Modeling of a Slotted MAC Protocol for MANETs

M. Coupechoux, B. Baynat, C. Bonnet, and V. Kumar

***Abstract*—Global positioning systems like GPS or GALLILEO will soon provide a very good timing accuracy, making possible the synchronization of nodes in a mobile ad hoc network (MANET). With this assumption, TDMA based MAC protocols can provide a very good utilization of the shared radio resources. This paper presents an analytical model for the performance evaluation of slotted MAC protocols with reservation for MANETs. A fully connected network is assumed and nodes generate a ON/OFF exponential traffic. The analysis is based on the study of a discrete time Markov chain. The methodology is applied to a recently proposed protocol, called CROMA [6], but can also be applied, with suitable modifications to any slotted protocol with reservation.**

I. 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 Internet access, 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 control are: to be able to reuse the resources as efficiently as possible, to avoid congestion and collisions, to be fair, reliable, and energy efficient. Many MAC try to address these issues. 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 [9], MACAW [4], FAMA [8], IEEE 802.11 [1]. 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 [14] claims that it may not do very well in a multi-hop environment. According to [14], 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. In this family of protocols, MACA-BI [12] was the first one to be receiver oriented, i.e., the transmission of a packet is initiated by the receiver that sends a short control packet in order to reserve the channel and to invite the sender to transmit. As the receiver does not have the exact knowledge of packet queue at the sender, it must rely on a traffic prediction algorithm.

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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 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 focus in this paper on slot allocation protocols for MANETs.

Unfortunately, most of the scheduling problems are NP-complete. For example, Arikan [2] 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 [7]. 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. FPRP [15] proposes a five-phase handshaking supported by a pseudo-Baysian algorithm to enable a faster convergence of the reservation procedure. CATA [13] uses four mini-slots in each time-slot to enable unicast and multicast transmissions. DPRMA [10] extends the classical centralized and slotted packet reservation multiple access (PRMA) scheme to a distributed PRMA. CROMA [6] is receiver oriented and allows multiple connections per slot.

The paper is organized as follows. In section II, we give a short description of the MAC protocol CROMA (Collision-free Receiver Oriented MAC). A more precise description as well as a study of the correctness can be found in [5]. Section III explains the proposed analytical model. Section IV gives a close-form formula for the slot utilization of CROMA in the case where each frame has a single time slot. In section V, this analysis is extended to the multislot case.

II. Overview of CROMA

CROMA is a medium access protocol for MANETs that dynamically schedules transmissions in a slotted environment. It operates on a single-frequency channel with omni- directional antennas. All nodes are assumed to be synchronized. CROMA is receiver oriented because a slot in the frame is associated to a single receiver. Moreover, any communication between two nodes must be preceded by a preliminary reservation phase.

In CROMA, time is divided into frames, that are in turn divided into a fixed number (L) of slots. Each slot is further divided in two signaling mini-slots, for REQ (request) and RTR (ready-to-receive), and a data transmission phase (see Figure 1). The REQ-mini-slot is used by requesting nodes during the random access phase to reserve the slot. The RTR-mini-slot is used by their intended receivers to acknowledge requests. After the reservation of the slot, RTR packets are also used in successive frames to acknowledge data packets and to poll different senders. During the data phase, the sender transmits a data packet of fixed length, eventually obtained after segmentation.

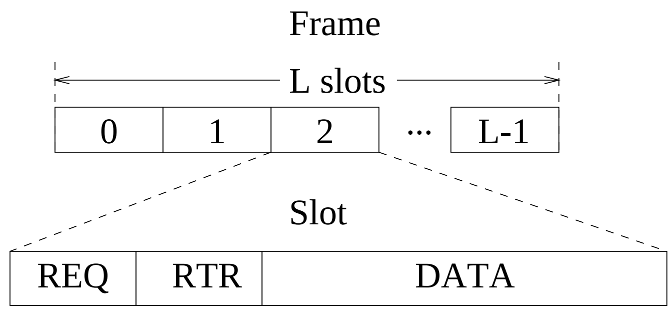

Fig. 1. Frame structure of CROMA

The reservation of a free slot is done via a REQ/RTR dialogue similar to the traditional RTS/CTS handshake. Then, the transmission of a data burst is done on the same slot in successive frames. Once the connection is established, the sender is no longer required to send requests. On the other hand, the receiver sends a RTR at each second mini-slot to reserve the channel and to prevent the hidden terminal effect. The receiver is said to have got the floor on the slot. The slot is no longer free until the release of the connection.

Now, CROMA allows multiple reservations on the same slot. The receiver indeed maintains a list of senders that managed a successful reservation and will poll them in the successive frames. This feature is illustrated on Figure 2 that shows two successive reservations on the same slot i. In frame j, the REQ/RTR dialogue starts the connection between nodes A and B: A sends a REQ packet with its address. B sends back a RTR, that contains a field to acknowledge the reservation (ackreq), and a field to poll node A (pol). The RTR is also received by node C that is now aware of a communication on slot i with B as receiver. During the data phase, A, that has just been polled by B, is allowed to transmit a packet with its address A and a sequence number 0. We say that B has got the floor on slot i. In frame j+1, C establishes a connection with B. With the RTR, node B acknowledges the reservation with the field ackreq, acknowledges the packet transmitted by node A in frame j, and polls node C. In frame j+2, B now polls A. With the RTR, it also acknowledges the data packet of C with sequence number 0. In frame j+3, node B polls node C and acknowledges the data packet of A with sequence number 1.

So, RTRs are used by receivers to acknowledge requests, as well as previous data transmissions, and to poll the senders that managed a successful reservation. It is clear that slots are associated to receivers. In that sense, CROMA is receiver-oriented. This feature favores the spatial reuse of resources since only the zone around the receiver has to be secured with respect to collisions. Moreover, the parallelism of connections reduce the number of collisions of control packets and allows finer flow controls and QoS negociations.

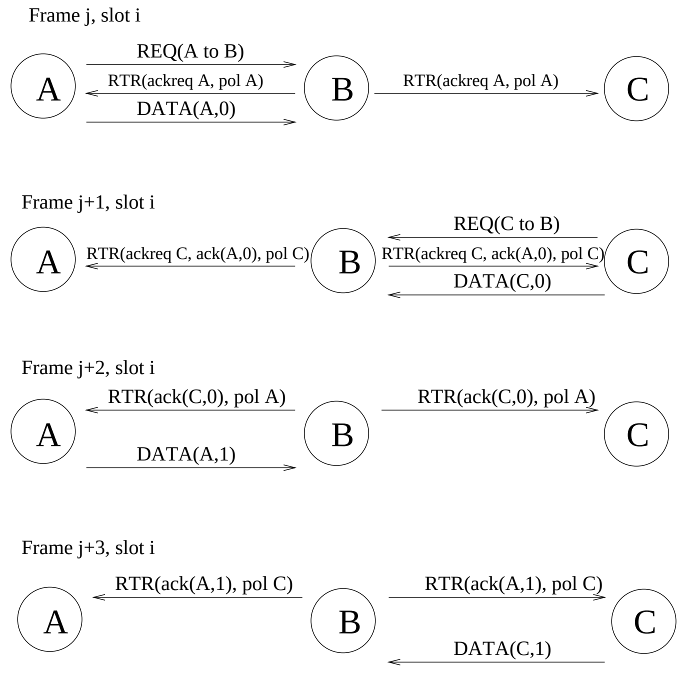

Fig. 2. Example of two parallel connections on a slot with CROMA

These are the basic principles of CROMA; a precise description of the protocol including packet formats, MAC header, reservation, transmission, and release phases, as well as the correctness analysis are available in [5] (a journal paper is on progress). However, these details are not required for the approximate slot utilization analysis that follows.

III. Model for the Slot Utilization Analysis

In this section, we describe our analytical model for the slotted MAC protocol. From this model will be derived the slot utilization of CROMA as a function of the probability p to send a REQ-packet for a given source-destination pair. Let's enumerate the hypothesis of our model.

1) We consider a fully-connected network of N synchronized nodes;
2) all packets are of constant length and are transmitted over an assumed noiseless channel;
3) there are L slots per frame;
4) in order to bound the delay of a connection, 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 on it;
5) a receiver can only be associated with a single slot. This hypothesis can be in practice relaxed, but for the sake of tractability of the model, we limit the analysis to that case;
6) a node can be a sender on several slots of the frame. While being in communication on a slot, a node can

send a REQ on another slot of the frame to start another connection;
7) the traffic between any two nodes s and d is a ON/OFF traffic;
8) 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. Thus, the average message length (AML) is $1/(1-q)$;
9) the OFF periods are modeled by series of slots without transmission following 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 slot;
10) a non persistent policy is assumed for retransmissions after a failure. This hypothesis explains that we can consider a fixed probability p to start a communication.

The system is described by the number of parallel connections on the slots at the end of the frame, $(a_0, a_1, ..., a_{L-1})$, where

- a_i is the number of current connections on slot i, as described in the previous section, all these connections have the same receiver,
- $0 \leq a_i \leq MIN(K, N-1)$ (see hypothesis 1 and 4),
- $S = \sum_{i=0}^{L-1} 1_{\{a_i>0\}} \leq MIN(N, L)$, (see hypothesis 3 and 5).

For the sake of simplicity, the states doesn't describe neither the receiver associated to each slot, nor the list of associated senders. The vector $(a_0, a_1, ..., a_{L-1})$ 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.

From a frame to another, we can have the following transitions on slot i :

- $a_i \rightarrow a_i + 1$ ($a_i < K$): a reservation has been successful on slot i AND no communication has come to the end,
- $a_i \rightarrow a_i$: (there is a successful reservation AND this is the end of a communication) OR (there is no successful reservation AND no communication is ending),
- $a_i \rightarrow a_i - 1$ ($a_i > 0$): (there is no successful reservation AND this is the end of a communication).

Note that on slot i a single reservation can be successful and a single communication can come to the end during a frame. A transition probability between states $(a_0, a_1, ..., a_{L-1})$ and $(b_0, b_1, ..., b_{L-1})$ is assumed to be the product of the transition probabilities associated to each slot:

$$P\left((a_0, a_1, ..., a_{L-1}) \rightarrow (b_0, b_1, ..., b_{L-1})\right) = \prod_{i=0}^{L-1} P(a_i \rightarrow b_i) \quad (1)$$

IV. One Slot Analysis

In this section, $L = 1$. In this simple case, we can derive a close-form formula for the slot utilization.

The system is described by the number of parallel connections on the considered slot at the end of the frame (the DTMC

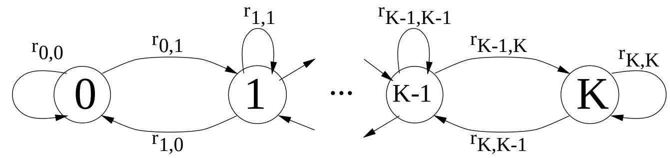

Fig. 3. Discrete time Markov chain representing the state of the slot, for $N \geq K$.

is shown on Figure 3). Let's now compute the transition probabilities $r_{i,j}$ of this Markov chain. Remember that the probability for a source-destination pair to enter a ON period is p. Thus the probability that a node sends a request on a free slot is the probability that this node has a request for at least one of the destinations. Or 1 minus the probability that it has no request for any destination:

$$p' = 1 - (1-p)^{N-1} \; . \quad (2)$$

Thus, on a free slot, a successful reservation occurs if and only if (iff) only one single 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

$$\theta(0) = \begin{pmatrix} N \\ 1 \end{pmatrix} p'(1-p')^{N-1} \; . \quad (3)$$

On an occupied slot with n connections, a receiver has got the floor on the slot and successively polls n senders that managed to reserve resources. Here, a successful reservation occurs iff only one node among the $N - (n+1)$ nodes not currently in connection is sending a request. Therefore, the probability to have a successful reservation on an occupied slot is

$$\theta(n) = \begin{pmatrix} N-(n+1) \\ 1 \end{pmatrix} p(1-p)^{N-(n+1)-1} \; . \quad (4)$$

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 probability $r_{n,n+1}$ is thus given by:

$$r_{n,n+1} = \theta(n) q \; . \quad (5)$$

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

$$r_{n,n-1} = (1-\theta(n))(1-q) \; . \quad (6)$$

From these two equations, we obtain directly $r_{n,n}$ for $0 < n < K$:

$$r_{n,n} = 1 - r_{n,n+1} - r_{n,n-1} \; . \quad (7)$$

In state 0, the slot is free and so:

$$r_{0,1} = \theta(0) \quad (8)$$
$$r_{0,0} = 1 - r_{0,1} \; . \quad (9)$$

In state K:

$$r_{K,K} = 1 - r_{K,K-1} \; . \quad (10)$$

The transition matrix is now $P = \{r_{i,j}\}_{0 \leq i,j \leq K}$. The stationary probabilities are obtained by solving the global balance equation $\vec{\pi} = \vec{\pi}P$, that enables to express all the probabilities in function of π_0:

$$\pi_n = \frac{\pi_0}{1-q}\left[\frac{q}{1-q}\right]^{n-1}\prod_{k=0}^{n-1}\frac{\theta(k)}{1-\theta(k+1)}\ , \qquad (11)$$

for all $n \in \{1, \cdots, K\}$, with $\theta(K+1) = 0$. The system is totally described with the normalizing equation: $\sum_{n=0}^{K}\pi_n = 1$. At last, the slot utilization of the protocol is given by:

$$\begin{aligned} U &= 1 - \pi_0 && (12)\\ &= 1 - \frac{1}{1+\sum_{n=1}^{K}\frac{1}{1-q}\left[\frac{q}{1-q}\right]^{n-1}\prod_{k=0}^{n-1}\frac{\theta(k)}{1-\theta(k+1)}} && (13)\end{aligned}$$

Figure 4 shows the slot utilization of CROMA, U, as a function of the probability p for different average message length ($AML = 2$, 10 and 100 packets). We can see that CROMA can achieve a very high slot utilization provided that the average message length is high.

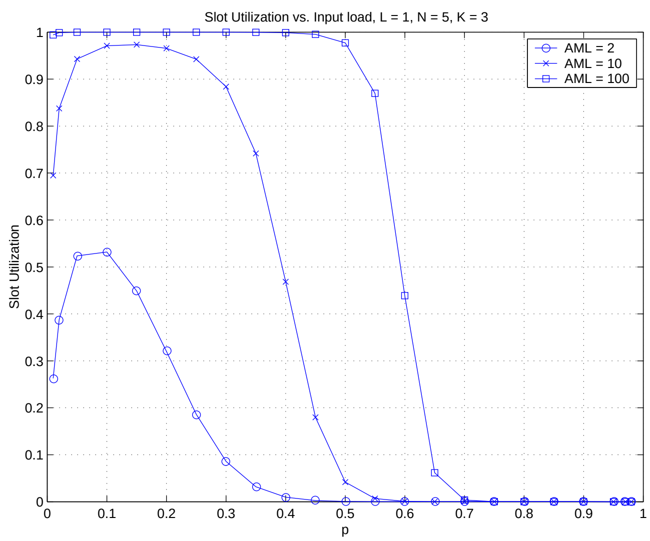

Fig. 4. Slot Utilization vs. offered load, L = 1, N = 5, K = 3

From the DTMC, the average number of connections, N_c on the slot can also be derived:

$$N_c = \sum_{n=0}^{K} n\pi_n\ . \qquad (14)$$

Figure 5 shows the average number of connections for different AML values. It is clear that the delay transmission of a burst is increasing with this mean number.

V. Multislot Analysis

In this section, we extend the previous result to the general case with L slots. We first compute the transition probabilities, while differentiating an occupied slot, a free slot and a full slot. For the sake of readability, we only consider the case $K \leq N$.

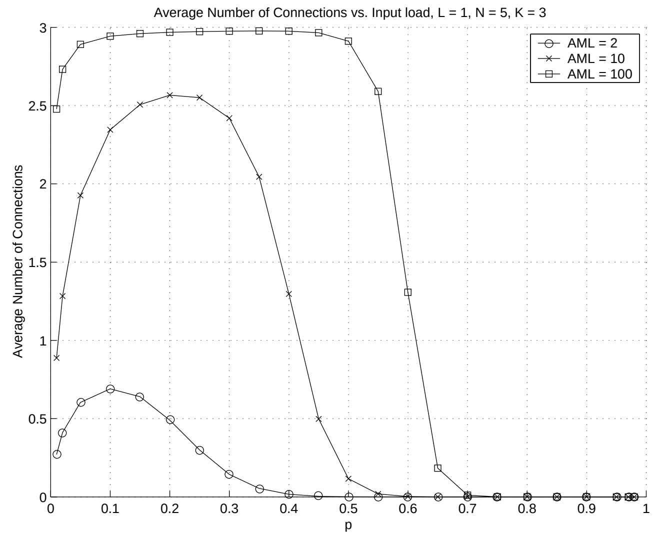

Fig. 5. Average Number of Connections vs. offered load, L = 1, N = 5, K = 3

A. Occupied Slot

Let's consider an occupied slot i by the receiver d with a_i simultaneous connections (this is the case, where $0 < a_i < K$).
The nodes that are likely to send a REQ to d are nodes that are currently not in communication with d, their number is $N - 1 - a_i$. The probability for such a node s to send a REQ on slot i is p (see hypothesis 9). Thus, the probability of a successful reservation is:

$$\theta_i = \binom{N-1-a_i}{1} p\,(1-p)^{(N-1-a_i)-1}\ . \qquad (15)$$

Note that if $a_i = N - 1$, all nodes have a connection with the considered receiver, so that there is no REQ on this slot, and $\theta_i = 0$.

Now the probability that a message is ending is (see hypothesis 8): $1 - q$. We can now derive the transition probabilities for slot i:

$$\begin{aligned} P(a_i \to a_i + 1) &= \theta_i q && (16)\\ P(a_i \to a_i) &= \theta_i(1-q) + q(1-\theta_i) && (17)\\ P(a_i \to a_i - 1) &= (1-\theta_i)(1-q) && (18)\end{aligned}$$

B. Free Slot

Let's now consider a free slot i ($a_i = 0$). There are $S = \sum_{i=0}^{L-1} 1_{\{a_i>0\}}$ occupied slots in the frame, i.e., S receivers, since a receiver is associated to a single slot (see hypothesis 5).

On the considered free slot i, N senders are likely to send a REQ for $N - S$ possible receivers. Indeed, a node is allowed to send traffic to several receivers in parallel on different slots, so all nodes are likely to start a new communication on i. Moreover, requests on i can be addresses to any of the $N - S$ nodes that are not receivers on another slot because i is not attributed.

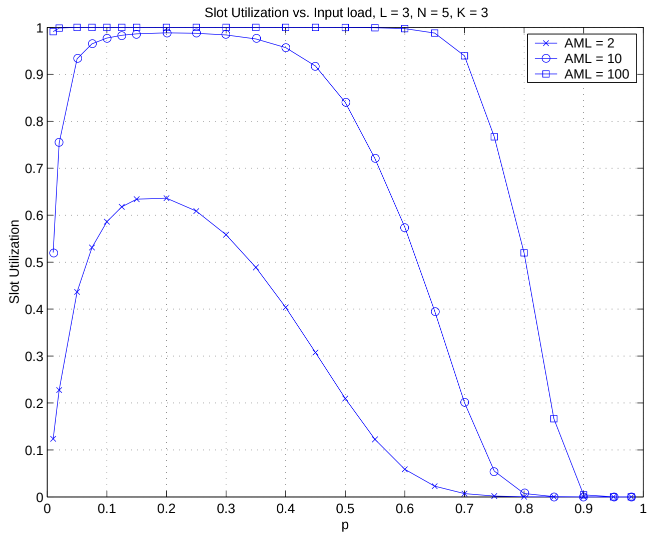

Fig. 6. Slot utilization vs. input load, L = 3, N = 5, K = 3

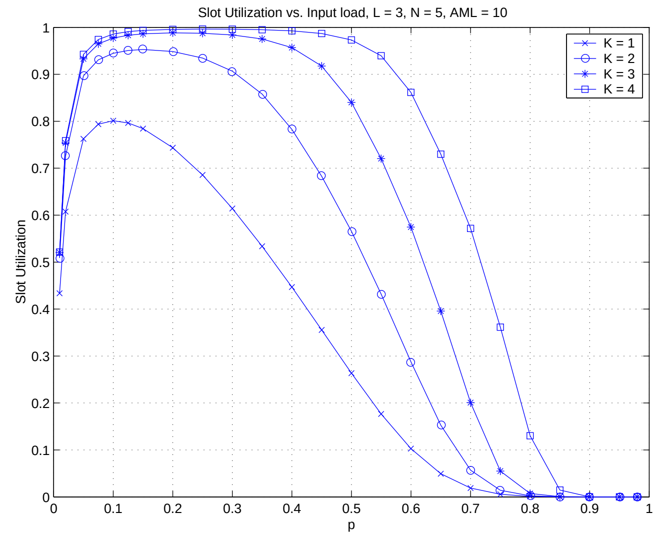

Fig. 7. Slot utilization vs. input load, influence of K, L = 3, N = 5, AML = 10

Let's consider a node s. The probability that s has n REQ for the $N-S$ possible receivers is

$$p_1(n) = \binom{N-S}{n} p^n (1-p)^{N-S-n} \tag{19}$$

if s also belongs to the S receivers, and

$$p_2(n) = \binom{N-S-1}{n} p^n (1-p)^{N-S-n-1} \tag{20}$$

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

$$p(n) = p_1(n)\frac{S}{N} + p_2(n)\frac{N-S}{N} \; . \tag{21}$$

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

$$\begin{aligned} \beta &= \sum_{n=1}^{N-S} Pr[\text{s sends a REQ on i}|\text{s sends n REQ}]p(n) \quad (22)\\ &= \sum_{n=1}^{N-S} min\left(\frac{n}{L-S}, 1\right) p(n) \; . \end{aligned}$$

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

$$P(0 \to 1) = \binom{N}{1} \beta(1-\beta)^{N-1} \tag{23}$$

$$P(0 \to 0) = 1 - P(0 \to 1) \tag{24}$$

C. Full Slot

Let's at last consider a full slot ($a_i = K$). The transition probabilities are obvious:

$$P(K \to K) = \theta_i(1-q) + q(1-\theta_i) \tag{25}$$

$$P(K \to K-1) = 1 - P(K \to K) \; . \tag{26}$$

D. Performance

The global balance equation $\vec{\pi} = \vec{\pi} P$ is solved using any numerical method, e.g., the iterative method of Gauss-Seidel (see [3] or [11]).

Figure 6 shows the slot utilization of CROMA as a function of p for different average message lengths. CROMA can achieve very high slot utilization provided that the AML is high. Note that values of p near 1 are not realistic in a real implementation because of the backoff algorithms. So the point of operation of a highly loaded CROMA network is probably for $p < 0.5$.

Figure 7 shows the influence of K on the system performance. There is a clear gain of channel utilization as K increases. However, this is obtained at the cost of higher delays. This is shown on Figure 8, where the average number

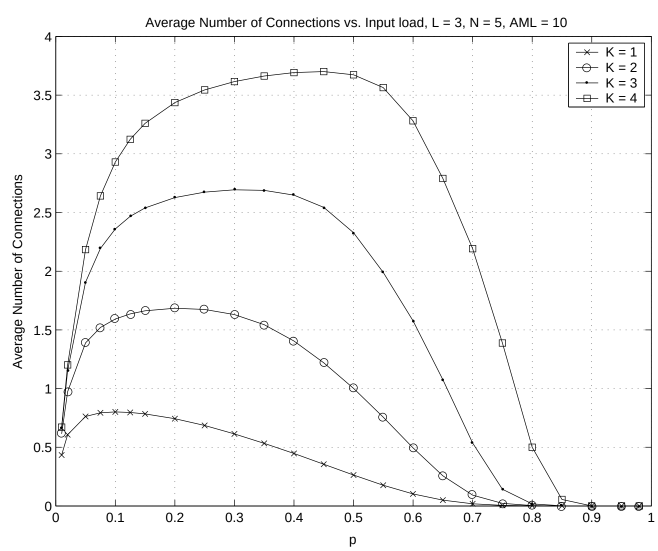

Fig. 8. Average number of connections vs. input load, influence of K, L = 3, N = 5, AML = 10

of connections per slot is plotted. A higher number of connections per slot implies a higher delay for the burst transmissions.

VI. Conclusion

We focus in this paper on slotted MAC protocols for MANETs with reservation. A methodology is proposed that allow the computation of the slot utilization as a function of input load. The method is based on the analysis of a discrete time Markov chain that can be solved in the general case with any numerical algorithm.

A special case has been studied which is the recently proposed MAC protocol CROMA. This protocol is receiver-oriented and allows multiple connections on a single slot. It has been shown that CROMA can achieve very high channel utilization. This utilization can be improved by increasing the maximum number of connections on a slot, however at the cost of a higher transmission delay.

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