CROMA - a New Medium Access Protocol for Mobile Ad hoc Networks

M. Coupechoux*°, C. Bonnet*, and V. Kumar°
*Institut Eurecom, Mobile Communications Department, Sophia Antipolis, France
°Alcatel CIT, Research and Innovation, Marcoussis, France
Tel.+33 1 69 63 43 59, Fax.+33 1 69 63 43 60, marceau.coupechoux@ms.alcatel.fr

Abstract

A new medium access protocol for mobile ad hoc networks, called CROMA is proposed. CROMA is collision-free and receiver-oriented. It operates in a slotted environment in a dynamic and distributed way. In this protocol, receivers act as local base-stations and can manage one or several communications on a single slot. Thus, sophisticated functions are allowed at higher layers. Moreover, the hidden terminal as well as the exposed terminal problems are handled by CROMA. A theoretical analysis and extensive simulations show that CROMA can reach very high throughput provided that senders reserve receiver resources for several slots.

Keywords: ad hoc networks, manet, medium access, TDMA, receiver oriented, collision-free, slotted environment.

1 Introduction

In recent years a lot of effort has been spent in the design of protocols for mobile ad hoc networks. Such packet networks are mobile and multi-hop and operate without any fixed infrastructure. This can be a low cost and easily deployable technology to provide high speed Internet access in a wireless environment, to organize networks of sensors, or to complement the coverage of future cellular networks.

In this paper, we pay special attention to the medium access control (MAC) sub-layer. It has a lot of impact on the system performance and its design is a very challenging issue. MAC should control access to the medium and share the channel between source-destination pairs and/or flows of data in a dynamic and distributed way. Some desirable features of the access protocol are its ability to reuse the resources as efficiently as possible, to avoid congestion and collisions, to be fair, reliable, and energy efficient.

Many MAC protocols try to address these issues. In the literature two categories of schemes have been proposed.

1. The contention based schemes, and
2. The conflict-free schemes.

In the contention based protocols, the channel has to be acquire by the nodes for each packet to be transmitted. Examples of contention based schemes are CSMA/CA, MACA, MACAW, FAMA, IEEE 802.11. The latter seems to be very popular in most of the testbeds because IEEE 802.11b products are available off the shelf. Although IEEE 802.11 is flexible, robust and simple, a recent paper claims that it may not do very well in a multi-hop environment. According to [1], 802.11 has still the hidden terminal problem, does not handle the exposed terminal problem at all and its backoff strategy leads to severe unfairness.

On the other hand, conflict-free protocols allow the reservation of the channel for a certain amount of time or data and transmissions are conflict-free. Deterministic scheduling may be preferred for networks with heavy load, carrying mixed traffic and realizing sophisticated functions at higher layers. That is the reason why we propose in this paper a slot allocation protocol for mobile ad hoc networks.

Unfortunately, most of the scheduling problems are NP-complete. For example, Arikan [4] has shown that constructing an optimal schedule for the point-to-point scheduling problem to optimize throughput is NP-complete. And this is the same for the broadcast scheduling problem based on throughput optimization, as proved by Ephremides and Truong [3]. Consequently, MAC designers have focussed on sub-optimal, dynamic and decentralized solutions for the slot assignment problem.

A first class of scheduling protocols relies on the allocation of priorities to nodes. A given slot is assigned preferably to the node with the highest priority according to its offered traffic. Slots can be allocated by using a control channel, e.g. in [2]. Priorities of the neighbors are assumed to be known at each node and are allocated in a pseudo-random way as in [5]. Then different strategies can be applied for the allocation of the priorities in order to have a fair and efficient share of the channel (see e.g. [10]). However, these protocols suffer from a high overhead due to the control channel or they do not address the problem of the distributed and dynamic assignment of priorities.

On the other hand time-spread protocols seem to be very attractive because they are topology-independent (see e.g. [6] or [7]). However, the frame length makes them less scalable and this class of protocols faces also the problem of distributed and dynamic code assignment.

At last the necessity to address the problem of mobility, topology changes, and scalability gives rise to a family of protocols where the reservation of the slots is done via a random access, most of the time a handshaking, combined with a carrier sensing mechanism. FPRP [8] proposes a five-phase handshaking supported by a pseudo-Baysian algorithm to enable a faster convergence of the reservation procedure. CATA [9] uses four mini-slots in each time-slot to enable unicast and multicast transmissions. The protocol proposed in this paper comes within this family of protocols. It tries to adapt the advances of the most popular contention based protocols to a slotted environment in order to increase their efficiency.

The paper is organized as follows. In section 2, we give a precise description of our proposed MAC protocol. We examine the correctness of this protocol in section 3. Section 4 gives an approximate throughput performance through analysis and simulations in a fully connected network. At last, sections 5 and 6 focus on discussion, conclusion and further work.

2 Protocol Description

The Collision-free Receiver-oriented MAC (CROMA) is a medium access protocol for mobile ad hoc networks that schedules transmissions in a slotted environment. It is a dynamic and distributed protocol that operates on a single-frequency channel with omnidirectionnal antennas. In CROMA, a requesting node has to reserve resources at its intended receiver during the random access phase. These resources are reserved for a message that is made of a certain number of data packets. A sender is allowed to transmit a packet on a slot when it is polled by the receiver. The latter can share its resources among several senders, e.g. according to higher layers requirements. The number of simultaneous communications on a single slot is however limited by the protocol. So each receiver acts as a local base-station. When topology changes or at the end of a message, the transmission is released and a new random access phase begins.

2.1 Frame Structure

CROMA divides time in frames that are divided in L equal time-slots. Synchronization is a very critical issue for all distributed TDMA systems. However, as in [8] and [9], this paper focuses on the protocol description and considers that synchronization is a realistic assumption (see Section 5 for discussion on this topic). Each time-slot is divided in three parts: two mini-slots, called REQ (request) and RTR (ready to receive) for the signaling and a data transmission phase, called DATA (see Fig. 1). The REQ-mini-slot is used by requesting nodes for the random access phase, the RTR-mini-slot is used by their intended receivers to acknowledge requests and previous data transmissions, and to poll the senders that managed a successful reservation. During the DATA phase, senders transmit data packets when they are polled by the receiver.

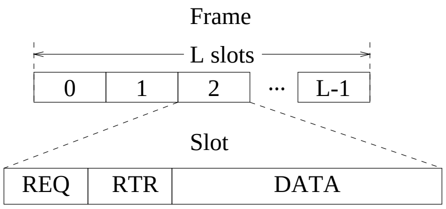

Figure 1: Frame Structure of CROMA

2.2 Reservation

In the reservation phase requesting nodes contend to get access to a receiver. This access is done in a random way during the REQ phase of the slots as follows.

1. The requesting node listens during an entire frame to the activity in its neighborhood.
2. It chooses for its transmission a slot where its intended receiver has already the floor, or a slot where it sensed no activity. In the first case, the

slot is said to be occupied, whereas in the second case, the slot is said to be free.

3. On the chosen slot, the reservation is done by using the slotted ALOHA scheme on the successive REQ-mini-slots of this slot. In case of failure, a backoff algorithm is started.
4. If the request is correctly received by the intended receiver and if the communication is allowed, the receiver acknowledges the request in the next RTR.
5. The sender whose request has been successful waits for the polling by the receiver.

The REQ-packet is made of the MAC addresses of the requesting node and of its intended receiver. A field is also foreseen for QoS requirements needed by the communication.

Note that an RTR-packet has a field, called the access field, to answer the requesting nodes. This field can take three values: ACKREQ, NACKREQ, or 0. In the first case, a request has been successfully received and the communication has been allowed by the receiver. On receiving NACKREQ, the requesting node knows that the request has been successfully received, but the transmission is not allowed. This can be the case, if some QoS requirements cannot be fulfilled by the receiver, or if the number of communications on this slot has reached its maximum value. If the receiver didn't receive correctly the REQ-packet because of bad channel conditions or collision, it sends 0 in the access field. If the sender receives ACKREQ, it enters the transmission phase. If it receives NACKREQ, the sender has to choose another slot in the next frame for sending its request. If it receives 0 or does not receive anything during the RTR-mini-slot, it starts a random backoff algorithm before retrying its request.

2.3 Transmission

During the transmission phase, receivers of which resource has been reserved in the reservation phase, do a polling among their associated senders. When a sender recognizes its address in the RTR-packet, it sends in the same slot a data packet. Each sender/receiver pair maintains for the current communication a counter of their transmissions that is incremented at each packet. With this sequence number, the receiver is able to acknowledge the last correctly received data packet. For that, the sequence number is put in a particular field of the RTR, called the acknowledgement field.

Fig. 2 shows an example of transmission phase with a receiver and three senders. It is clear that each receiver acts as a local base-station with respect to its associated senders. Thus, the polling mechanism allows a high flexibility for the scheduling of different flows by higher layers. Moreover, several parallel communications are possible on a given time-slot.

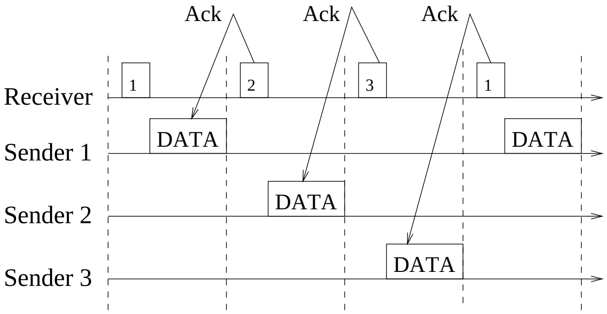

Figure 2: Polling during the Transmission Phase

2.4 Release

An established communication can be interrupted in two cases. At the end of a message, the sequence number of the last packet is put to the value EOT that stands for end of transmission. EOT informs the receiver that the communication is at the end. If the last packet is correctly received, the receiver does not re-schedule the sender at the next slot. However, it acknowledges the last packet with its next RTR, even if it has no sender to poll.

During a communication a sender may receive several RTR, i.e., it receives noise during the RTR phase of the slot and it interprets that noise as a collision. In this case, a collision may occur during the DATA phase of this slot. In this case, the communication is interrupted and a new reservation has to be made. This point will be more detailed in section 3.

3 Correctness

In this section, we will show that CROMA is correct, i.e., that it is collision-free in both fixed and mobile environment in the common cases, i.e., when capture is not considered.

Let's consider a fixed topology. Then two data packets cannot collide, the proof follows. If a receiver receives more than one data packet, no more than one can be destined to it because the MAC address of the sender is specified in the RTR-packet, and the MAC address is unique.

So let us assume that a receiver receives several data packets and a single one is destined to it. In this case the considered receiver has sent an RTR in the same slot. Thus all senders have received this RTR. As some of them sent data with another destination, they must have received another RTR from their respective receiver. So they have received several RTR without interrupting their communication. This is impossible.

Fig. 3 now assume a dynamic topology. Two concurrent communications on a slot are shown. On the left hand side of the figure, these communications are sharing the same slot but they do not interfere because they are far away enough. On the right hand side of the figure, the same nodes have moved and communications may interfere. All possible relative movement have been studied. For the sake of symetry, only four cases are presented representing hidden and exposed terminal situations. In some cases, the communications have to be interrupted because one node has received several RTR-packets. In some other cases, the sharing of the slot is still possible and the protocol takes advantage of the spatial reuse of the resources. Note that the two first cases show that the hidden terminal problem is handled by the protocol. The two last cases show that an exposed terminal is able to transmit data. This is an advantage of the polling mechanism.

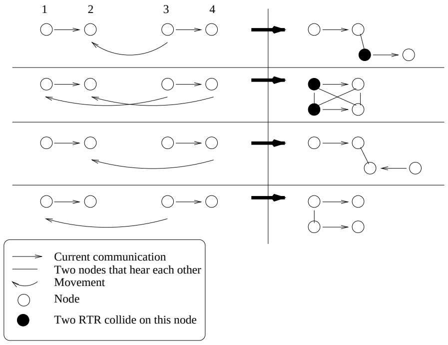

Figure 3: Interference between Two Communications Sharing the Same Slot

4 Throughput Analysis

In this section we calculate the approximate throughput, i.e., the slot utilization of the protocol CROMA in a fully connected network. Following [9] we claim that this topology is the worst case in terms of interference, contention, and spatial reuse because CROMA guarantees a collision-free transmission of data after reservation and in a multi-hop environment.

4.1 Analysis for one slot per frame

In this section we derive the slot utilization of CROMA as a function of the load of REQ-packets submitted to the network by N nodes. Moreover, we assume that the frame has only one slot of duration T, and that the number of parallel communications on a slot is limited to K. At each node, the total load of requests from the higher layer including retransmissions is modeled by a Poisson process with parameter g. Moreover, each node has a buffer of one packet for its requests. If the buffer is full as a new request from the higher layer comes, the old request is thrown. These are common assumptions for the performance evaluation (see e.g. [9]).

Each communication is made of the transmission of a single message, whose length in terms of number of packets is geometrically distributed with parameter. Thus the average message length (AML) is $1/(1-q)$, i.e., in average, a message consists of $1/(1-q)$ data packets. For the transmission of each of these, one time-slot is needed. The probability that a message ends after the transmission of a data packet is $1-q$, and the probability that this packet is not the last one of the message is q. The message destinations are supposed to be uniformly distributed among all nodes.

The system is described by the number of parallel communications on the considered slot at the end of the frame. This number is a discrete-time stochastic process, whose state space is also discrete. Moreover, this process is independent of its history because the Poisson process as well as the geometric law are memoryless. Consequently, this process is a discrete time Markov chain (DTMC). Since the state space is finite, the chain is always ergodic.

Let's now compute the transition probabilities $r_{i,j}$ of this Markov chain. The probability that a node sends a request on a free slot is the probability that at the beginning of the slot, the higher layer has sent at least one request to the MAC layer and is given by $p = 1 - e^{-gT} = 1 - e^{-G}$, where $G = gT$. This value becomes $p' = p/(N-1) = \frac{1-e^{-G}}{N-1}$ on an occupied slot. Indeed, on an occupied slot, a receiver is polling senders during the RTR-mini-slot. A requesting node, hearing at the address of the receiver, will send a request on this slot iff it is destined to the receiver. The probability that a request is destined to this receiver is $1/(N-1)$ because destinations of the requests are assumed to be uniformly distributed among all nodes. Thus, on a free slot, a successful reservation occurs iff only one node among N is sending a request during the REQ-mini-slot. Consequently the probability to have a successful reservation on a free slot is $\theta(0) = Np(1-p)^{N-1}$. On an occupied slot with n communications, a successful reservation occurs iff only one node among the $N-(n+1)$ nodes not currently in communication is sending a request. Therefore, the probability to have a successful reservation on an occupied slot is $\theta(n) = (N-n-1)p'(1-p')^{N-(n+1)-1}$. In state $0 \leq n < K$, there is a transition to state $n+1$ iff a successful request is received and this is not the end of the current message. The transition state $r_{n,n+1}$ is thus given by: $r_{n,n+1} = \theta(n)q$. In state $0 < n < K$, there is a transition to state $n-1$ iff there is no successful request and this is the end of a message, so $r_{n,n-1} = (1-\theta(n))(1-q)$. From these two equations, we obtain directly $r_{n,n}$ for $0 < n < K$: $r_{n,n} = 1 - r_{n,n+1} - r_{n,n-1}$. In state 0, the slot is free and so $r_{0,1} = \theta(0)$ and $r_{0,0} = 1 - r_{0,1}$. In state K, the transition to state $K-1$ occurs iff this is the last packet of a message. So $r_{K,K-1} = q$ and $r_{K,K} = 1-q$. Now let set $\theta(K+1) = 0$. The stationary probabilities are obtained by solving the local balance equation $\vec{\pi} = \vec{\pi}P$, where $P = (r_{i,j})$ is the transition matrix:

$$\pi_n = \frac{\pi_0}{1-q}\left[\frac{q}{1-q}\right]^{n-1}\prod_{k=0}^{n-1}\frac{\theta(k)}{1-\theta(k+1)}\ , \qquad (1)$$

for all $n \in \{1, \cdots, K\}$. The system is totally described with the following equation: $\sum_{n=0}^{K} \pi_n = 1$. At last, the slot utilization of the protocol is given by: $U = 1 - \pi_0$. Fig. 4 shows the slot utilization, U, as a function of the total load of requests, NG for different average message length. We can see that CROMA can achieve a very high throughput provided that the average message length is high.

4.2 Simulations for L slots per frame

In this section, the throughput of CROMA in the case of more than one slot is provided thanks to extensive simulations. These latter re-produce the assumptions of the previous section and run over a long time in order to get accurate results. Here, we assume that a node is allowed to play the role of receiver on several slots of the frame, that nodes can establish several MAC-connections simultaneously with different receivers and adopt a persistent policy.

At the end of each frame, the slot utilization, U, is estimated by computing the mean value on all frames since the beginning of the simulation. The 95% confidence interval around this value is also computed. Then, the simulations stops if the length of this interval is lower than 5% of the average value. Fig. 5 shows the throughput as a function of the total load of requests, including retransmissions for a frame of $L = 10$ slots, $N = 5$ nodes, and a maximum of $K = 3$ communications per slot. We observe that in this case that CROMA can achieve a very high throughput, even for a high offered load. In Fig. 6, the number of nodes is 16, the average message length is 10, and the number of slots in the frame is $L = 5$ and $L = 16$. When $L = 16$, the throughput is stable still at high input load. However, when $L = 5$, the maximum is rapidly reached at 0.94.

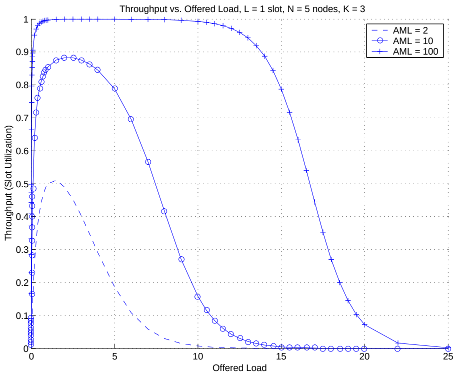

Figure 4: Throughput vs. Offered Load, L = 1 slot, N = 5 nodes, K = 3 communications

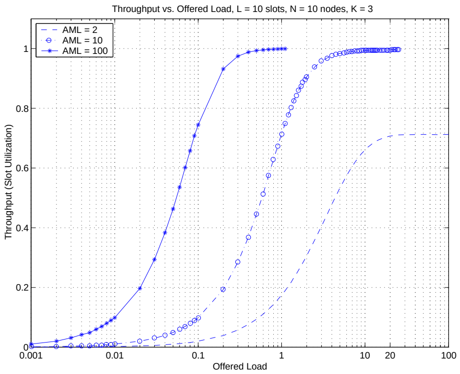

Figure 5: Throughput vs. Offered Load, L = 10 slots, N = 10 nodes, K = 3 communications

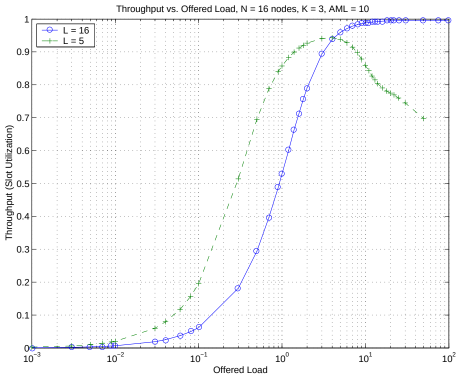

Figure 6: Throughput vs. offered Load, N = 16 nodes, AML = 10, K = 3 communications

5 Discussion

The protocol that has been presented in this paper is a basic version of CROMA. Many extensions of the protocol are foreseen for its design. One of the key parameter for the performance of CROMA is the average message length for which resources of the receiver are reserved. Longer is the AML, better is the throughput of the protocol because only one reservation has to be done per message. In order to increase the efficiency of CROMA, a specific queue management can be proposed in order to group several packets for the same receiver. At last the issue of synchronization is critical for CROMA like for all slotted MAC protocols. An example of solution is the use of the GPS for a global synchronization.

6 Conclusion

In this paper, a new MAC protocol, called CROMA has been proposed for mobile ad hoc networks. CROMA operates in a slotted environment, it is collision-free and receiver-oriented. The reservation of the resources is made through a random access phase on each slot of the frame. The transmission is done thanks to a polling by the receivers. Thus, receivers of a connection act as local base-stations and sophisticated functions at higher layers can be easily implemented. The correctness of CROMA has been proven. Even with a dynamic topology, CROMA handles both the hidden and the exposed terminal problems. Theoretical analysis and extensive simulations show that CROMA can reach very high throughput in a fully connected network provided that the average message length is large. Moreover, the slot utilization of CROMA is very stable even in a highly loaded environment.

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