A Self-Balanced Receiver-Oriented MAC Protocol for Multiple-channel Ad-Hoc Networks

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I. INTRODUCTION

A mobile Ad Hoc network is a self organizing system of wireless nodes that requires no fixed infrastructure. In the event any two nodes cannot communicate directly, each node must act as a relay, forwarding packets on the behalf of other nodes. Generally, MAC protocols may be broadly classified into two groups based on their strategy for determining access rights: deterministic access protocols or random access protocols.
Deterministic allocation protocols assign to each node in the network a permanent transmission schedule indicating in which of the synchronized slots time and data channels (frequencies, spreading codes or their combinations) the node may transmit. These protocols have bounded delay but suffers low performances at low load [2]. Moreover if the network is highly mobile, these protocols may potentially become instable as maintaining transmission schedules uses almost all nodes capabilities. In [3], a mobility transparent scheme was proposed as a solution to the previous problem but the achievable throughput is very low since no spatial reuse is used.

Random access protocols do not need global network synchronization and are well suited for bursty data traffic. They have to address the problem of collisions and hidden terminals. Many contention protocols have been designed for single channel mobile Ad Hoc networks. Karn [4] proposed MACA protocol which attempt to detect collisions at the receiver by establishing a RTS/CTS exchange procedure; receiver which correctly receives a RTS message answers by sending a CTS message. To reduce signalization overhead and collisions at high load, invitation based protocols were proposed [5, 6]. In [6] a receiver oriented, collision free protocol over TDMA system was suggested and was shown to improve the throughput.
The exchange of RTS/CTS messages solve the problem of hidden terminals but with poor efficiency; the reason is that hidden terminals still cannot receive, as they are forbidden to answer to RTS messages.

Multiple channels radio networks permit multiple stations, within the range of the same receiver, to transmit concurrently without collision. Here again, receiver initiated scheme, as proposed in [8, 9] are shown to improve network throughput.
Several protocols have been proposed for taking advantage of spreading codes for multiple access. Sousa and Silvester [7] analyzed the throughput of some code assignment schemes such as transmitter-based, receiver-based, or transmitter-receiver-based. The code assignment problem is trivial if the network size is small, it becomes inefficient to assign a unique code to each transmitter or receiver when the network size grows or the topology changes.

A performance limitation of all random access protocols is that they cannot provide delay guarantees. This occurs at high load when nodes spend most of time trying to resolve contention, so it is evident that this leads to a quasi deadlock situation.

The main goal of this work is to present a new MAC protocol for CDMA ad-hoc networks and derive its performances through a Markov chain modeling. The proposed protocol is receiver-oriented, fully distributed, code assignment free, and does not need global network synchronization. Section II deals with the MAC protocol description and the fundamental design choices behind it. In section III we derive the equivalent Markov chain model for the proposed system, and use it to obtain the achievable throughput and system delay. In section IV we examine the numerical results of the analytical model and discuss the performances of the system. Finally, in section V, we present simulation results of Sebroma with NS2 tool [10].

II. Protocol Description

We propose a realistic and fully distributed multiple access scheme for multi-channels ad hoc networks. The basic philosophy of the developed scheme, is to reduce as much as possible signalization overhead and avoid global network synchronization due to the difficulties related to its practical realization. All nodes are given the same responsibility (i.e flat architecture), hence, single points of failure are avoided and the protocol becomes topology transparent. A code division multiple access scheme is used, where all nodes share a common signaling channel (code) and each of them uses a randomly chosen code for each communication setup. This simplifies the code assignment functionality since no inter-node collaboration is needed. Only one transmission at time is allowed on the common signaling channel. To minimize collisions at high loads, each communication is preceded by a collision-avoidance handshake procedure initiated by the ready nodes. A node becomes ready receiver if it has no activity durring a random period of mean "T". Only local synchronization is performed, during each handshake, between each receiver and its intended transmitters. The synchronization is maintained for data transfer between the receiver and the contention-winner. Transmitters are given a random period of mean "T_{out}" to setup communication for their own traffic(ready transmitter). In case of failure, they become directly ready receivers in order to eventually serve other nodes traffic, and retry later to transmit their own packets until success. Hence, each node carries fairly other nodes traffic as well as its own traffic, this ensure the permanent presence of ready receivers in the network and hence maintain the network communications capability. This is what we call self-balancing aspect of the protocol(in sens of number of receivers and transmitters simultaneously present in the network)

A. Network Access

Each node has an ID allowing to distinguish it from other nodes[1] and transmits, after a random time period of mean T without activity(i.e. without getting a packet to transmit from the uplayer), on the common signaling channel, an invitation message RTC (ready to communicate message) containing a synchronization sequence, its ID and a code ID randomly chosen at each RTC message transmission (Fig. 1). The synchronization sequence allows the listening nodes to detect the transmission of the RTC message and get synchronized with its sender in order to be able to correctly receive its message. The code in the RTC message is used later for communication setup. Randomly choosing this code, at each RTC message sending, avoids the need of a centralized code assignment. collision on the common signaling channel is reduced by the use of random period T and by asynchrony of the system, and it's resolved by making multiples attempts.

[1] it can be either randomly chosen among a set of large number of possible ID's or derived from its hardware ID, or associated to its IP address, ...

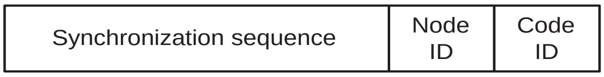

Fig. 1. RTC message form

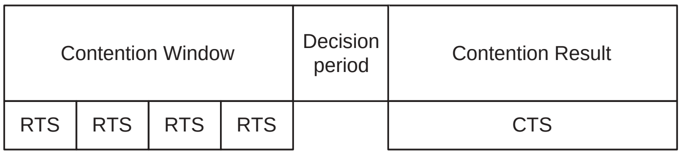

Fig. 2. Communication setup on the receiver code

B. Communication Setup

Nodes to node communications are initiated by the receivers. Each ready receiver sends RTC message inviting the interested ready transmitters to compete for starting a communication with it. The RTC message is followed by the communication setup phase. The communication setup is realized on the data channel chosen by the receiver and denoted in the RTC message. It consists on a contention phase, contention resolution phase and eventually data transfer phase. A contention window is dedicated to the reception of the Request to Send (RTS) messages and it is divided into R several contention sub-windows in order to reduce the collision probability[2] Among the successfully decoded RTS messages, the receiver answers the accepted request [3] by sending a Clear to Send (CTS) message (Contention resolution phase). Then data transfer can start(Fig. 2).

If a ready transmitter fails to reach its destination in a given random time period T_{out}(because of collisions or a not available receiver), it sends directly an RTC message and tries to receive others nodes traffic. Right after the end of its RTC message if no communication is successfully setup, or after the end of the data traffic transfer in the contrary case, the Ready transmitter restarts a new random waiting period for invitation messages RTC. This procedure allows unlocking situations where numerous transmitters are trying simultaneously to initiate a communication, which keep all of them blocked infinitely.

Here again, Contention among ready transmitter is reduced by the use of random waiting periods T_{out} and multiple contention sub-windows and resolved by making multiples attempts.

C. Modes Diagram

We define the system modes as follow (Fig. 3):

1) Idle Mode: a station is given a random time periode of mean T for getting packets from its uplayer. Durring this time, it's said to be in the *Idle mode*. If no new packet is received during T, the node becomes Ready Receiver and passes to the *RTC mode*, otherwise it becomes Ready Transmitter and passes to the *RTT mode*.

2) Ready To Communicate Mode: A ready receiver is said to be in the *RTC mode* when it is sending RTC message, if it success to initiate a communication it passes to the *COM mode*, otherwise it goes back to the *Idle mode*.

3) Ready To Transmit Mode: Ready transmitter is given a random time periode of mean T_{out} to reach its destination. If it does not succeed, it becomes directly ready receiver and passes to the RTC_{BL} mode (ready receiver but with a packet to transmit: blocked transmitter), otherwise it passes to the *com mode*.

4) COM Mode: A pair of stations(ready receiver and ready transmitter) is said to be in the *COM mode* when they are communicating. At the end of the communication, the two nodes go to the Idle mode.

[2]we may reserve one or several higher priority sub-windows for multicasting, handover traffic...
[3]based on requests priority, capability criterion...

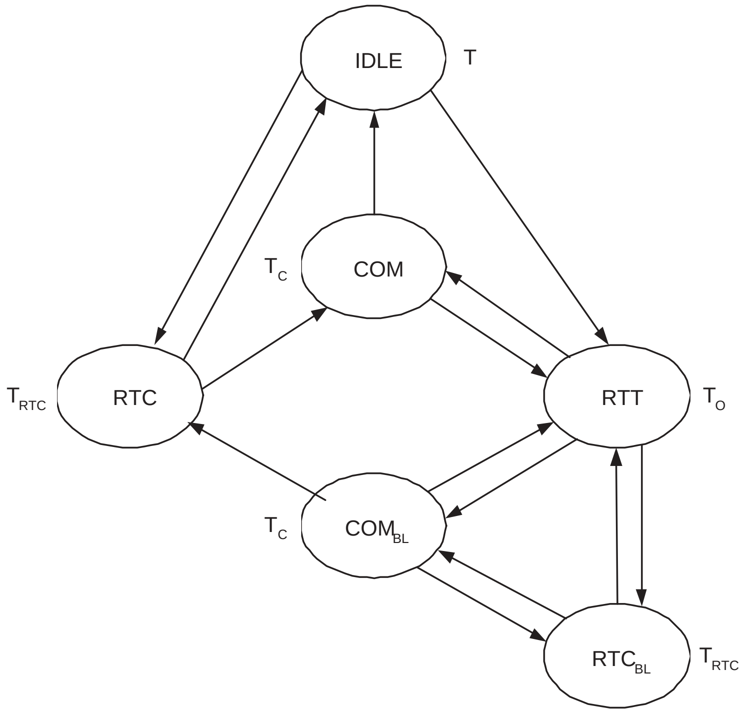

Fig. 3. Modes diagram

5) RTC$_{BL}$ Mode: A blocked transmitter is said to be in the *RTC$_{BL}$ mode* when it is sending RTC message after expiration of its time period T_{out}. If it success to initiate a communication (as receiver), it passes to the COM_{BL} mode, otherwise, it goes back to the *RTT mode*.

6) COM$_{BL}$ Mode: A pair of stations (blocked transmitter and ready transmitter) is said to be in the *COM$_{BL}$ mode* when they are communicating . At the end of the communication, the blocked transmitter goes back to the *RTT mode* while the ready transmitter becomes directly ready receiver and passes to the *RTC mode*. Hence, the ready transmitter participate also in unloking the situation where there is numerous blocked transmitters waiting for RTC messages.

D. Example

Figure (4) illustrates message exchanges in the main network scenarios.
in the first case, node A has no traffic to send after time period T on the Idle state, so node A becomes ready receiver, sends RTC message on the common channel and waits for reply from any correspondent. Node B is ready transmitter and has a packet for node A, so it sends RTS message on the data channel choosen by A. node A replies then with a CTS, and the data transfer starts. At the end of the communication, the two nodes return to the Idle state.

Now, in the second case, node A has received a packet to send from the up-layer before than the time period T expires, he enters the RTT state and waits invitation message RTC from its destination. Node B receives a packet to send to node A, he enters then the RTT state and wait invitation message from its destination. After a time period T_{out} in the *RTT mode*, node A did not succeed to reach its destination, he enters the RTC$_{BL}$ mode (since he can not transmit, it tries to receive) and sends an RTC message(as blocked transmitter), node B is still in the RTT state and has a packet for it, so they start a communication: A and B are now in the *COM$_{BL}$ mode*. At the end of the communication, node A returns to the *RTT mode* while node B goes to the *RTC mode*.

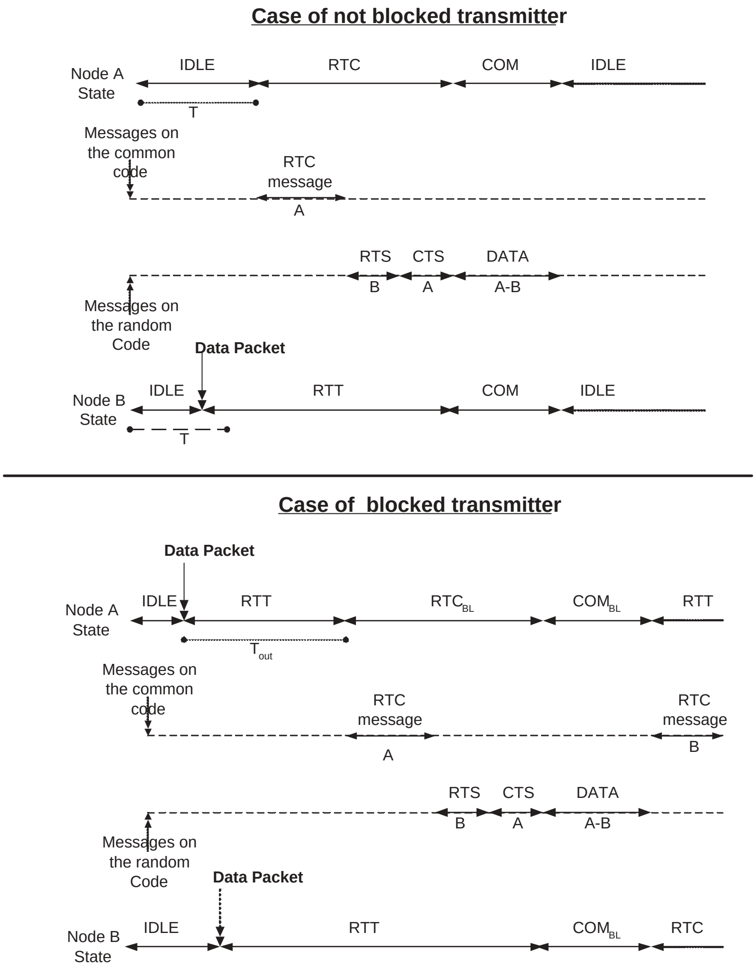

Fig. 4. Example of control messages exchanges

III. Throughput-Delay Analysis

For the analysis of the protocol, we consider a single-cell fully connected network containing N radio units which can communicate directly. Each node can operate in either transmitter or receiver modes but not in both simultaneously.

the physical layer offers (D+1) orthogonals and identical channels(D for data and one for signalization). Packet arrival is modeled by a Poisson process of rate λ packets/sec, we further assume that packet arrival queues are of maximum length of one packet. The elementary time-unit is taken equal to the Time spent in the RTC mode T_{RTC}. time spent in Idle mode and the RTT mode is exponentialy distributed with mean T and T_{out} respectively. Packets length is assumed to be geometrically distributed with parameter q. The average packet length is then given by $\overline{L} = \frac{1}{1-q}$. Moreover transmitter-receiver couples are assumed to be equi-probable (i.e. uniform traffic matrix).

A. Markov Chain Model

We use a five-dimensional continuous-time Markov chain to model the considered asynchronous system.

B. Transition Rates

The system activities can be summarized by the quintuplet (i, j, k, l, m), where i is the number of communicating pairs, j the number of communicating pairs involving blocked transmitters, k the number of ready transmitters, l the number of ready receivers, and m the number of blocked transmitters sending RTC messages. Similarly, let S_i be the set of communicating pairs, S_j the set of communicating pairs involving blocked transmitters, S_T the set of ready transmitters, S_R the set of ready receivers, and $S_B L_T R$ the set of blocked transmitters sending RTC messages.
The transition rate Tr from state I to state J is defined as the rate at which the system makes a transition to state J when at state I and it is given by $Tr[I \rightarrow J] = \nu(I \rightarrow J)P[I \rightarrow J]$, where $\nu(I \rightarrow J)$ is the inverse of the average time spent in state I before transiting to state J and $P[I \rightarrow J]$ is the probability of transitioning to state J from state I..
The set of possible system state transitions is detailed below:

- A transition of the system from state [i,j,k,l,m] to state [i,j,k+1,l,m] corresponds to the transition of one node from the *Idle mode* to the *RTT mode* and its transition rate is given by

$$Tr\,(i, j, k, l, m \rightarrow i, j, k+1, l, m) = \nu\,(Idle \rightarrow RTT)\,P\,(i, j, k, l, m \rightarrow i, j, k+1, l, m)$$

  Where

$$\begin{aligned} P\,(i, j, k, l, m \rightarrow i, j, k+1, l, m) &= P\,(Idle \rightarrow RTT) \\ &= (1 - \exp\,(-\eta\lambda T)) \end{aligned}$$

  $\eta = N - 2i - 2j - k - l - m$ and $\nu\,(Idle \rightarrow RTT) = \lambda$.
  Hence

$$Tr\,(i, j, k, l, m \rightarrow i, j, k+1, l, m) = \lambda\,(1 - \exp(-\eta\lambda T) \tag{1}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j,k,l+1,m] corresponds to the transition of exactly one node from the *Idle mode* to *RTC mode* and its transition rate is given by

$$Tr\,(i, j, k, l, m \rightarrow i, j, k, l+1, m) = \nu\,(Idle \rightarrow RTC)\,P\,[i, j, k, l, m \rightarrow i, j, k, l+1, m]$$

  Where
  $P(i, j, k, l, m \rightarrow i, j, k, l+1, m) = P(Idle \rightarrow RTC) = \exp(-\eta\lambda T)$ and $\nu(Idle \rightarrow RTC) = \frac{1}{T}$
  Hence

$$Tr\,(i, j, k, l, m \rightarrow i, j, k, l+1, m) = \frac{\exp(-\eta\lambda T)}{T} \tag{2}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j,k,l-1,m] corresponds to the transition of exactly one node from the *RTC mode* to *Idle mode* and its transition rate is given by

$$\begin{aligned} Tr\,(i, j, k, l, m \rightarrow i, j, k, l-1, m) &= \nu\,(RTC \rightarrow Idle)\,P\,(i, j, k, l, m \rightarrow i, j, k, l-1, m) \\ &= \nu\,(RTC \rightarrow Idle)\,P(\,RTC \rightarrow Idle\,) \end{aligned}$$

  We have that

$$\begin{aligned} P(\,RTC \rightarrow Idle) &= P(\text{a node in } S_R \text{ fails to initiate a communication}) \\ &= P(\text{synchronization failure}) + P(\text{synchronization success}) \\ &\quad [\,P(\text{collision on data channel}) + P(\text{no collision on data channel}) \\ &\quad [P(\text{no source in } S_T) + P(\text{source in } S_T)\ P(\text{collision on RTS sub-windows})\ ]] \end{aligned}$$

With

$$\begin{aligned}
P(\text{synchronization success }) &= \begin{cases} 1\, if\ l = 1\ and\ m = 0 \\ 0\ otherwise \end{cases} \\
P(\text{collision on data channel}) &= \frac{i+j}{D} \\
P(\text{source in } S_T) &= \frac{k}{N-1} \\
P(\text{collision on RTS sub-windows}) &= \left[\sum_{i=2}^{k} C_k^i \left(\frac{1}{R(N-1)}\right)^i\right] \\
&= \left[\left(1+\frac{1}{R(N-1)}\right)^k - \frac{k}{R(N-1)} - 1\right] \\
\nu(RTC \to Idle) &= \frac{1}{T_{RTC}}
\end{aligned}$$

Then

$$Tr \quad (i,j,k,l,m \to i,j,k,l-1,m) = \begin{cases} \frac{1}{T_{RTC}} \left[\frac{i+j}{D} + (1-\frac{i+j}{D})\left[1-\frac{k}{N-1}+\frac{k}{N-1}\left[\left(1+\frac{1}{R(N-1)}\right)^k - \frac{k}{R(N-1)} - 1\right]\right]\right] & if\ l = 1\ and\ m = 0 \\ \frac{1}{T_{RTC}} \quad otherwise \end{cases} \tag{3}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j,k+1,l,m-1] corresponds to the transition of exactly one node from the RTC_{BL} *mode* to *RTT mode* and its transition rate is similar to the one given by Eq. (3)

$$Tr \quad (i,j,k,l,m \to i,j,k,l-1,m) = \begin{cases} \frac{1}{T_{RTC}} \left[\frac{i+j}{D} + (1-\frac{i+j}{D})\left[1-\frac{k}{N-1}+\frac{k}{N-1}\left[\left(1+\frac{1}{R(N-1)}\right)^k - \frac{k}{R(N-1)} - 1\right]\right]\right] & if\ m = 1\ and\ l = 0 \\ \frac{1}{T_{RTC}} \quad otherwise \end{cases} \tag{4}$$

- A transition of the system from state [i,j,k,l,m] to state [i+1,j,k-1,l-1,m] corresponds to the simultaneous transition of one ready receiver node from the *RTC mode* and one ready transmitter node from the *RTT mode*, to the *COM mode*. Its transition rate is given by

$$Tr\,(i,j,k,l,m \to i+1,j,k-1,l-1,m) = \nu\,((RTC,RTT) \to COM)\,P\,(i,j,k,l,m \to i+1,j,k-1,l-1,m)$$

Where

$$P\,(i,j,k,l,m \to i+1,j,k-1,l-1,m) = P\,(\,(RTC,RTT) \to Com\,)$$

and

$$\begin{aligned}
P\,(\,(RTC,RTT) \to Com\,) &= P(\text{communication setup success}) \\
&= P(\text{synchronization success})P(\text{no collision on data channel}) \\
&\quad P(\text{a source node is within } S_T)P(\text{no collision on at least one RTS sub-windows})
\end{aligned} \tag{5}$$

$$\begin{aligned}
P[\text{synchronization success }] &= \begin{cases} 1\, if\ l = 1\ and\ m = 0 \\ 0\ otherwise \end{cases} \\
P(\text{no collision on data channel}) &= 1 - \frac{i+j}{D} \\
P[\text{source node in } S_T] &= \frac{k}{N-1} \\
P[\text{no collisionon at least one RTS sub-windows}] &= \left[2 + \frac{k}{R(N-1)} - \left(1+\frac{1}{R(N-1)}\right)^k\right]
\end{aligned}$$

Then

$$Tr\left[i,j,k,l,m \to i+1,j,k-1,l-1,m)\right] = \begin{cases} \frac{1}{T_{RTC}}\left(1-\frac{i+j}{D}\right)\frac{k}{(N-1)}\left[2+\frac{k}{R(N-1)}-\left(\frac{1}{R(N-1)}\right)^k\right] \; if\; l=1\; and\; m=0 \\ 0\; otherwise \end{cases} \tag{6}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j+1,k-1,l,m-1] corresponds to the simultaneous transition of one blocked transmitter node from the RTC_{BL} *mode* and one ready transmitter from the RTT *mode*to the COM_{BL} *mode*. Its transition rate is similar to the one given in Eq. (6)

$$Tr\left[i,j,k,l,m \to i,j+1,k-1,l,m-1)\right] = \begin{cases} \frac{1}{T_{RTC}}\left(1-\frac{i+j}{D}\right)\frac{k}{(N-1)}\left[2+\frac{k}{R(N-1)}-\left(\frac{1}{R(N-1)}\right)^k\right] \; if\; m=1\; and\; l=0 \\ 0\; otherwise \end{cases} \tag{7}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j,k-1,l,m+1] corresponds to the transition of one ready transmitter node from the *RTT mode* to RTC_{BL} *mode* and its transition rate is given by

$$\begin{aligned} Tr\left[i,j,k,l,m \to i,j,k-1,l,m+1\right] &= \nu\left(RTT \to RTC_{BL}\right) P\left[i,j,k,l,m \to i,j,k-1,l,m+1\right] \\ &= \nu\left(RTT \to RTC_{BL}\right) P[\; RTT \to RTC_{BL}\;] \end{aligned} \tag{8}$$

$$\begin{aligned} P[\; RTT \to RTC_{BL}] &= P[\text{a node in } S_T \text{ fails to initiate communication during time period } T_{out}] \\ &= 1 - P[\; RTT \to COM] - P[\; RTT \to COM_{BL}] \end{aligned}$$

SO:

$$Tr\left[i,j,k,l,m \to i,j,k-1,l,m+1)\right] = \begin{cases} \frac{1}{T_{out}}\left[1-\left(1-\frac{i+j}{2D}\right)\frac{1}{(N-1)}\left[\frac{(1+P_{NC})^k - kP_{NC}-1}{k}\right]\right] \; if\; l+m=1 \\ 1\; otherwise \end{cases} \tag{9}$$

- A transition of the system from state [i,j,k,l,m] to state [i-1,j,k+1,l,m] corresponds to the simultaneous transition of two communicating nodes from the *COM mode*, one to the *Idle mode* and the other to the *RTT mode* . Its transition rate is given by

$$\begin{aligned} Tr\left[i,j,k,l,m \to i-1,j,k+1,l,m\right] &= \nu\left(\text{COM} \to \text{(Idle,RTT)}\right) P\left[i,j,k,l,m \to i-1,j,k+1,l,m\right] \\ &= \nu\left(\text{COM} \to \text{(Idle,RTT)}\right) P[\text{COM} \to \text{(Idle,RTT)}] \end{aligned} \tag{10}$$

$$\begin{aligned} P[\text{COM} \to \text{(Idle,RTT)}] &= P[\text{synchronization success}] \\ & \quad [\text{and another communication is setup on a currently used data channel}] \\ &= \begin{cases} \frac{i+j}{D}\; if\; l+m=1 \\ 0\; otherwise \end{cases} \end{aligned} \tag{11}$$

So:

$$Tr\left[i,j,k,l,m \to i-1,j,k+1,l,m\right] = \begin{cases} \frac{1}{T_{RTC}}\frac{i+j}{D}\; if\; l+m=1 \\ 0\; otherwise \end{cases} \tag{12}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j-1,k+1,l,m+1] corresponds to the simultaneous transition of two communicating nodes from the COM_{BL} *mode*, one to the RTC_{BL} *mode* and the other to the *RTT mode*. Its transition rate is similar to the one given by equation(12)

$$Tr\left[i,j,k,l,m \to i,j-1,k+1,l,m+1\right] = \begin{cases} \frac{1}{T_{RTC}}\frac{i+j}{D}\; if\; l+m=1 \\ 0\; otherwise \end{cases} \tag{13}$$

- A transition of the system from state [i,j,k,l,m] to state [i-1,j,k,l,m] corresponds to the simultaneous transition of two communicating nodes from the *COM mode* to the *IDLE mode*. Its transition rate is given by:

$$\begin{aligned} Tr\left[i,j,k,l,m \rightarrow i-1,j,k,l,m\right] &= \nu\left(\text{COM} \rightarrow \text{IDLE}\right) P\left[i,j,k,l,m \rightarrow i-1,j,k,l,m\right] \\ &= \nu\left(\text{COM} \rightarrow \text{IDLE}\right) P[\text{COM} \rightarrow \text{IDLE}] \end{aligned} \tag{14}$$

$$Tr\left[i,j,k,l,m \rightarrow i-1,j,k,l,m\right] = \begin{cases} \frac{1}{LT_{RTC}}\left[1 - \frac{i+j}{D}\right] \; if \; l+m=1 \\ 1 \; otherwise \end{cases} \tag{15}$$

- A transition of the system from state [i,j,k,l,m] to state [i,j-1,k+1,l+1,m] corresponds to the simultaneous transition of two communicating nodes from the COM_{BL} *mode*, one to the *RTC mode* and the other to the *RTT mode*. Its transition rate is similar to the one given in Eq. (15)

$$Tr\left[i,j,k,l,m \rightarrow i,j-1,k+1,l+1,m\right] = \begin{cases} \frac{1}{LT_{RTC}}\left[1 - \frac{i+j}{D}\right] \; if \; l+m=1 \\ 1 \; otherwise \end{cases} \tag{16}$$

At steady state, the rate of flow into any given state must equal the rate of flow out of the state. The steady state probability vector P is given by the solution of the equation

$$P = Q.P \quad \text{Where} \quad Q_{ij} = \frac{\sum_j Tr_{ji}}{\sum_j Tr_{ij}} \tag{17}$$

C. Average Throughput and Delay

We have derived the transition rates under a continuous-time Markov chain model. The performances of SEBROMA are measured in terms of average channels utilisation and average system delay. The evaluation of this parameters is based on the knowledge of the steady state probabilities of each of the Markov chain's states. Hence, we first calculate the states probabilities by solving numerically the linear system of equations obtained from the global balance equation (Eq. 17). The normalized average network throughput corresponds to the number of nodes in both the *COM mode* or the COM_{Bl} *mode*, and can be expressed as follows

$$Th_N = \sum_{\substack{i,j,k,l,m \\ 2i+2j+k+l+m \leq N}} (i+j) P(i,j,k,l,m) \tag{18}$$

The system delay is defined as the required time for a new packet to be sent to the destination. In our model, this includes the time spent by a node, successively, in the *RTT mode* before succeeding the handshake, in the *RTC*$_{BL}$ trying to serve other nodes traffic while having a blocked packet to sent, in the *COM*$_{BL}$ *mode* serving other nodes traffic while having a blocked packet to sent, and in *COM mode* transmitting its own packet. Let B be the average number of blocked nodes, by Little's result, the average system delay (normalized to packet length) is given by

$$\text{Delay} = \frac{N_{BL} + N_{COM}}{Th_N} \tag{19}$$

With N_{BL} is the average number of blocked nodes in the system and N_{COM} is the average number of communicating pairs.

$$N_{BL} = \sum_{\substack{i,j,k,l,m \\ 2i+2j+k+l+m \leq N}} (j+k+m)P(i,j,k,l,h) \quad (20)$$

$$N_{COM} = \sum_{\substack{i,j,k,l,m \\ 2i+2j+k+l+m \leq N}} (i+j)P(i,j,k,l,h) \quad (21)$$

IV. Analytical Model Results

In this section, we present the average throughput and delay performance of SEBROMA derived from the analytical model.

figures (5,6) depicts respectively the achievable normalized throughput per user pair and the normalized packet delay Vs normalized T and T_{out} (T=T_{out}) for a network of size N=8, normalized packet length PL=50, 20 data channels and differents probability of packet arrival P. figures (7,8) shows the same performances measures for a network of size N=10, normalized packet length PL=20, 10 data channels and differents probability of packet arrival P. In the two case the maximum throughput and the minimum delay are approximatly achieved for $T = T_{out} = T_{RTC}$, independently from all others parameters.

Figures (9,10) depicts respectively the achievable normalized throughput per user pair and the normalized packet delay Vs the Number of data channels for a network of size N=10, normalized packet length PL=20, T=$T_{out} = T_{RTC}$ and differents probability of packet arrival P. Throughput and delay increase when the number of data channels increases and saturates from Dch=20. Note that for well choosen number of data channels, the performances of the protocol become independent of the network load.

Figures (11,12) depicts respectively the achievable normalized throughput per user pair and the normalized packet delay Vs normalized packet length for a network of size N=10, 10 data channels, T=$T_{out} = T_{RTC}$ and differents probability of packet arrival P. Throughput increases and delay decreases with increasing packet length and saturate from PL=90. Here again, from PL=20, the protocol performances become load independent.

Figures (13,14) depicts respectively the agregate normalized throughput and the normalized packet delay Vs probability of packet arrival for networks of size N=10 and N=12, 20 data channels, T=$T_{out} = T_{RTC}$ and normalized packet length 20 and 100. Througput and Delay are quasi constants. This because nodes alternates fairly between transmission and reception phases, so all nodes succeed to transmit in a bounded delay and by consequence use efficiently the system capacity.

V. Future work

Performances obtained from numerical results are very promizing. To confirm them, we still need to find analytically the optimal values for T and T_{out}. Actually, we are studying the problem of finding the steady state probabilities of general closed network of queues.

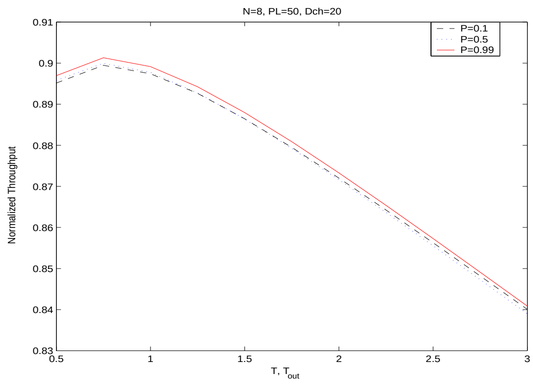

Fig. 5. Normalized Throughput vs T and T_{out}

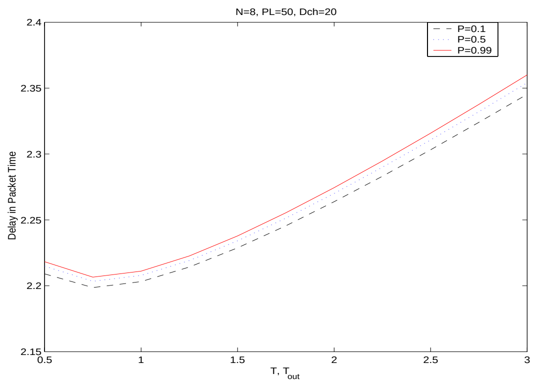

Fig. 6. Normalized Delay vs T and T_{out}

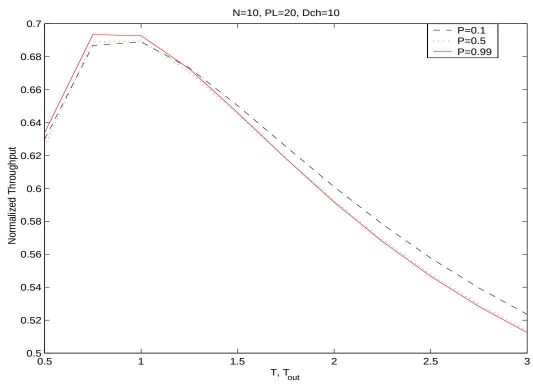

Fig. 7. Normalized Throughput vs T and T_{out}

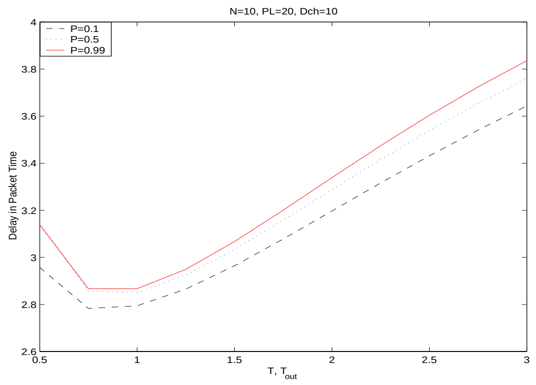

Fig. 8. Normalized Delay vs T and T_{out}

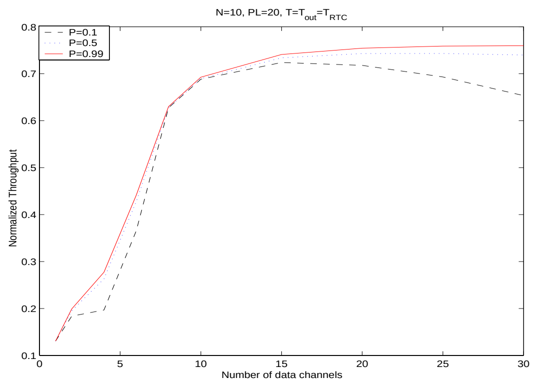

Fig. 9. Normalized Throughput vs Number of Data Channel

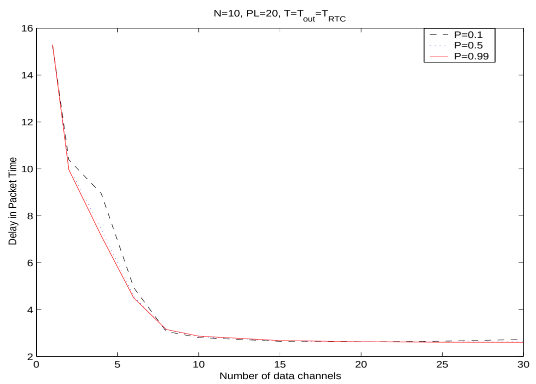

Fig. 10. Normalized Delay vs Number of Data Channel

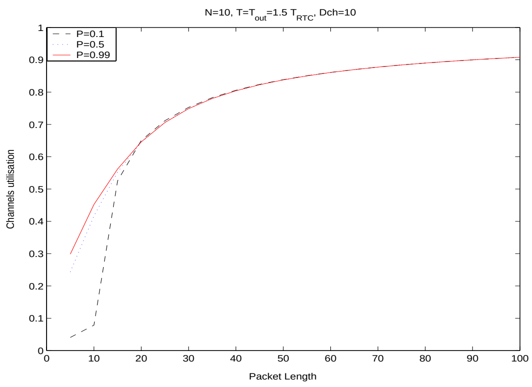

Fig. 11. Normalized Throughput vs packet length

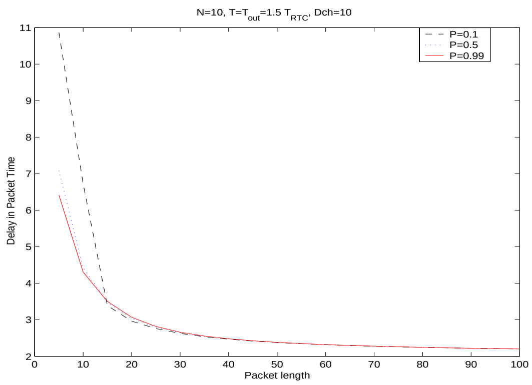

Fig. 12. Normalized Delay vs packet length

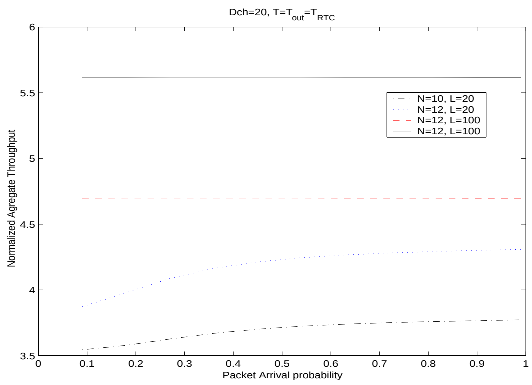

Fig. 13. Normalized Agregate Throughput vs Probability of Packet Arrival

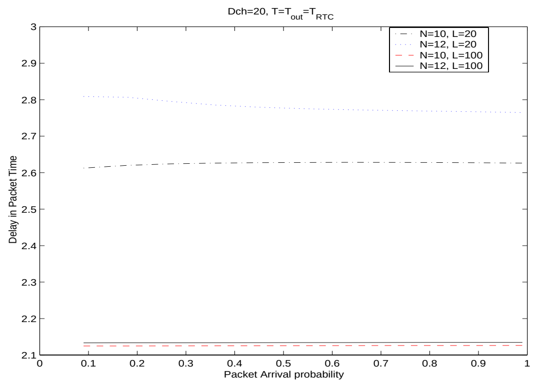

Fig. 14. Normalized Delay vs Probability of Packet Arrival

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