CROMA - A SLOTTED MAC PROTOCOL FOR MANETS WITH MULTISLOT COMMUNICATIONS

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ABSTRACT

TDMA based MAC protocols can provide a very good utilization of the shared radio resources, especially at high input loads, in synchronized mobile ad hoc networks (MANETs). Global positioning systems like GPS or GALLILEO should provide a very good timing accuracy for synchronization of nodes. This paper presents a medium access protocol for mobile ad hoc networks, called CROMA (Collision-free Receiver-Oriented MAC). It operates in a slotted environment, in a dynamic and distributed way. In this protocol, receivers act as local base stations on a given slot. This paper gives a particular focus on the multislot communications feature of the protocol, which is described in details and analyzed through simulations in a challenging multihop situation. Moreover, an analytical study of CROMA in a fully-connected network is provided.

1. INTRODUCTION

In this paper, we pay special attention to the medium access control (MAC) sub-layer of MANETs. It has a lot of impact on the system performance and its design is a very challenging issue. In the literature two categories of schemes have been proposed: (1) the contention based schemes; (2) the conflict-free schemes.

In the contention based protocols, the channel has to be acquired by the nodes for each packet to be transmitted. Examples of contention based schemes are CSMA/CA, MACA [1], MACAW [2], FAMA [3], IEEE 802.11 [4].

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. TDMA scheduling may be preferred for networks with heavy load, carrying mixed traffic and realizing sophisticated functions at higher layers.

Unfortunately, most of the scheduling problems are NP-complete [5]. Consequently, MAC designers have focussed on sub-optimal, dynamic and decentralized solutions for the slot assignment problem.

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 [6, 7]. The protocol proposed in this paper comes within this family of protocols. It tries to make use of the advantages of the contention based protocols to a slotted environment in order to increase their efficiency. In particular, the aim of CROMA is to achieve a high slot utilization, thanks to an original reservation and polling scheme.

2. PROTOCOL DESCRIPTION

In CROMA, time is divided into frames, each of them is divided into a fixed number L of time-slots, further divided in three mini-slots (see Fig.1) [8]. Each slot can be temporarily and locally attributed to the receiver of a communication link depending on topology changes and traffic patterns. When a receiver is occupying a slot, it is allowed to poll several senders among its neighbors. The number of current communications for each slot is however limited by the protocol to a pre-defined value K.

The polling packet, called RTR for Ready-To-Receive and sent by the receiver, is used to reserve the channel and to invite a sender to send a data packet. In that sense, CROMA is a receiver-oriented protocol since a slot in the frame is associated to a single receiver.

CROMA doesn't rely on a traffic prediction algorithm at the receiver. Indeed, a requesting node has to reserve resources at its intended receiver during a random access phase. The reservation process is done by sending a REQ packet during the first mini-slot of the slot. This reservation is needed only at the beginning of a packet train. After the reservation, the REQ mini-slot is free in successives frames for other reservations. When a receiver has no longer traffic to poll, communications are released and the slot is free for another receiver [8].

At last, CROMA has a multislot communications feature. When it is activated, a communication can be split over several slots. This allows a better utilization of all the slots of the frame.

Each data packet includes a "buffer status" field that indicates whether the sender's buffer exceeds a pre-defined value, MS_THRESH. If it is the case, the receiver is requested for finding a free slot in the frame in order to split the communication. Thus, two or several slots in the frame can be attributed to a single sender-receiver pair.

For a new slot, the receiver has not priority. Indeed, if it has chosen a free slot and receives or senses a packet during the REQ phase of this slot, it refrained from sending a RTR. With this algorithm, new communications that are initiated by REQ packets have priority on already running communications that request a new slot.

Fig.2 shows an example of splitting. On the left hand side, a reservation is done by the sender on slot i, the buffer status field is set to 0. On the right hand side, the buffer exceeds the threshold, "buffer status" is set to 1. Slot j is attributed to the receiver until the end of the communication on this slot. Acknowledgement is done thanks to sequence numbers included in RTR and DATA packets.

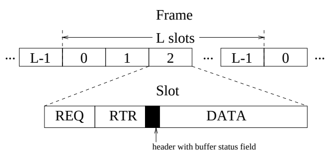

Fig. 1. Frame structure of CROMA

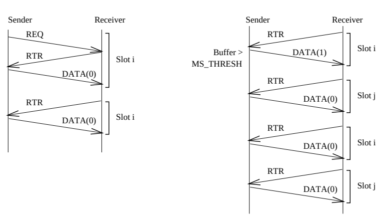

Fig. 2. Example of multi-slot communication.

3. ANALYTICAL STUDY

First of all, we describe our analytical model for the slotted MAC protocol CROMA. For the sake of simplicity a simple version of the protocol is analyzed with restrictive features. From this model will be derived the slot utilization of CROMA as a function of the probability p to send a REQ for a given source-destination pair. Let's enumerate the hypothesis of our model (proposed in [9]) for a fully connected network of N synchronized nodes and L slots per frame.

1. the maximum number of connections on a slot is K, i.e., when a receiver is already polling K different senders on a slot, no new REQ is allowed;

2. a receiver can only be associated with a single slot.

3. the traffic between any two nodes s and d is a ON/OFF traffic;

4. the ON periods are modeled by bursts of packets following a geometrical distribution. The length of a message follows a geometrical law with parameter q.

5. the OFF periods are modeled by a geometrical distribution. If a source s doesn't communicate with a destination d, there is a probability p that s wants to communicate with d at the next frame;

The system is described by the number of parallel connections on the slots at the end of the frame, $(a_0, a_1, ..., a_{L-1})$. Let's consider a slot i occupied by the receiver d. The probability of a successful reservation is:

$$\theta_i = \left(\begin{array}{c} N-1-a_i \\ 1 \end{array} \right) p\,(1-p)^{(N-1-a_i)-1} \quad . \tag{1}$$

Now the probability that a message is ending is : $1-q$. We can now derive the transition probabilities for slot i:

$$\begin{aligned} P(a_i \to a_i+1) &= \theta_i q && (2)\\ P(a_i \to a_i) &= \theta_i(1-q) + q(1-\theta_i) && (3)\\ P(a_i \to a_i-1) &= (1-\theta_i)(1-q) && (4) \end{aligned}$$

Let's now consider a free slot i. There are $S = \sum_{i=0}^{L-1} 1_{\{a_i>0\}}$ occupied slots in the frame. The probability that a sender s has n REQ for the $N-S$ possible receivers is

$$p_1(n) = \left(\begin{array}{c} N-S \\ n \end{array} \right) p^n (1-p)^{N-S-n} \tag{5}$$

if s also belongs to the S receivers, and

$$p_2(n) = \left(\begin{array}{c} N-S-1 \\ n \end{array} \right) p^n (1-p)^{N-S-n-1} \tag{6}$$

otherwise. Thus, the probability that s has n requests is:

$$p(n) = p_1(n)\frac{S}{N} + p_2(n)\frac{N-S}{N} \; . \tag{7}$$

Now, the probability that s sends a REQ on the free slot i is:

$$\beta = \sum_{n=1}^{N-S} min\left(\frac{n}{L-S}, 1\right) p(n) \; . \tag{8}$$

At last, there are N possible senders like s, so the transitions probabilities for i are:

$$P(0 \rightarrow 1) \;=\; \binom{N}{1}\beta(1-\beta)^{N-1} \qquad (9)$$

$$P(0 \rightarrow 0) \;=\; 1 - P(0 \rightarrow 1) \qquad (10)$$

Let's at last consider a full slot. The transition probabilities are obvious: $P(K \rightarrow K) = \theta_i(1-q) + q(1-\theta_i)$ $P(K \rightarrow K-1) = 1 - P(K \rightarrow K)$.

The steady state equations $\vec{\pi} = \vec{\pi}P$ are solved using any numerical method, e.g., the iterative method of Gauss-Seidel [10]. Fig.3 shows the slot utilization of CROMA as a function of p for different average message lengths. Analysis and simulations (dotted lines) are compared and the figure shows a good adequation of the two methods.

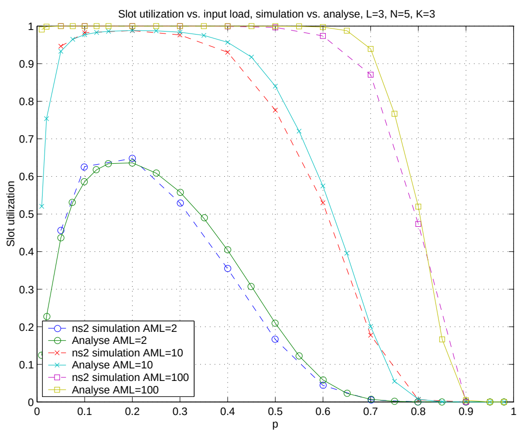

Fig. 3. Slot utilization vs. input load, L = 3, N = 5, K = 3

4. MULTISLOT COMMUNICATIONS

In this section, we provide simulation results and compare the performances of CROMA with those of the standard IEEE 802.11 (DCF mode) and we show the influence of the multislot communications capability of CROMA.

Table 1. Simulation Parameter Values

Parameter	**Value**
DATA Packet size	512 bytes
K	3
PHY Data Rate	2 Mbps
ON distribution	Exponential
OFF distribution	Exponential
Peak Rate	256 Kbps
Mean OFF time	0.5 s

4.1. Influence of the frame length

We consider a challenging topology shown on Fig.4 and often used in the literature [3]. Four end-to-end communications are running in parallel:0-1-2-3, 0-5-2-7, 7-6-5-4, and 3-6-1-4. Simulations have been done using ns2 with an ON / OFF traffic (Tab.1). Fig.5 shows the throughput of CROMA as a function of the input load for different values of L, and without the multislot communications feature (the threshold is infinite). It is clear that CROMA outperforms IEEE 802.11 in all cases. However, the performance of CROMA is very dependent on the frame length when the multislot communications feature is not activated.

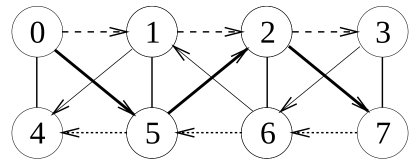

Fig. 4. A mulithop topology, the "squares topology"

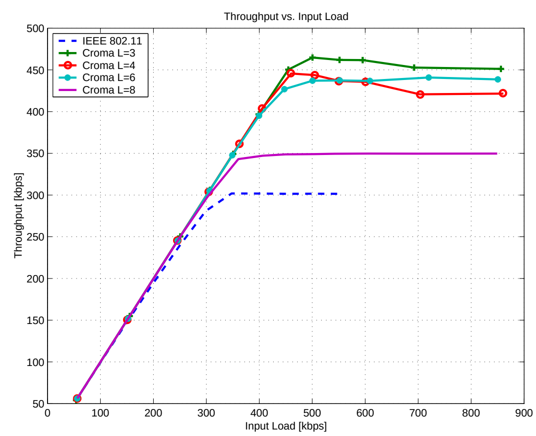

Fig. 5. Throughput vs. input load, squares topology

4.2. Network Throughput

Let us look at the influence of the multislot feature on the network performance when the number of slots in the frame is low, e.g. $L = 3$.

Fig.6 shows the influence of MS_THRESH on the network throughput. It is clear that the feature has no influence in this case. The maximum throughput reaches approximatly $475Kbps$ and CROMA clearly outperforms IEEE 802.11.

This effect is easily understandable. At high input load, all communications indeed share a few number of slots so that the frame is always fully occupied. In this case, there are no slot left for multislot communications. Moreover, multislot communications have not priority over new communications so that they have no chance to appear. As a consequence, whatever MS_THRESH is, the multislot communications feature has no influence. The effect is different

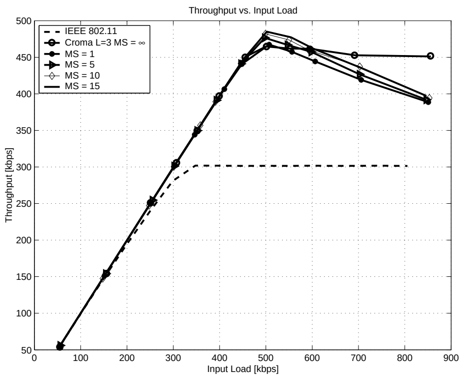

Fig. 6. Throughput vs. input load, influence of MS_THRESH, squares topology, $L = 3$

when the number of slots increases. Fig.7 shows the performance of CROMA $L = 8$. As soon as the multislot capability is activated, a clear increase of the maximum achievable throughput is observed (about $100Kbps$).

With the given topology, $L = 8$ is not an optimal choice if the multislot capability is not activated. In this case, one or two slots are always free because each communication has its own slot and cannot use several slots, resulting in a loss in capacity. With the new feature, all slots are used for data transmissions. However, the effective value of the threshold

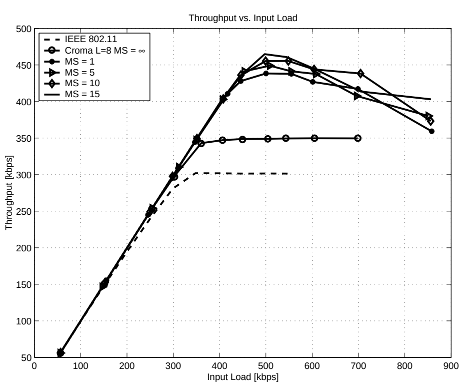

Fig. 7. Throughput vs. input load, influence of MS_THRESH, squares topology, $L = 8$

has little impact on the maximum achievable throughput. At high input load, it only influences the time at which the request for a new slot is started. A negative effect of the multislot feature is the instability observed at high input load. While the throughput is stabilized when $MS\_THRESH = \infty$ (at $350Kbps$), it is slowly decreasing for $MS\_THRESH \neq \infty$. This effect was also observed for low values of L and is due to fairness problems among different flows of a end-to-end communication. Indeed, as links can use several slots in an opportunistic manner, flows with less contention get more bandwidth. This leads to a small unfairness that is not present when the multislot feature is not activated. Fig.8 shows that allowing multislot communications reduces the influence of the frame length. Performances are similar for $L = 3, 4, 6$ and 8.

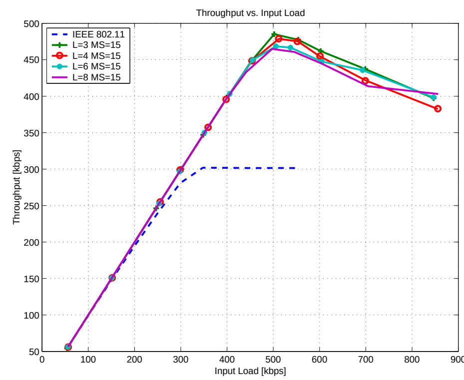

Fig. 8. Throughput vs. input load, influence of L, squares topology, $MS\_THRESH = 15$

4.3. Mean packet delay

All gains in network throughput obtained thanks to the multislot communications imply a gain in mean packet delay at high input load. Let us now look at the behavior of the protocol at low input load. Fig.9 and 10 show the influence of MS_THRESH on CROMA for $L = 3$ and $L = 8$.

As expected, IEEE 802.11, that implements a CSMA/CA based random access does better than CROMA at low input load. It is also shown that the multislot capability has a negative effect on the mean packet delay for $L = 3$ and small values of the threshold. As MS_THRESH increases, the degradation is smaller and smaller, and the performance of $MS\_THRESH = 15$ is very close to the desactivated case. For $L = 8$, the better utilization of the channel implies a better mean packet delay. This suggests that it is not usefull to increase too frequently the number of slots when the load is low because it may delay the reservation of new communications. Moreover, in CROMA the acknowledgement is done in the next RTR packet of the same slot. Thus, at the end of a communication, a slot may be lost if the receiver has nobody to poll. This is often the case at low input load where messages are also short. This results in an increase of the lost slots because the multislot communications lower the mean

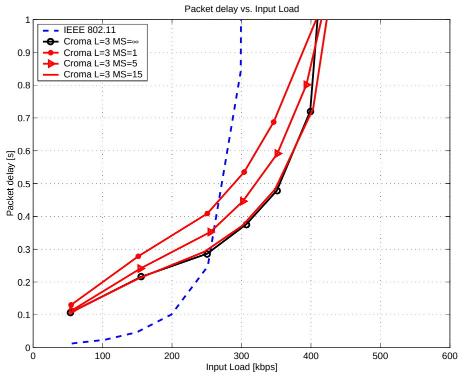

Fig. 9. Packet delay vs. input load, influence of MS_THRESH, squares topology, $L = 3$

message length per slot. This effect is not visible anymore at high input load because communications are longer and senders are more often multiplexed on the same slot.

As a conclusion, the performance in term of mean packet delay is preserved provided that MS_THRESH is sufficiently high in order to prevent multislot communications at very low input load.

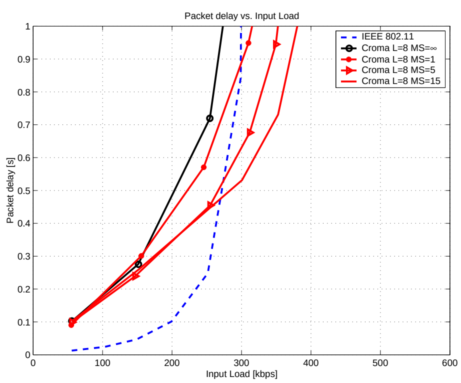

Fig. 10. Packet delay vs. input load, influence of MS_THRESH, squares topology, $L = 8$

5. CONCLUSION

This paper has presented a slotted MAC protocol for ad hoc networks, called Collision-free Receiver Oriented MAC. In CROMA, time is divided into frames and slots. Nodes are allowed to do reservations of resources thanks to REQ packets. A particular slot in the frame is then reserved for the transmission of a packet train. CROMA solves the hidden and exposed terminal problems and thus outperforms IEEE 802.11 in term of throughput and channel utilization. An analytal study has shown that CROMA can reach a high slot utilization provided that the packet trains are long. Simulations focused on the multislot communications feature of CROMA, i.e., the possibility for a sender to split its connection on several slots. This feature has a significant impact on the network throughput. However, the key parameter, MS_THRESH, has to be adequatly chosen to not degrade the mean packet delay for small values of the frame length.

6. REFERENCES

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