

Analysis and Evaluation of a Decentralized Multiaccess MAC for Ad-hoc Networks

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Abstract

In mobile ad-hoc radio networks, terminals are mobile and heterogeneous, the architecture of the network is continuously changing, communication links are packet oriented and radio resources are scarce. Therefore, mechanisms on how to access the radio channel are extremely important in order to improve network efficiency and, when needed, to guarantee QoS. However, due to these network harsh conditions, decentralized Medium Access Control (MAC) protocols designed specifically for ad hoc networks are scarce. In this paper we present a novel decentralized multiaccess MAC protocol for Ad Hoc networks. This MAC protocol is an hybrid CDMA-TDMA in which a cross layer approach has been followed in order to maximize network throughput. A theoretical analysis of the system is presented ending up with closed expressions for the throughput and delay of the network and some simulations are presented to evaluate the performance of the system.

Keywords

Ad-hoc, Cross Layer, Decentralized, CDMA, MAC, Multiaccess.

I. Introduction

Traditionally, MAC mechanisms are used to face-off the classical collision resolution problem in single-access channels. That is, if two or more nodes send packets through the radio channel simultaneously these packets collide and consequently, information is lost. To recover the information, the collided packets have to be retransmitted. Although the common aim in such single-access channels is a MAC able to come close to efficiency equal to one by avoiding collisions as much as possible, the approach considered in MAC design is different whether the system is centralized or decentralized. In this paper, we will focus on such decentralized systems.

Regarding to decentralized MAC algorithms, a Request-to-Send and Clear-to-Send handshake for channel reservation during transmission is presented in [1] and references therein. In other mechanisms such as CSMA [2],[3], the channel is sensed before transmission to know whether it is idle or busy. Finally, in basic TDMA systems like Bluetooth (not totally decentralized but still considered ad-hoc) [4], collision is avoided by assigning a slot time to each node. Clearly, the collision resolution efficiency of each of these techniques will mainly depend on the traffic load of the network and none of them is designed to adapt to traffic load changes. Therefore, the optimal MAC procedure for decentralized systems would be similar to the one presented in ADAPT [5] able to evolve, according to an increase of the traffic load, from a contention to a conflict-free mode [6] in a decentralized fashion.

However, these MAC techniques do not consider multiple-access communication and hence, show low channel use

efficiency. Furthermore, the introduction of diversity, such as code diversity or space diversity, allows multipacket reception (MPR) at PHY layer and shows improvement in system performance [7],[8]. However, no cross-layer approach is taken, i.e., techniques on how to access the channel are not modified. Consequently, it comes to one's mind, that the knowledge of this new PHY capability at the MAC layer should provide valuable information in the design of new MAC techniques. This idea of using interaction between layers in order to improve and reach an optimal system performance is known as cross-layer [9].

Concerning decentralized MAC, little has been reported for ad hoc multiaccess systems where nodes can transmit directly to each other and any node is a potential receiver or transmitter. An interesting work is presented in [10] where a comparison of a CDMA Aloha based decentralized system with MPR receivers is compared with its equivalent centralized system.

The CDMA-TDMA based MAC protocol for ad hoc networks presented here is an extension of the work in [11] that aims throughput maximization in decentralized multiaccess environments. Particularly, this protocol is intended to dynamically evolve from a contention to a conflict-free mode while efficiently managing time and code resources by means of two degrees of freedom, the retransmission probability P_r and the number of codes to be allocated to a particular node N_c , and what is more, always accounting for the receiver MPR capability.

The remainder of this paper is structured as follows. In section II we present the model of an ad hoc network. The receiver and network MPR capabilities are explained in section III. Section IV is devoted to the analysis and optimization of the system. This analysis is based on a two dimensional Markov chain and ends up with closed expressions for the optimization of the throughput and the delay of the network. Finally, we present simulation examples and comparisons with existing systems in section V and conclusions and further work are presented in section VI.

II. System Model

We consider a single-hop (fully connected) packet oriented CDMA-TDMA ad-hoc network in which all nodes are identical and share the same common channel. The spreading codes are supposed to be known by all the nodes in the network. Each node can be either transmitter or receiver but not both at the same time, i.e., half duplex communication is assumed. Synchronization and association procedures could be similar to the ones in [3] and are not tackled here. Hence, it is assumed that every node is perfectly synchronized and knows the number of nodes present in the network.

The network is characterized by both, the number of users M in the network and the number of codes N to be used in this network (usually $M \geq N$). Time is slotted and each time slot is

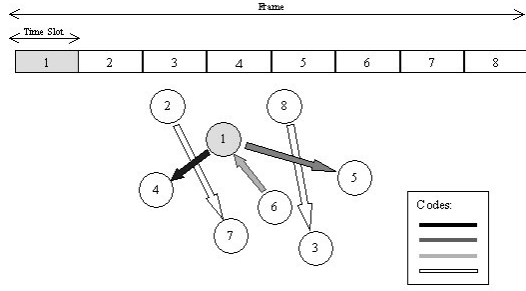


Figure 1: System Example

assigned to one node. The duration of a slot is the time needed for the transmission of a data packet. During one time slot, the node owning that slot, i.e., the node to whom that slot has been assigned have N_c codes ($N_c \leq N$) to transmit its packets simultaneously. Meanwhile, the remaining $M-1$ nodes contend for the residual codes N_r ($N_r = N - N_c$). The node owning the slot is called multiple node and the nodes contending for the N_r codes are called simple nodes. At the beginning of a slot, the multiple node sends its packets with probability equal to one, with the possibility to send up to N_c packets through N_c different codes simultaneously (one packet per code). On the other hand, simple nodes contend for sending one packet at the most. Besides, during the contention, a simple node with a packet waiting for retransmission, also called backlogged simple node, retransmits its packet with probability equal to P_r through a code chosen randomly from the N_r codes. If on the contrary, a simple node has a packet to be transmitted for the first time, i.e., is an unbacklogged simple node, the packet is transmitted with probability equal to one and again, through a code chosen randomly from the N_r codes. As the multiple node is changing in a slot by slot basis, a node becomes a multiple node once every M slots.

With the contention of codes described, it is possible that some simple nodes choose the same code for transmitting a packet simultaneously. If this is the situation, such packets collide and are lost. Codes used by more than one node simultaneously are named collided codes and consequently, packets sent by means of these collided codes are named collided packets. On the contrary, packets sent simultaneously through different codes are called non-collided packets.

Besides, another parameter that will characterize the network described here, is the number of free nodes M_f that are in reception mode at given time, i.e., M_f accounts for nodes that are not in transmission mode. Clearly, due to the existence of a node with N_c codes that can send more than one packet simultaneously, the total number of packets (including collided ones) sent throughout the network is not equivalent to the number of nodes in transmission mode.

Figure 1 presents an example of a system with eight nodes. The length of the frame depends on the number of nodes, in that example, the frame is 8 time slots long. In slot 1, the multiple node is the node 1 and uses 2 codes ($N_c=2$) to send packets to nodes 4 and 5 (codes are indicated by means of arrows of different grey shade). Nodes 2 and 8 also transmit a packet to nodes 7 and 3 respectively. However, nodes 2 and 8 randomly choose the same code and hence, packets collide and are lost. Notice that in that example, $M_f = 4$ (nodes 3, 4, 5 and 7 are not in transmission mode). Besides, node 6 sends a packet to node 1, although this packet do not collide, it is also lost because node 1 is in transmission mode. In that situation and considering a fully connected network, nodes 5 and 4 would receive 5 packets to demodulate but only 1 among these 5 is intended for each of them. Success in transmission would

depend on the MPR capabilities of the receivers. In the following slot, the general behavior of the network would be similar as the one stated here. However, in slot 2, the multiple node would be node 2 and node 1 would become a simple node. Notice that each node becomes a multiple node once every eight slots.

III. Receiver and Network MPR Capabilities

The receiver MPR capability will mainly depend on the SNR and the Multiple Access Interference (MAI). Let's assume that the receiver architecture is a bank of matched filters, data is BPSK modulated, the total number of received packets is m and that the system is totally synchronized. Under the Gaussian assumption on the MAI, the Bit Error Rate (BER) at the output of the matched filters corresponding to non-collided codes can be computed by:

$$BER(m) = Q \left(\left(\frac{3Sp}{m-1+3Sp\sigma^2} \right)^{\frac{1}{2}} \right) \quad (1)$$

In (1), Sp refers to the spreading gain of the spreading codes. Assuming that errors occur independently in a packet, the number of errors i in a packet with length P_i is a binomial random variable with probability mass function:

$$B(i, P_i, BER) = \binom{P_i}{i} BER^i (1 - BER)^{P_i-i} \quad (2)$$

And hence, considering that up to t errors can be corrected in a packet, the Packet Error Probability (PER) as a function of m can be computed as:

$$PER(m) = 1 - \sum_{i=0}^t B(i, P_i, BER(m)) \quad (3)$$

We recall that in our system nodes choose codes randomly and hence, in the event of two or more nodes using the same code, packets are lost due to collision. Therefore, given statistical independency between packets and if there are L non-collided packets (i.e. packets sent through different codes), the number of successfully received packets l among a total of m packets is also a binomial random variable with probability mass function:

$$c_{m,l}(L) = B(l, L, 1 - PER(m)) \quad (4)$$

Unfortunately, the problem arises when in ad-hoc networks the values of $c_{m,l}(L)$ that characterize the MPR capability of the receiver, do not completely characterize the multipacket reception capability of the network. First, since transceivers are half-duplex, a node in transmission mode cannot successfully receive packets and second, a node can successfully demodulate a packet not intended for him. In this two situations packets are lost. Furthermore, in our system packets are lost due to collision of codes. Bao and Tong [10], have done work on modifying the receiver MPR capability to characterize the MPR capability of the network accounting for the properties of ad-hoc networks. However, this characterization is not enough in the problem stated here. Consequently, we define $r_{m,l}(M_f, L)$ as the probability that l out of m packets are successfully received by their intended receivers in the network given that M_f nodes are in reception mode and that L out of m packets have not collide. Notice that when $M_f = 0$, i.e., no node is in reception mode, then,

$r_{m,l}(0,L)=0$. The connection between $c_{m,l}(L)$ and $r_{m,l}(M_f L)$ is provided by the following theorem:

Theorem: Given that a total of m packets are transmitted and L out of these m packets are non-collided packets and that $M_f (\geq M-L)$ nodes are in reception mode, the probability that there are $l \leq L$ successfully received packets by their intended receivers in the network is given by:

$$r_{m,l}(M_f, L) = \sum_{n=l}^l \sum_{j=\min(n,1)}^{\min(n,M_f)} q_{L,n} \frac{\binom{M_f}{j}}{\binom{M_f}{n}} \left(\sum_{(\sum a_j)=n} \frac{n!}{a_1! a_2! \dots a_J!} \left(\sum_{(\sum b_i)=l} \left(\prod_{i=1}^J d_{L,a_i,b_i} \right) \right) \right) \quad (5)$$

Where:

$$q_{L,n} = \binom{L}{n} \left(\frac{M_f}{M-1} \right)^n \left(1 - \frac{M_f}{M-1} \right)^{L-n}$$

$$d_{L,a_i,b_i} = \sum_{k=b_i}^{L-(a_i-b_i)} \frac{\binom{a_i}{b_i} \binom{L-a_i}{k-b_i}}{\binom{L}{k}} c_{m,k}(L)$$

In (5), $q_{L,n}$ is used to determine the probability that n among L non-collided packets reach their intended nodes and d_{L,a_i,b_i} is used to determine the probability of successfully receive b_i packets when a_i packets are intended for that node. A proof of (5) is shown in [11].

IV. System Analysis and Optimization

Before we proceed to the analysis of the system, it is important to state the following five assumptions:

1. Nodes generate packets according to independent Poisson processes with an equal arrival rate of λ packets/slot.
2. Perfect feedback information about the status of transmission is received instantaneously by each node.
3. All nodes have the same receiver architecture.
4. Packets in a node have equal probability to be transmitted to any other node.
- 5a. From the time a simple node generates a packet until that packet is successfully received, the user is blocked in the sense that he cannot generate (or accept from his input source) a new packet for transmission, i.e., a simple node can hold at most a packet at a time.
- 5b. The multiple node can hold at most N_c packets at a time.

Notice that assumptions from 1 to 5.a are considered standard assumptions [10]. From this assumptions, the analysis of the system is based on a Markov chain model. For a M node network, the Markov chain is a two dimensional $(N_c+1) \times M$ state chain which models both, the number of backlogged packets in the multiple node buffer which is in the range of $[0, N_c]$ and the number of simple nodes in backlogged state which is in the range of $[0, M-1]$. For our analysis, we will consider that the multiple node do not change from slot to slot and is always the same node. However, considering that all nodes are identical and from a network point of view, this assumption is considered valid for the computation of the stationary probabilities of the Markov chain that models our system.

This Markov chain is characterized by a transition matrix \mathbf{P} in which each entry is $P_{(i,n),(j,k)}$ and denotes the probability of network state to go from state (i,n) to state (j,k) in one time slot. The transition from one state to another of the Markov chain is determined by two events, i) the difference between unsuccessful transmissions of unbacklogged packets of the

multiple node and the successful retransmissions of backlogged packets of the multiple node and ii) the difference between the number of unsuccessful transmissions from unbacklogged simple nodes and the number of successful retransmissions from backlogged simple nodes. The computation of \mathbf{P} and the stationary distribution of the network state $\boldsymbol{\pi}$ is fully explained in [11].

Throughput and Delay Optimization

The network throughput is defined as the number of packets successfully received by their intended nodes in one time slot on the average when the system is in its steady-state. Hence, given the system is in state (i,n) , the expected number of packets successfully received by their intended nodes is:

$$\beta(i,n) = \sum_{z=0}^{N_c-i} \sum_{x=0}^{M-n} \sum_{y=0}^n Q_{z,x,y} \left(\sum_{t=0}^{x+y} S_{x+y,t} \left(\sum_{l=0}^{z+i+t} l r_{m,l}(M_f, L) \right) \right) \quad (6)$$

Where, $Q_{z,x,y}$ is the probability of transmitting a total of $z+i+x+y$ packets when the system is in state (i,n) and $S_{x+y,t}$ computes the probability of having t non-collided packets when $x+y$ packets have been sent by simple nodes. For the computation of $Q_{z,x,y}$ and $S_{x+y,t}$ the reader is referred to [11]. Therefore, averaging for all the possible states and considering similarity among all users, the network throughput, depending on N_c and P_r , becomes:

$$\bar{\beta}_{N_c, P_r} = \sum_{i=0}^{N_c} \sum_{n=0}^{M-1} \beta(i,n) \pi_{i,n} \quad (7)$$

Besides, the system delay defined as the time on the average since the packet is generated until it is successfully received can be computed following [15]:

$$\bar{D} = \frac{\sum_{i=0}^{N_c} \sum_{n=0}^{M-1} (i+n) \pi_{i,n}}{\bar{\beta}_{N_c, P_r}} + R \quad (8)$$

In (8), R is the deterministic delay which is, the transmission delay added to the average delay since the packet is generated until it is transmitted for the first time and then, $R=1+0.5$ slots.

It is well known that Aloha systems may present some instability. However, it is possible to properly adjust P_r in order to stabilize the system and consequently maximize the throughput and minimize the delay in the steady state. In our system, we use two parameters (P_r and N_c) to stabilize the system. For system optimization, expressions (7) and (8) must be maximized and minimized numerically:

$$\bar{\beta}_{\max} = \arg(\max_{N_c, P_r} (\bar{\beta}_{N_c, P_r}))$$

$$\bar{D}_{\min} = \arg(\min_{N_c, P_r} (\bar{D}_{N_c, P_r})) \quad (10)$$

V. Simulations

In this section we present the results obtained from simulations of a 5 node ad-hoc network, i.e., $M=5$ for various designs. First, we have considered a N code CDMA-TDMA based ad-hoc network as the one described throughout this paper. Under assumptions presented in section IV and considering that the multiple user do not change and is always the same, the performance of the network in terms of throughput and delay has been evaluated for $N=2,3,4,5$. Finally, a 5 node Aloha based CDMA ad-hoc network has been also simulated and results have been compared. In simulations, data Modulation is BPSK, $S_p=11$, $L_p=1000$ bits, $\text{SNR}(1/(\sigma^2))=10$ and number of correctable errors (t)=10 bits.

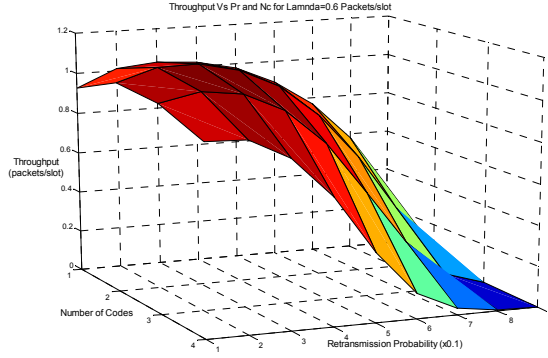


Figure 2: Throughput for CDMA-TDMA system

Aloha based CDMA ad-hoc network description

The Aloha based CDMA ad-hoc network considered is the decentralized system presented in [10]. This system considers a time slotted ad-hoc network with M nodes where each node can communicate with any other node and where no hidden or exposed terminals are considered. Besides, it is a CDMA network where each node has a unique assigned code for transmission (then, the number of codes N is equal to the number of nodes M) and the access to the channel is controlled by means of an Aloha procedure with retransmission probability P_r . Although this is not the aim of the work presented in [10], that system can be optimized, in terms of throughput and delay, by adjusting P_r in accordance with the traffic load λ . This is what we have done in simulations in order to make comparisons with the CDMA-TDMA system.

Throughput and Delay

Regarding to the CDMA-TDMA based system, figures 2 and 3 depict the dependence of throughput and delay respectively as a function of the retransmission probability P_r and the number of codes N_c when $\lambda=0.6$ packets/slot and $N=5$. Figure 2 shows a maximum throughput for $N_c=2$ and $P_r=0.3$ while figure 3 shows a minimum delay for $N_c=1$ and $P_r=0.3$. We have seen that values that lead to a maximum throughput do not necessarily correspond to those that minimize delay. The reason for this behavior is that packets might experience different treatment, i.e., while packets belonging to the multiple node are retransmitted with probability one, packets from simple nodes are retransmitted with probability P_r . Consequently, increasing N_c might increase the number of packets transmitted by the multiple node resulting in a throughput improvement. However, it might also incur in unexpected high delay of some packets from simple nodes which in turn, increases the packet delay in the average. From a design point of view, values of P_r and N_c for optimization will depend on whether data is throughput or delay sensitive.

We have also evaluated throughput and delay when the traffic load per user changes from 0.2 packets/slot to 2 packets/slot. Figures 4 and 5 depict throughput and delay respectively for both the Aloha based CDMA system and the CDMA-TDMA based system with $N=2,3,4,5$ codes. For each value of λ , the CDMA-TDMA based system presents a pair of values (P_r, N_c) for throughput maximization and delay minimization. In the same way, for the Aloha based CDMA system a value (P_r) that optimizes performance is shown. We see that for traffic loads higher than 0.7 packets/slot the CDMA-TDMA system with 5 codes ($N=5$) outperforms the CDMA system in terms of throughput. On the other hand, regarding to the delay, this improvement in performance is shown to occur at about 1 packet/slot. We can also observe, that even with a system with

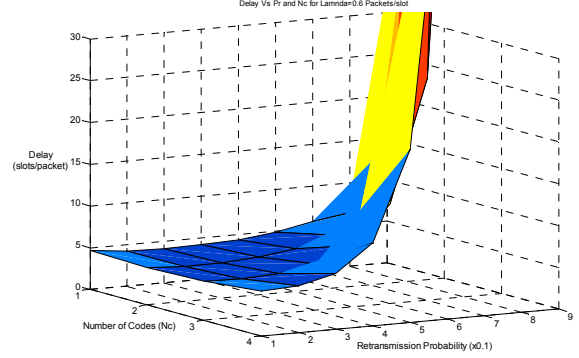


Figure 3: Delay for CDMA-TDMA system

only 3 or 4 codes ($N=3$ or 4), it is also possible to outperform the CDMA system in both throughput and delay. From this results it can be concluded that whereas the CDMA becomes saturated at about 0.4 packets/slot, the CDMA-TDMA protocol can improve performance by reallocating resources (codes and time) more efficiently. We might think that at high traffic loads, the system is acting as a TDMA system where at each time slot not only time but also code resources are given to a particular node. On the other hand, at low traffic, we see that the fact of choosing codes randomly increases the probability of collisions and hence, presents poor system performance.

Additionally, at very high traffic loads, the CDMA-TDMA based system with 4 codes outperforms, in terms of throughput, its equivalent with 5 codes. This is mainly because the system with 5 codes allow more packets to be transmitted simultaneously and due to the characteristics of the network MPR capability, the number of packets to be transmitted simultaneously should be limited in order to not having excessive multiuser interference.

Multiple Node vs. Simple Node

One of the main assumptions of the design presented in this paper is the consideration of the fact that the multiple user changes in a slot by slot basis, even though during the analytical development of throughput and delay expressions the multiple node has been considered to be the same. Numerical results show that if the multiple node is changed in a slot by slot basis results do not exactly match with analytical ones. This is because under assumptions 5.a and 5.b in section IV, when the multiple node is changed the size of its buffer also changes and hence, some packets might be lost. However, if the multiple node is not changed in a slot by slot basis but is changed once every n slots in order to give time the system to be stabilized, the system shows same performance as in analytical results. The number of slots for the system to be stabilized depends mainly on N_c and λ , but empirically it has been seen that with n between 8 and 12, good results are obtained.

Figures 6 and 7 show the comparison between the Aloha based CDMA system with respect to the LAMAN based system with $N=5$ codes when N_c changes from 1 to 4. We can also see that in case that we limit N_c equal to 2, it is also possible to outperform the Aloha CDMA system, i.e., limiting the number of codes to allocate to the multiple user to only 2 is enough to reduce the number of collisions and hence, increase throughput and decrease delay with respect to the Aloha based CDMA system. By reducing N_c , the size of the multiple node buffer is also reduced and hence, it is possible to minimize the number of slots n . We also can see that for

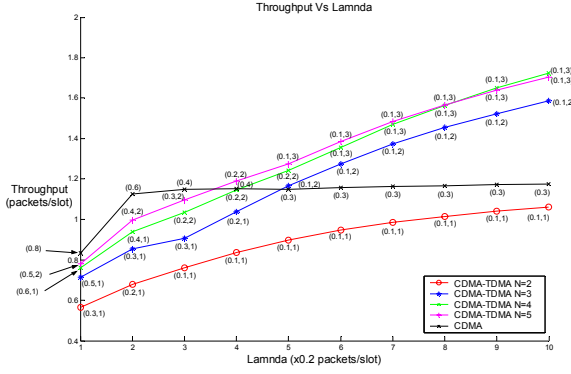


Figure 4: Throughput for different designs

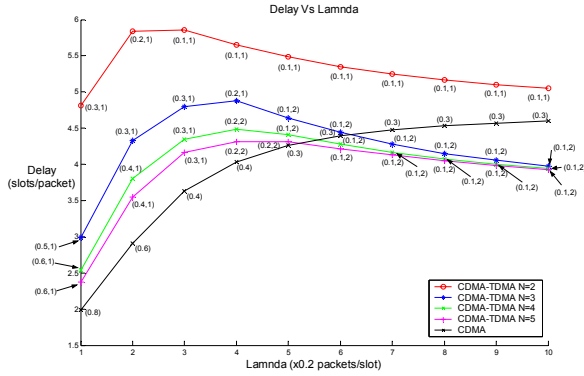


Figure 5: Delay for different designs

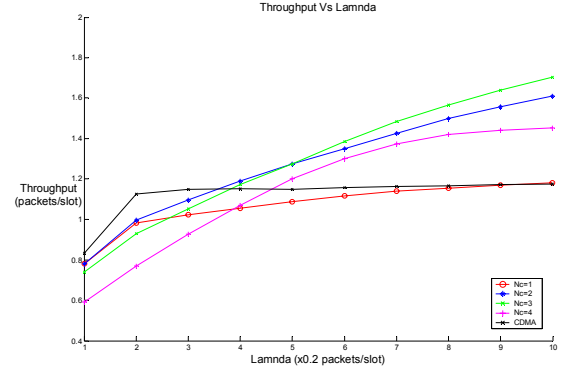


Figure 6: Throughput for different values of N_c

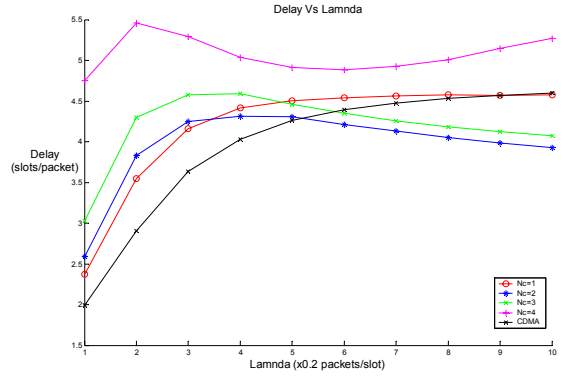


Figure 7: Delay for different values of N_c

$N_c=1$, the CDMA-TDMA based system performs worst than the Aloha based CDMA because there exists the fact that codes are chosen randomly. However, we see that at high traffic loads and consequently at very low retransmission probabilities, the probability of collision is very low and then the behavior of both systems matches.

VI. Conclusions

In this paper, a decentralized multiaccess MAC for Ad-hoc Networks has been presented. This MAC has been shown to be able to evolve, in a totally decentralized fashion, from random to TDMA access as the traffic load increases. Basically, the system described is an hybrid CDMA-TDMA ad-hoc network which by means of giving priority to different nodes at different time slots, allocating many codes to the user with priority and adjusting the packet retransmission probability, network resources are efficiently managed. Closed expressions for throughput and delay are developed and the optimization of the system performance is based on numerical maximization and minimization of such expressions. Numerical results illustrate that, at high traffic loads, the CDMA-TDMA system outperforms the CDMA based one.

Reconfigurable MAC

The results obtained through simulations show that the optimal performance is achieved, depending on the traffic load, by different MAC procedures. Hence, this conclusions suggest that further work should focus on the design of a reconfigurable MAC which could be able to dynamically switch from an Aloha based CDMA system to a CDMA-TDMA based system. Furthermore, since the decision region do not appear to be clearly defined and might depend on many different parameters, it is proposed the use of fuzzy logic techniques in order to take decisions on reconfigurability.

References

- [1] D. Kim, C.-K. Toh and Y. Choi, *ROADMAP: a Robust ACK-Driven Media Access Protocol for Mobile Ad Hoc Networks*, Military Communications Conference., 200, Vol. 2, 2001, Page(s): 983-987.
- [2] L. Kleinrock and F. Tobagi, *Packet Switching in Radio Channels: Part1: CSMA Modes and Their Throughput - Delay Characteristics*, IEEE Trans. Comm., COM-23 Page(s):1400-1416
- [3] ANSI/IEEE Std 802.11, 1999 Edition.
- [4] <http://www.bluetooth.com/dev/specifications.asp>
- [5] I. Chlamatac et Al., *ADAPT: A Dynamically Self-Adjusting Media Access Control Protocol for Ad Hoc Networks*. General Conference, IEEE Globecom 1999.
- [7] J. Ward and R.T. Compton, *Improving the Performance of Slotted ALOHA Packet Radio Network with an Adaptive Array*, IEEE Transactions on Communications., vol. 40, NO. 2, Feb. 1992.
- [8] S. Roy and H.Y. Wang, *Performance of CDMA Slotted ALOHA Multiple Access with Multiuser Detection*, Wireless Communications and Networking Conference 1999, vol. 2, 1999 Page(s): 839 -843.
- [9] C. Anton-Haro and M.A. Lagunas, *Array Processing Techniques for Wireless: a Cross-Layer Perspective*, International Forum on Future Mobile Telecommunications and China-EU Post Conference on Beyond 3G, 2002
- [10] J. Q. Bao and L. Tong, *A Performance Comparison Between Ad Hoc and Centrally Controlled CDMA Wireless LANs*, IEEE Transactions on Wireless Communications Volume: 1 Issue: 4 , Oct 2002, Page(s): 829 -841
- [11] M. Realp and A. I. Perez-Neira, *Decentralized Multiaccess MAC Protocol for Ad-Hoc Networks*, Accepted for the 14th IEEE PIMRC, 2003.