACK, as in IEEE 802.11 [6]. Also R-ALOHA-like mechanisms [7] have been proposed to access and reserve slots in a framed medium, although in these proposals medium critical aspects, such as the hidden-terminal problem, have often been overlooked. The hidden-terminal problem is normally encountered in ad-hoc networks and arises when terminals, that have complete broadcast connectivity within a cluster, present limited connectivity with terminals belonging to different clusters. It can therefore happen that terminal B "sees" terminals A and C, but A and C do not see each other so that they can not coordinate their transmissions and avoid collisions at terminal B (see [8] for a comprehensive review of point-to-point protocols proposed to avoid the hidden-terminal problem in point-to-point communications).

Because of their incomplete connectivity and their changing topology, mobile ad-hoc networks pose a severe challenge on routing algorithms, and especially on broadcast service that must exploit multi-hop connections, like in wired networks. Furthermore, efficient routing procedures must exactly know the neighbors that can be reached by a single hop transmission. However, differently to wired networks, where connections with neighbor nodes are automatically activated so that routing and application information can be propagated, in ad-hoc networks layer two connections can only be used once they have been established by a neighbor discovering procedure.

Although neighbors communicate in the broadcast medium, the difficulties in making a reliable single-hop broadcast communication has lead to propose flooding, and its variants, as the preferred means on which propagate routing and broadcast service [9]. With flooding, each neighbor that receives a broadcast packet retransmits it just once until all terminals are reached. However, this practice is highly inefficient in networks that present an high degree of connectivity, as in the case with traffic platoons. In fact, in networks of n terminals where all of them "see" each other, flooding requires n transmissions of the same information whereas a reliable connectivity information on terminals reachable in one hop would require just one transmission.

Furthermore, in vehicular control applications, vehicles continuously exchange some background information, such as cruise parameters, which is intrinsically single-hop broadcast because directed mostly to neighbor vehicles. Again, a flooding procedure would saturate the whole network with information of no use for most terminals.

The above limitations and inefficiencies could be avoided by a MAC service able to provide a reliable single-hop broadcast channel to communicate with neighbors in the radio transmission range. With this basic service the MAC can immediately be extended to offer additional services such as:

- prompt and reliable layer two connectivity information on which reliable routing and multihop broadcast service can be built;
- single-hop broadcast service, especially needed for car control applications;
- a fail safe means to reserve additional bandwidth and QoS as the applications require, in a complete distributed way.

In this paper we present such a protocol, the Reliable R-ALOHA (RR-ALOHA), which is a distributed MAC layer architecture that implements a reliable single-hop broadcast channel among all neighbor terminals. RR-ALOHA extends the R-ALOHA protocol to safely operate in an environment that suffers from the hidden-terminal problem, and is also able to provide reserved channels of variable bandwidth according to terminals needs, as required by QoS procedures.

Though the proposed MAC protocol can be made to operate on the physical layer of different standards, it is particularly apt to the slotted physical layers such as the one provided by the UMTS Terrestrial Radio Access TDD that has been chosen in the FleetNet Project [1].

Recently, a protocol devised for reliable channel reservation in ad-hoc networks, FPRP [10] has been proposed. As this protocol presents some aspects that are close to RR-ALOHA, a short discussion of targets and operations of the two protocols will be given after RR-ALOHA introduction, in the next section.

The paper is organized as follows. In Section II we present the basics of the new protocol, show its correct operation and discuss its relation with FPRP. 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 proposed MAC protocol

For sake of simplicity we refer to a physical layer that operates with a slotted time axis assumed unique all over the network. Slots are grouped into frames of length N.

We here describe the basic protocol, RR-ALOHA, whose main purpose is to assign, in a distributed way as in R-ALOHA, a basic channel (BC) to each terminal. BC is intrinsically broadcast, composed of one slot per frame, and propagates, beside application information, service information that guarantees reliable use of the broadcast capability of the channel. This basic service can then be used to reserve additional slots on the frame, either for point-to-point or broadcast operation as required by applications.

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 and avoid to collide with ongoing transmissions.

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 basic channels to distribute the terminal's view of the state of each slot in the frame, therefore providing the information and acknowledgment for any transmission on the channel.

A. RR-ALOHA basic operation

The packets transmitted in the basic channel 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 Frame (SF), i.e., the N slots preceding the considered slot. The status information of a slot specifies whether it contained a successfully decoded packet, together with the identity of the transmitting station (BUSY slot), or not (FREE slot). At each slot, the FIs received in the SF are used to update the status of the following N slots. A slot is recognized as reserved (RES) if coded as BUSY in at least one FI, otherwise it is defined available (AV).

An AV slot can be used to transmit a packet by any terminal that wish to set up the BC. If the transmission is successful, it will be recognized by all the terminals and the corresponding slot will be signaled in the FI as a BUSY slot. Otherwise it is recognized as FREE, meaning that the transmission attempt has failed and the terminal must attempt again in a subsequent AV slot. A RES slot is dedicated to the terminal who has acquired it: no other terminal can use it until it is released.

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.

At network start up, all slots are AV, and terminals start transmitting according to the protocol described until all of them have acquired their own BC. Further channels can be acquired by signaling the request in the BC. BC are automatically released as terminals turn off or exit the transmission range of all other terminals active in the frame.

B. RR-ALOHA correctness

To show the correct operation of the protocol, let us refer to the case shown in Figure 1 in which terminals are grouped into clusters A, B, C, and D. The terminals of each cluster enjoy full connectivity within the cluster but do not communicate between clusters if they are disjoined. In this case transmissions of different clusters do not interfere each other and slots are completely reused, giving rise to different frames in

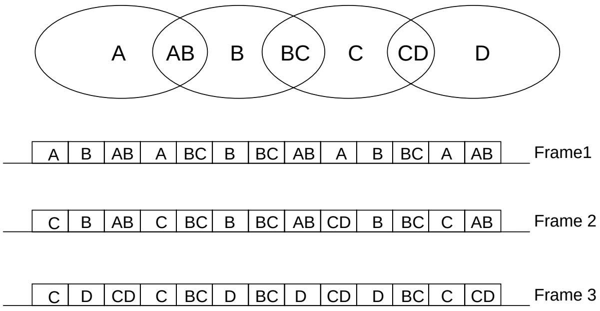

Fig. 1. *Example of how transmissions in frames become organized.*

different clusters. If clusters overlap, a typical scenario in the application considered, terminals belonging to joint subsets AB, BC, and CD, have full connectivity with both adjacent clusters and therefore suffer from the hidden terminal problem. For example, terminals in A do not see all terminals in B. However, as long as at least one terminal is active in set AB, it will provide, according to RR-ALOHA, the FI regarding all the clusters it belongs to (more than two in the general case). The FIs prevent terminals in A to interfere with terminals in B and vice-versa. All the terminals of A and B transmit in their own slots on the same frame, Frame 1 in figure 1. Again terminals of BC see the transmissions of both B and C but not those in A that do not belong to B. Terminals in C do not receive transmissions from the set AB an therefore are free to reuse the slots that are also used by A, yielding Frame 2 in figure 1. Frame 3 represents a possible frame used by terminals in clusters C and D.

C. Comparison with FPRP

FPRP, like RR-ALOHA, aims to establish channels on a frame in a distributed and reliable way. However, many are the differences in the procedure and in the achieved goals. In the following, we just mention the most relevant differences and make some comments, leaving elsewhere a more detailed comparison.

RR-ALOHA establishes a slot reservation immediately, upon a successfully transmission, which is known, through FI, to all the involved terminals within one frame. Differently, in FPRP reservations are accomplished in five phases. The first phase uses special slots in the frame to make reservations for information slots because in reservation slots the other stations listen to discover collisions. In which case a negative acknowledgment is transmitted back, solving the hidden terminal problem (second phase). In phase three the originating terminal repeat the access to reserve information slots, and in phase four all terminals that see the reservation transmit an acknowledge to inform hidden terminals of the confirmed reservation. A fifth phase is used to rearrange transmissions and eliminate deadlocks.

A first relevant difference is that RR-ALOHA continuously provides the terminals with up-to-date connectivity information, that avoid the hidden terminal problem at set up, but also in subsequent periods when new terminals enter and leave the cluster. FPRP, on the contrary, reserve the channel by exchanging some signaling messages in the initial phase only, and can not prevent subsequent collisions as new terminals, which use the same slot, enter the cluster as hidden terminals.

Furthermore, FPRP appears to be slower, more complicated and less reliable than RR-ALOHA, but, most important, it requires the capability to detect collisions (in phase two), which is absolutely not granted in the wireless environment. Furthermore, correct operation is based on the successful decoding of NACK messages, which also can not be guaranteed.

III. Performance evaluation

In this section we present some preliminary performance evaluation 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 in the FI for each slot. Since the active terminals must transmit at least once in a frame, N depends on the number of terminals M that the system must accomodate.

In addition, if we allow any terminal to set up additional channels, N must be much larger than M. For example, as reasonable figures for the inter-vehicular communication scenario, 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 (STI) that serves to identify the station that has successfully captured a slot. This is needed because the same slot can contain different transmissions, all correctly detected at some terminals due to the hidden terminals effect. Their STI, broadcast in the FI by the active terminals, allow transmitting terminals to assess the actual capture of the slot. These STI are selected at random and changed if already in use. An STI of 8 bit is sufficient for the network size assumed.
- a Priority Status field (2 bits). This information can be used to distinguish channels with different QoS: channels with lower priority can be preempted by higher priority transmissions.

With $M = 100$ and $N = 200$ the overhead introduced by the FI is 2200 bit. Further fields to be transmitted in a slot are those relevant to the RR-ALOHA operation, such as the identifier 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. To achieve a MAC efficiency of about 50% would require packet sizes of about

5000 bits. The overall frame duration, assuming a 10 Mb/s channel speed, will be 100 ms, an acceptable value for the time resolution needed by the application to detect connection changes.

If the number of slots in a frame is greater than the number of stations, as assumed above, the efficiency increases because the FI information need not to be transmitted more than once in a frame, i.e. one in each M slots used by the basic channel. This overhead compression would require packets with variable structure and different payload and, in our example reduces the overhead to 25%.

A further FI overhead reduction can be obtained by including the STI only for slots that are accessed for the first time. This information, in fact, as seen above, is needed by the MAC in the access phase only. The FI is then reduced to 600 bit, and the packet size can be set to about 2000 bit, which, with the 3.84 Mb/s channel of UTRA-TDD, still yields a 100 ms frame.

B. Time responsiveness

An important performance figure of the protocol is the time needed to a new active terminal to acquire the broadcast channel. According to RR-ALOHA, a new terminal willing to set up a channel will attempt transmission with probability p in the next AV slot. The probability that one among k contending terminals gains access, i.e., its transmission is 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. 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 2 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 suffer from the hidden terminal effect, so that all transmissions are ”heard” by all stations.

We have considered three cases in which the number of terminals (M) and the number of slots in a frame (N) 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, 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 AV slot.

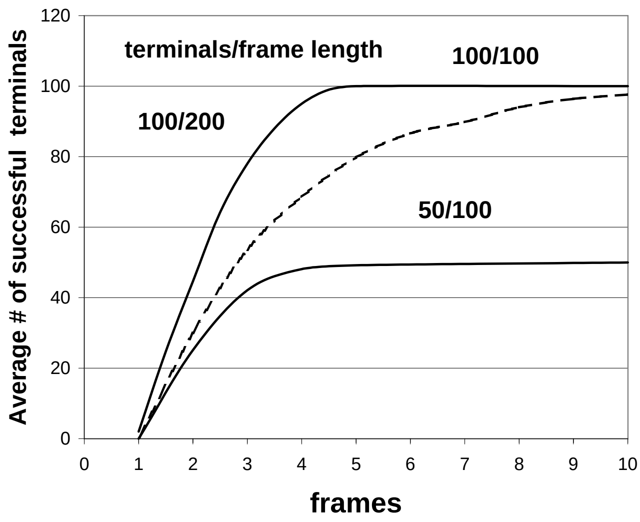

Fig. 2. *Average number of terminals that have successfully accessed their slot as function of the frame number.*

IV. Conclusions

In this paper we have presented RR-ALOHA, a novel MAC protocol able to guarantee a reliable single-hop broadcast communication in an ad-hoc network environment where the hidden terminals problem exists. This protocol has been designed for the inter-vehicle communication architecture based on UTRA-TDD slotted physical channel, but can be easily modified to operate on other standard physical layers.

The information used by the terminals to correctly share the common slotted channel in a completely distributed way is exchanged through the Frame Information transmitted by all terminals together with their payload information. The RR-ALOHA enable any active terminal to reserve a channel by assigning a slot in the frame. A terminal willing to use an higher speed channel may extend its reservation to more slots in a frame using the basic channel.

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 channel set-up delay is of the order of few hundreds of ms, a value suitable for most of the applications in the inter-vehicle communication scenario. A 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] Hartenstein H., B. Bochow, A. Ebner, M. Lott, M. Radimirsch, D. Vollmer, *Position-Aware Ad Hoc Wireless Networks for Inter-Vehicle Communications: the Fleetnet Project*, Proc. ACM MobiHOC 2001, Long Beach, USA, Oct. 2001.

[2] 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.

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

[4] M. Mauve, J. Widmer and H. Hartenstein, *A Survey on Position-Based*

Routing in Mobile Ad-Hoc Networks, in IEEE Network Magazine, November 2001.

[5] E.M. Royer and C.K. Toh, *A review of current routing protocols for ad hoc mobile wireless networks*, In IEEE Personal Communications, April 1999.

[6] 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.

[7] 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.

[8] 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.

[9] Brad Williams, Tracy Camp, *Comparison of broadcasting techniques for mobile ad hoc networks*, Proc. ACM MobiHOC, Lausanne, Switzerland, June 2002.

[10] Chenxi Zhu , M. S. Corson, *A Five-Phase Reservation Protocol (FPRP) for Mobile Ad Hoc Networks*, Wireless Networks, Volume 7, Issue 4, September 2001.