Self-Balanced Receiver-Oriented MAC for Ultra-wideband Mobile Ad Hoc Networks

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***Abstract*— A novel medium access control protocol for ultra-wide band mobile (UWB) ad-hoc networks, that we call self-balanced receiver-oriented MAC (SEBROMA), is presented. SEBROMA is fully distributed and does not need a global network synchronization. The proposed scheme is analyzed through Markov chain modeling and it is shown to guarantee a bounded system delay and a non vanishing throughput even at high network loads.**

I. Introduction

With the recent Federal Communications Commission (FCC) decision to adopt rules allowing ultra wide bandwidth (UWB) devices, it is clear that UWB is an exciting technology that has unique characteristics when used for wireless communications. We take a UWB system to be loosely defined as any wireless transmission scheme that occupies a bandwidth between 1 and 10Ghz and more than 25 % of it's carrier frequency in the case of passband system. The most common UWB transmission scheme is based on transmitting information through the use of short-term impulses, whose positions in time are modulated by a binary information source. Similar to direct sequence spread-spectrum, the position can further be modulated by an M-ary sequence called time-hopping sequence for mitigating inter-user interference. This type of UWB modulation is a promising candidate for military imaging systems as well as other non-commercial sensor network applications because of its robustness to interference from signal (potentially from other non-UWB systems) occupying the same bandwidth. Based on recent documentation from the FCC [1] it is also being considered for commercial ad-hoc networking applications based on peer-to-peer communications.

A mobile Ad Hoc networks 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 behalf of other nodes. Generally, MAC protocols for Manets may be broadly classified into two groups based on their strategy for determining access rights: deterministic access protocols or contention protocols.

Deterministic allocation protocols assign to each node in the network a permanent transmission schedule indicating in which of the data channels (time, frequencies, spreading codes or their combinations) the node may transmit. These protocols have bounded delay but suffer low performances at low load. Moreover if the network is highly mobile, these protocols may potentially become unstable as maintaining transmission schedules use almost all nodes capabilities. In [2], 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 need to address the problem of hidden terminal. Karn [3] proposed MACA protocol which attempts 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. Many variations of this protocol were proposed, like FAMA [4], which tries to ensure a robust handshaking through the use of longer RTS/CTS messages. To reduce signalization overhead at high load, invitation based protocols were proposed. In [5] a receiver oriented, collision free protocol over TDMA system was suggested and was shown to improve the throughput.

The exchange of RTS/CTS messages does not really solve the problem of hidden and exposed terminals; the reason is that, although exposed terminals are permitted to send their RTS messages to request the channel, they will not receive any CTS replies when an other node is transmitting on the single channel. Also the hidden terminals still can not receive, as they are forbidden to access the channel (replying to RTS messages).

Multiple channel networks solves the previous problems; multiple channel radio networks permit multiple stations, within the range of the same receiver, to transmit signalisation messages as well as traffic data concurrently without interfering. Several MAC protocols using spreading codes for multiple access have been proposed. Sousa and Silvester [6] 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. Here again, receiver initiated schemes, as proposed in [7], are shown to improve network throughput in multiple channel networks.

A performance limitation of all collision avoidance MAC protocols is that they cannot provide inter-packet delay guarantees. This occurs at high loads when nodes spend most of

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there time trying to resolve contention in order to transmit their own packets, leading to a quasi deadlock situation.
The main goal of this work is to present a new MAC protocol for ultra-wide band mobile ad-hoc networks and derive its performances through a Markov chain modeling. The proposed protocol uses UWB signalization capability to mitigate multiuser interference, it is receiver initiated, 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 suggested system, and use it to obtain the achievable throughput and system delay. Finally in section IV we examine the numerical results and discuss the performance of the system.

II. Protocol Description

Here we suggest a new realistic and fully distributed multiple access scheme for UWB mobile ad-hoc networks, which is able to take advantage of the properties of the underlying physical layer, in particular its robustness to multi-user interference. The basic philosophy, of the developed scheme, is to reduce as much as possible the signalization overhead and avoid global network synchronization due to the difficulties related to its practical realization. Moreover, 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 time-hopping code(TH) multiple access scheme is used, where all nodes share a common signaling channel (TH code) and each of them uses a randomly chosen code for each data transfer. This simplifies the code assignment functionality since no inter-node collaboration is needed. Each communication is preceded by a collision-avoidance handshake procedure initiated by receiving nodes. Furthermore, no global synchronization is needed and only local synchronization is performed, during each handshake, between each receiver and its intended transmitters. The synchronization is eventually maintained for data transfer between the receiver and the contention-winner transmitter. Each node carries fairly other nodes traffic as well as its own traffic in order to ensure the balance between the number of transmitters and receivers in the network. Transmitters which are not able to setup a communication for their own traffic, become receivers in order to eventually serve other nodes traffic, and retry later to transmit their own packets until success.

A. Network Access

The procedure is simplified since collaboration from other nodes is reduced. Each node has an ID allowing to distinguish it from other nodes [1] and transmits, pseudo-randomly in time, a ready to communicate message (RTC) containing a synchronization sequence followed by its ID, an information field, and a time-hopping code randomly chosen at each message transmission (Fig. 1). The synchronization sequence allows the listening nodes to detect the transmission of the RTC message and get synchronized with its transmitter in order to be able to correctly receive its message. The time hopping code, contained in the RTC message, can be used either for contention resolution, multi-casting or broadcasting neighborhood information, depending on the value of the information field. Randomly choosing the code from a very large code set, at each RTC message sending, reduces the probability of having two nodes using the same time-hopping code and avoid the need of a centralized code assignment.

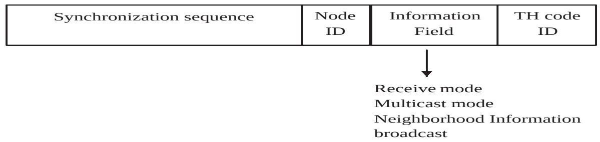

Fig. 1. RTC Message form

B. Communication Setup

Node to node communications are initiated by the receivers. Each node, ready to receive data from the other nodes, sends, at a pseudo-randomly chosen instant an RTC message with information field set to 'receive mode' inviting the potentially interested transmitters to compete for starting a communication with it, by sending a ready to send message (RTS). The RTC message is followed by a contention window [2]. This window is dedicated to the reception of the Request to Send messages, sent by the transmitters, using the time hoping code given by the receiver in the RTC message (Fig. 2). Among the successfully decoded RTS messages (no collisions), the receiver answers the accepted request [3] by sending a clear to send message (CTS) in a dedicated window (contention resolution window). The CTS message contains a time hopping code to be used for data transmission. If a transmitter fails to initiate a communication during a period T_{out} (because of collisions or a not available receiver), it sends a RTC message after which the node returns to the transmitting mode, right after the end of the RTC message if no communication is successfully setup or after the end of the data traffic in the contrary case. This procedure allows unlocking situations where a transmitter and its intended receiver are both trying unsuccessfully to initiate a communication, which keep both of them blocked.

C. Modes Diagram

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

1) Idle Mode: A station is said to be in the *Idle mode* if it is neither transmitting nor receiving packets from other stations. If no new packet is received during a, pseudo randomly

[1]it can be either randomly chosen among a set of large number of possible ID's (in order to reduce the probability of having two nodes with the same ID), or derived from its hardware ID, or associated to his IP address etc

[2]The contention window may be divided into several contention sub-windows among witch each transmitter chooses one randomly in order to reduce the collision probability. Furthermore we may reserve one or several higher priority sub-windows for multicasting and handover traffic

[3]based on requests priority and capability criterion

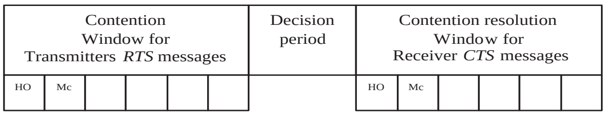

Fig. 2. Multiple Access on the receiver MA-TH code

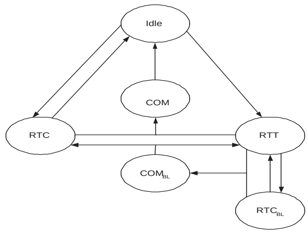

Fig. 3. Modes diagram

chosen, time-period T, the node passes to the *RTC mode*, otherwise it passes to the *RTT mode*.

2) RTT Mode: A station is said to be in RTT mode if it has a packet to send and its trying to transmit it. If it does not succeed to initiate a communication during a time-period T_{out} it passes to the *RTC$_{BL}$* mode otherwise it passes to the *com mode*.

3) RTC Mode: A station is said to be in the *RTC mode* if it is sending a RTC message, if it succeeds to initiate a communication it passes to the *COM mode*, otherwise it goes back to the *Idle mode*.

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

5) RTC$_{BL}$ Mode: A station is said to be in the *RTC$_{BL}$ mode* if it is sending a RTC message after one or several failures to initiate a communication(for the same traffic) in previous trials. If it succeeds to initiate a communication, it passes to the COM_{BL} mode, otherwise, it goes back to the *RTT mode*.

6) COM$_{BL}$ Mode: A pair of stations is said to be in the *COM$_{BL}$ mode* if they are communicating after one or several failures for the receiver to initiate a communication in previous trials. At the end of the communication, the receiver goes to the *RTT mode* while the transmitter passes to the *RTC mode*.

III. Throughput-Delay Analysis

We consider a single-cell, fully connected network containing N radio units which can communicate directly between each other. We also assume that each node receives equal power signals from all transmitters. Each node can operate in either transmitter or receiver modes but not in both simultaneously.
The interference on the common signaling channel(code) is modeled by a synchronization success probability $P_s(t) = \frac{1}{n^\alpha(t)}$ where $n(t)$ is the number of nodes(receivers) sending RTC messages at time-instant t. The interference parameter α measures the efficiency of the synchronization procedure and its sensibility to multiuser interference[4]. Moreover the effect of the interference, in data channels, on the achievable data rates is neglected. This assumption expresses the robustness of UWB systems to inter-user interference, particularly non-dense networks [8].
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 RTC message duration T_{RTC}[5], and 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.

The system activities can be summarized by the quintuplet (i, j, k, l, h), where i is the number of communicating pairs, j the number of communicating pairs involving blocked transmitters, k the number of active transmitters, l the number of reactive receivers, and h the number of blocked transmitters sending a RTC message. 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 $Tr[I \to J] = \nu(I \to J)P[I \to J]$, where $\nu(I \to J)$ is the inverse of the average time spent in state I before transiting to state J.
The set of possible system state transitions is detailed below

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

$$Tr\left[i, j, k, l, h \to i, j, k+1, l, h\right] = \eta\lambda\left(1 - \exp(-\lambda T)\right) \tag{1}$$

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

$$Tr\left[i, j, k, l, h \to i, j, k, l+1, h\right] = \frac{\eta \exp(-\lambda T)}{T} \tag{2}$$

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

$$Tr\left[i, j, k, l, h \to i+1, j, k-1, l-1, h)\right] = \frac{k}{T_{RTC}} \frac{l}{(N-1)} \frac{1}{(l+h)^\alpha} \left(\frac{N-2}{N-1}\right)^{k-1} \tag{3}$$

[4]If carrier sensing is used on the common signalization channel, the probability of synchronization success corresponds to $\alpha = 1$

[5]equivalent to slot-duration in slotted systems

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

$$Tr\left[i,j,k,l,h \to i,j,k-1,l,h+1\right] = \frac{k}{T_{out}}\left[1+\frac{1}{(l+h)^{\alpha}}\left[1-\frac{l+h}{N-1}-\left(\frac{N-2}{N-1}\right)^{k-1}\right]\right] \quad (4)$$

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

$$Tr\left[i,j,k,l,h \to i,j,k,l-1,h\right] = \frac{l}{T_{RTC}}\left[1+\frac{1}{(l+h)^{\alpha}}\left[1-\frac{k}{N-1}-\left(\frac{N-2}{N-1}\right)^{k-1}\right]\right] \quad (5)$$

- A transition of the system from state [i,j,k,l,h] to state [i-1,j,k,l,h] corresponds to the simultaneous transition of two nodes from the *COM mode* to the *Idle mode* and its transition rate is given by

$$Tr\left[i,j,k,l,h \to i-1,j,k,l,h\right] = \frac{i}{LT_{RTC}} \quad (6)$$

- A transition of the system from state [i,j,k,l,h] to state [i,j+1,k-1,l,h-1] corresponds to the simultaneous transition of, one transmitter node from the *RTT mode* and one receiver node from the RTC_{BL} *mode*, to the COM_{BL} *mode*. Its transition rate is similar to the one given in Eq. (3)

$$Tr\left[i,j,k,l,h \to i,j+1,k-1,l,h-1)\right] = \frac{k}{T_{RTC}}\frac{h}{(N-1)}\frac{1}{(l+h)^{\alpha}}\left(\frac{N-2}{N-1}\right)^{k-1} \quad (7)$$

- A transition of the system from state [i,j,k,l,h] to state [i,j,k+1,l,h-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. (5)

$$Tr\left[i,j,k,l,h \to i,j,k+1,l,h-1\right] = \frac{h}{T_{RTC}}\left[1+\frac{1}{(l+h)^{\alpha}}\left[1-\frac{k}{N-1}-\left(\frac{N-2}{N-1}\right)^{k-1}\right]\right] \quad (8)$$

- A transition of the system from state [i,j,k,l,h] to state [i,j-1,k+1,l+1,h] corresponds to the simultaneous transition of two nodes from the *COM mode*, one to the *RTT mode* and the other to the *RTC mode*. Its transition rate is similar to the one given in Eq. (6)

$$Tr\left[i,j,k,l,h \to i,j-1,k+1,l+1,h\right] = \frac{j}{LT_{RTC}} \quad (9)$$

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

$$P = Tr.P \quad (10)$$

where Tr is the transition rate matrix.

B. 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-Throughput 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 solve numerically the linear system of equations obtained from the global balance equation (Eq. 10). 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

$$Th_N = \sum_{\substack{i,j,k,l,h \\ 2i+2j+k+l+h\leq N}} (i+j)P(i,j,k,l,h) \quad (11)$$

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

$$\text{Delay} = \frac{N_{BL}+N_{COM}}{Th_N} \quad (12)$$

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

$$N_{BL} = \sum_{\substack{i,j,k,l,h \\ 2i+2j+k+l+h\leq N}} (j+k+h)P(i,j,k,l,h) \quad (13)$$

$$N_{COM} = \sum_{\substack{i,j,k,l,h \\ 2i+2j+k+l+h\leq N}} (i+j)P(i,j,k,l,h) \quad (14)$$

IV. Numerical Results and Discussion

In this section, we present the average throughput and delay performance of SEBROMA. Results are obtained for $T_{out} = T_{RTC}$. This value was found, experimentally by simulation, to be the optimum choice for parameter T_{out}. Figure (4) shows the achievable normalized throughput per user pair versus channel load for interference factor $\alpha = 1$, different values of network size N and average packet size 10 and 100 respectively. Load is defined as the number of packets arriving during time interval T, i.e., $Load = \lambda T$. We can see

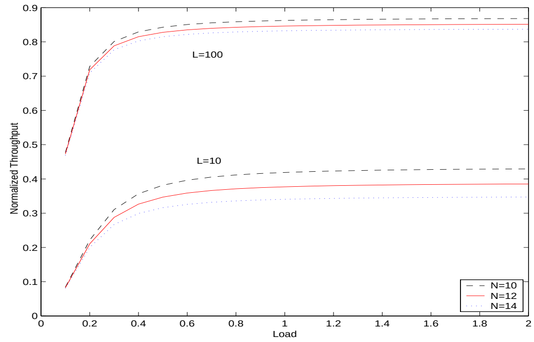

Fig. 4. Normalized throughput for L=10,100 and α=1

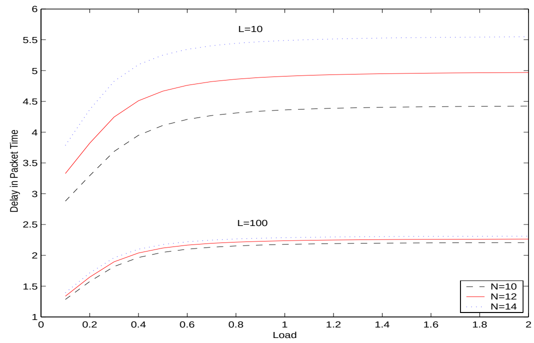

Fig. 5. Normalized delay for L=10,100 and α=1

that the throughput does not vanish for increasing network load even for small average packet size (10), while all other MAC protocols, proposed to date, [5,7] suffer a severe achievable throughput degradation at high network loads.

Figure (5) shows the achievable normalized delay per user versus channel load for $\alpha = 1$, different values of network size N and average packet size 10 and 100 respectively. As it can be seen, the average system delay saturates for increasing network load while standard contention MAC protocols [7] endure a delay increase for augmenting network load.

The observed results are due to the adaptive behavior of the nodes to the network's load. By alternating fairly transmission and reception phases, each node succeeds to transmit his traffic in a bounded time. Figure (6) depicts the number of ready transmitters and active receivers respectively, versus network load for $\alpha = 1$, network size $N = 10$, and average packet size 10. Where we define active receivers as nodes in *RTC mode* or in RTC_{BL} *mode*, and ready transmitters as nodes in *RTT mode*. We can see that the number of active receivers is slightly greater than the number of ready transmitters. This illustrates the efficiency of the proposed scheme in ensuring the balance of the system and explains the obtained results.

V. Conclusion and future work

In this work, we have presented SEBROMA, a receiver-oriented medium access control protocol for ultra-wide band mobile ad hoc network that does not need neither code assignment nor global network synchronization. SEBROMA con-

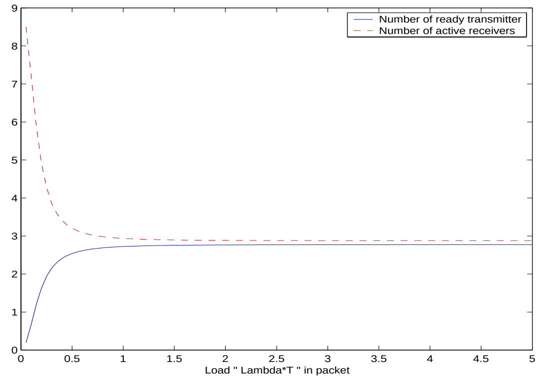

Fig. 6. The number of ready transmitters and active receivers for N=10, L=10 and α=1

strains only transmitting nodes to be continuously active, while receiving nodes oscillate between active and idle modes, which contributes to power save. The proposed scheme was analyzed through Markov chain modeling, and was shown to guarantee a bounded system delay and a non-vanishing throughput even at high network load. Like all receiver-initiated schemes, the system performance depends on the frequency at which the nodes send invitation messages. Our system depends also on the frequency $\frac{1}{T_{OUT}}$ at which nodes switch from RTT mode to RTC_{BL} mode. Early simulations with NS2(9) have shown the difficulties related to optimaly choosing this parameters. In future works, we will try to improve our protocol in order to reduce or avoid this dependency. We will also compare our system performance to those of synchronized schemes.

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