

## A Medium Access Protocol for Cognitive Radio Networks Based on Packet's Collision and Channels' Usage

Dina Tarek Mohamed  
[d.tarek@fci-cu.edu.eg](mailto:d.tarek@fci-cu.edu.eg)

Amira M. Kotb  
[a.kotb@fci-cu.edu.eg](mailto:a.kotb@fci-cu.edu.eg)

S.H.Ahmed  
[sana.ola@fci-cu.edu.eg](mailto:sana.ola@fci-cu.edu.eg)

Information Technology Department. Faculty of Computers and Information. Cairo University

### ABSTRACT

In Cognitive Radio Networks (CRNs); the unlicensed users named Secondary Users (SUs) are allowed to share the licensed wireless spectrum band with its licensed users name Primary Users (PUs) but without degradation in the PU's Quality of Service (QoS). As all the SUs have the same priority to access the licensed spectrum band; a spectrum sharing protocol is needed to fairly divide the available spectrum band among these SUs. Spectrum sharing protocols in CRNs are similar to Medium Access Control (MAC) protocols in regular networks. In this paper; a time slotted spectrum sharing protocol named Channel Usage and Collision Based MAC protocol (CUCB-MAC) is proposed. It is a modification of a MAC protocol named Collision-Based MAC protocol (CB-MAC), it depends on three parameters for the allocation of channels to the SUs; <sup>1)</sup> counting collisions number for each SU, <sup>2)</sup> predicting the availability probability for all the available channels and then <sup>3)</sup> excluding some of the available channels. It has been proved that using the proposed CUCB-MAC protocol outperforms the original CB-MAC protocol on all the measured performance metrics.

### KEYWORDS

Cognitive Radio Networks - Medium Access Control - Spectrum Sharing – Time Slotted - Collision - Renewal Theory

### 1 INTRODUCTION

In recent years there has been a huge increase in the access of the limited spectrum for mobile services, so the fixed spectrum assignment policy

to the unlicensed spectrum began to be inefficient, in addition to the large portion of the spectrum assigned to licensed holders or services that remains unutilized. A new communication technique named Dynamic Spectrum Access Network or Cognitive Radio network or Next Generation (xG) communication network, was proposed to provide the SUs with the capability to access the licensed spectrum opportunistically without any interference with its original users (Get the Best Available Channel).

CRN is a network that consists of wireless users, cognitive radio and dynamic spectrum access capabilities. Based on the intelligence of cognitive radio, the limited available spectrum and the unutilized wireless spectrum band, the cognitive radio network uses these factors to build a policy to allow its users (SUs) to share and access licensed wireless spectrum band with its original users (PUs) without any interference with these users, and without any degradation in their quality of service [1,4].

As there exist a large number of SUs and as all of these SUs have the right to access the available spectrum band, a spectrum sharing protocol must exist to coordinate the spectrum access with the SUs; by providing a scheduling technique to be able to divide the available spectrum band among the current SUs. Spectrum sharing is similar to medium access control (MAC) protocol in the current networks, but with different challenges for the cognitive radio networks due to the dynamic nature of the spectrum and the existence of two different sets of users; PUs and SUs. Surveys on MAC techniques for CRNs can be found in [5-10].

Even when using the most perfect spectrum sharing techniques, avoiding collision between PUs and SUs would be impossible. So; in the scheduling technique; due to the repeated collision occurrence, collision statistics (average number of collisions) must be taken into consideration. Using this concept a fair scheduling schema was developed in [11].

A time slotted spectrum sharing protocol is proposed in this paper, it depends on counting the number of collisions for each SU, predicting the ideality of the entire available channels and then based on the channel usage probability by each SU's nearby PUs at each time slot; channel exclusion process is done, before SUs' channel allocation process is performed. By the exclusion process; it can be anticipated that collision occurrence will be decreased when taking into consideration that any of the available channels has a high probability to be used by any PU allocated near by the SU requesting the channel, this SU won't be given this channel.

The rest of this paper is organized as follows; various MAC protocols classifications are explained in section 2. Related work is explained in section 3. In section 4, the proposed MAC protocol (CUCB- MAC) will be explained in details. Evaluation of the proposed protocol will be given in section 5. Finally summarized conclusion and future works will be illustrated in section 6.

## 2 MEDIUM ACCESS CONTROL PROTOCOLS CLASSIFICATIONS

From various readings it has been found that there is no single classification for spectrum sharing techniques in cognitive radio networks. In fact many classifications exist; some of these classifications are based on the spectrum access technique, others are based on architecture, on spectrum allocation behavior, on scope and on spectrum access time. These classifications will be explained in the rest of this section.

MAC protocols in CRNs can be categorized into three main categories according to the access method; random access MAC protocols, time

slotted MAC protocols and hybrid MAC protocols [5,6].

- **Random access MAC protocols;** in these protocols transmission is done at any time, so users don't have to be synchronized with the network. These protocols are mainly based on Collision Sense Multiple Access with Collision Avoidance (CSMA/CA).
- **Time slotted MAC protocols;** in these protocols; time is divided into slots, transmission must be done in the start of the slot. Users have to be widely synchronized with the network; this is done by dividing the time into slots for both data and control channels.
- **Hybrid MAC protocols;** combine both previous concepts in many ways. One way is to be partially time slotted such that the controlling signals transmission appears at synchronized time slots, while the data transmission is done at a random access schema. In another way; data and control transmissions might be done in a predefined period of time, using a superframe which is known to all the users in the network, during the control and data duration the channel access might be random.

MAC protocols in CRNs can be also categorized into two main categories according to the network's architecture or infrastructure; centralized MAC protocols and distributed MAC protocols [1,6,7,8].

- **Centralized MAC Protocols;** in these protocols there exist a central entity that controls the spectrum allocation and spectrum access processes. The sensing itself is distributed among the SUs in the network, then forwarded to the central entity that constructs the allocation map.
- **Distributed MAC Protocols;** in these protocols the spectrum allocation and spectrum access processes are done independently by each SU based on the local or probable global policies.

MAC protocols in CRNs can be categorized into two main categories according to spectrum allocation behavior; cooperative MAC protocols and non-cooperative MAC protocols [1,6,7,9,10].

- **Cooperative MAC Protocols;** in these protocols each node's interference information is shared among various nodes. This is usually done by constructing clusters to locally share the interference measurements.
- **Non-Cooperative MAC Protocols;** these protocols are selfish as they don't consider interference at other nodes; they only consider the node at hand.

MAC protocols in CRNs can be categorized into two main categories according to scope as intranetwork MAC protocols and internetwork MAC protocols [7].

- **Intranetwork MAC Protocols;** these protocols is concerned with spectrum allocation among SU in a single CRN.
- **Internetwork MAC Protocols;** these protocols allow various CRNs to perform location and spectrum overlapping.

MAC protocols in CRNs can be categorized into two main categories according to spectrum access technology; underlay MAC protocols and overlay MAC protocols [1,6,7,8].

- **Overlay MAC Protocols;** in these protocols SUs are allowed to access the portion of the spectrum that is not used by the PUs, so that the SUs' interference with any PU is minimized.
- **Underlay MAC Protocols;** in these protocols once the spectrum allocation map are constructed, the SUs transmit at a certain portion of the spectrum but with a certain transmission power that is considered noise to the PUs at that spectrum portion.

### 3 RELATED WORKS

In this section examples for MAC protocols designed mainly for CRNs will be illustrated. These protocols will be ordered ascendingly according to their published date.

A MAC protocol for wireless ad hoc cognitive radio networks which is based on Time Division Multiple Access (TDMA) is proposed in [12], it is named Energy Efficient Multichannel MAC

(ECR-MAC) Protocol. In this protocol it is assumed that the time domain is partitioned into beacons with predefined length. Each of these beacons intervals is split into three windows; Ad Hoc Traffic Identification Messages (ATIM) window, sensing window and communication window. The ATIM window is used for beacons and to transmit and receive control messages. The sensing window is used to perform the sensing process, which is done before the transmission of data to avoid any collision with any PU. The communication window is used when a SU chooses a channel, and it is detected to be idle, this SU will begin transferring the data in the communication window. But if the chosen channel is detected to be busy, this SU will transfer to the control channel to wait till the next beacon window.

The protocol proposed in [13] is designed for synchronous cognitive radio networks; it is a time slotted protocol that uses hopping sequences to exchange data. While sending; hopping is done by the SU's source over the licensed channels based on the SU's destination pseudo-random hopping sequence. While receiving, the SU's destination just switches between channels to get the sent packets. The same generating algorithm is used by all the SUs in the network to generate the hopping sequence. Each SU generates a fixed pseudo-random hopping sequence based on its unique ID i.e. its MAC address.

Scheduling the spectrum assignment for SUs in [14] is done based on the knowledge of both the PUs' activity profile and the mobility information of the SUs. A base station that acts as a central entity exists in this protocol, where each SU can directly communicate with it; each of these communications must be done on a separate channel at any instant of time to avoid any co-channel interference. Using the activity profile of the PUs, at each time slot the probability of existence of each PU is calculated by the base station. The process of scheduling the spectrum assignment for SUs is defined formally to be related to the Maximum Throughput Channel Scheduling problem (MTCS), in order to obtain maximum throughput by assigning the appropriate channel for each SU. The protocol designs a

general scheduling framework to solve the MTCS problem. Maximizing the throughput is expected to maximize the total Available Transmission Time (ATT).

A real-time MAC protocol for cognitive radio networks is presented in [15], this protocol provides a deterministic medium access and opportunistic spectrum allocation for heterogeneous traffic load. The scheduling in this MAC protocol is done based on the Earliest Deadline First (EDF) scheduling technique. The Earliest Deadline First is a dynamic priority scheduling technique used when designing a real-time system; it operates by increasing the priority of the task with shorter deadline, in other words the task with the earliest deadline is the one that will be executed first. Also a real-time analysis is used in this protocol acting as an admission control tool, so that it only allows traffic that won't endanger any of the deadlines.

A centralized MAC protocol named Fairness-oriented MAC (FMAC) protocol is proposed in [16]. It deals with the existence of several CRNs. SUs from the same network perform cooperative sensing, and then send this information to their central entity to make the final allocation decision. Each of these SUs needs to be equipped with two radios in order to; perform spectrum sensing and to perform data transmission.

The main idea of the collision based MAC protocol (CB-MAC) protocol [11] is to make a fair scheduling among SUs, this is done by not allowing some SUs to meet more collision than others. To guarantee such fairness; collision statistics such as the average number of collisions is used to prioritize SUs. Incoming SUs packets are retained in a buffer; so some of them will be served in the next time slots based on their priorities.

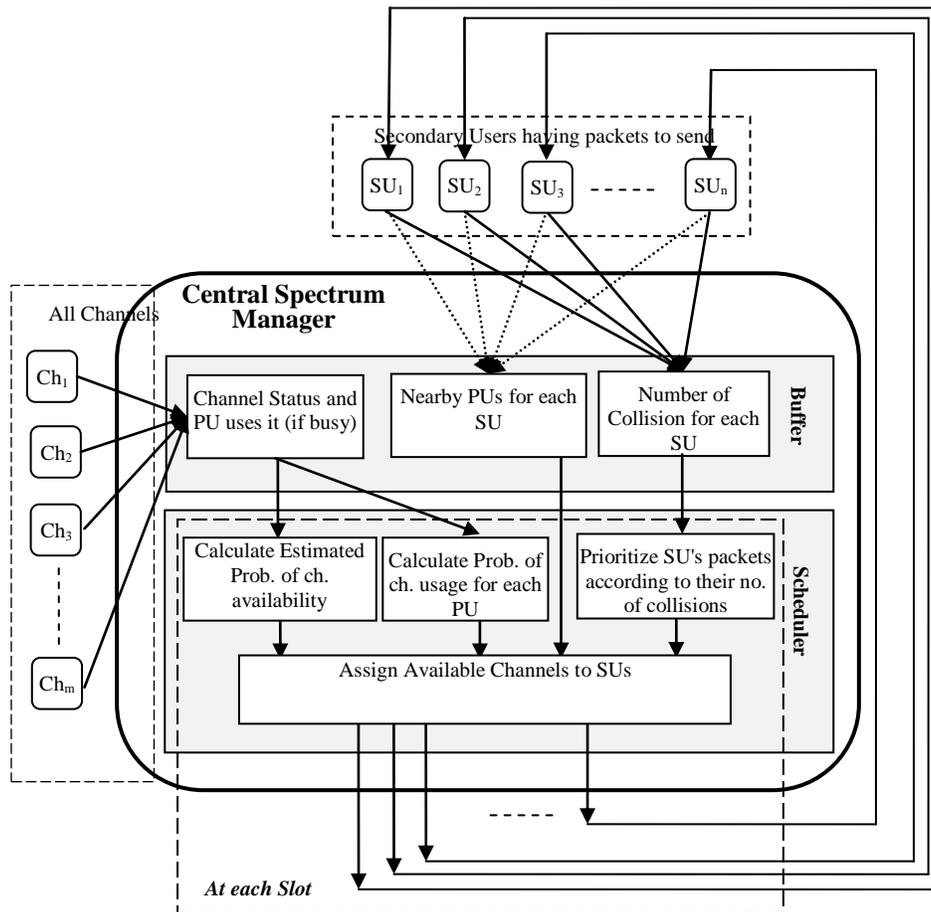


Figure 1. Proposed System Architecture (CUCB-MAC)

#### 4 CHANNEL USAGE AND COLLISION BASED MAC (CUCB-MAC) PROTOCOL

The proposed CUCB-MAC protocol is a centralized time-slotted spectrum sharing protocol based on counting the number of collisions for each SU, predicting the ideality of the entire available channel then excluding some of the available channels at each time slot.

The process of channel exclusion is performed at the central spectrum manager. It is done by performing these steps; first at each sample time the scheduler has to record status of all the available channels that are used by any PU, then the scheduler calculates the channel usage probability for each channel by each PU. The SU that is requesting a channel to send a packet must sense the surrounding area for any existing PUs and then sends to the scheduler a list contains all the PUs existing in the surrounding area. So the SUs -that have a nearby PU with high channel usage probability for any of the available channels the scheduler- are prohibited them from using these channels. Hence the protocol is named; Channel Usage and Collision Based Medium Access Control (CUCB-MAC).

Figure 1 shows the architecture of the proposed CUCB-MAC protocol.

It is obvious from this figure that the proposed protocol consists of three main parties; SUs, channels and central spectrum manager.

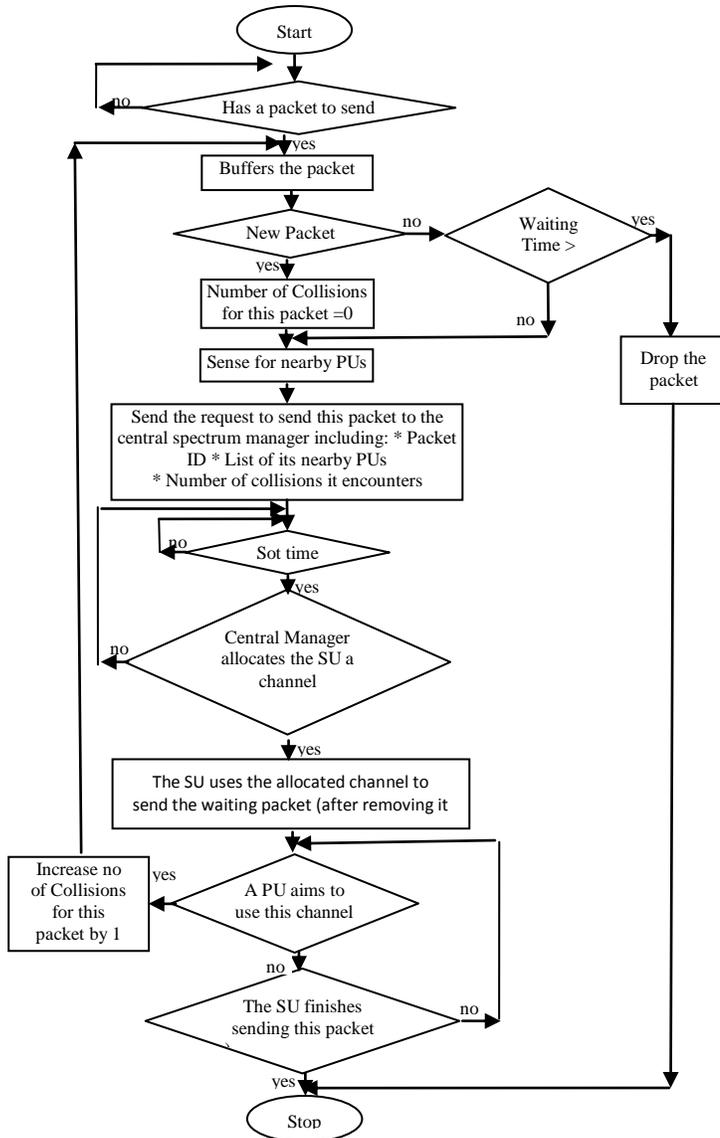
- SUs: represent any of the unlicensed user that need to send a packet.
- Channels: are the divided frequencies the SUs use to send their packets on.
- Central Spectrum Manager: acts as the central entity that is equipped with both the scheduler and the buffer. This buffer contains <sup>1)</sup>packets requests sent by the SU, <sup>2)</sup>the collected information from the SUs <sup>3)</sup>information about the channels. The scheduler uses the collected

information in its buffer to allocate the appropriate channel for the SUs' packets.

The CUCB-MAC protocol is divided into two main phases; one performed as the SUs, and the second is performed at the central spectrum manager.

##### 4.1 Phase 1: Performed at Secondary Users

If any SU needs to send a packet: first; it stores it at its buffer. Second, it senses the surrounding media to find all the nearby PU. Finally, it sends a request for the central spectrum manager that includes; the packet id, list of the nearby PUs and the number of collisions the packet encounters, waiting for a channel to be allocated to this packet by the central spectrum manager at the beginning of a next slot.



**Figure 2** Tasks Performed at each SU having a Packet to Send

Note that if the waiting time of the packet exceeds a threshold, this packet will be dropped. Figure 2 is a detailed flow chart for the sequence of tasks that each SU performs whenever it has a packet to send.

#### 4.2 Phase 2: Performed At Central Spectrum Manger

The central spectrum manger performs the most dominant tasks that is considered the substantial tasks in the proposed CUCB-MAC protocol. Some of these tasks are performed at the beginning of

each sample time while others are performed at the beginning of each slot time.

1. It calculates the estimated probability of all channels' availability at each time slot based on the channel status recorded at each sample.
2. It orders the SUs' packets requests based on each packets encountered number of collision was sent by the SUs.
3. It calculates the channel usage probability of all the available channels by each PU based on the channels statuses recorded at each time sample, and the list of nearby PUs included in the SU packet request.
4. It allocates the most appropriate channels for the SUs with packets requests. This task is performed with the usage of the output parameters form the last three tasks.

These tasks will be explained in details in the next subsections.

##### 4.2.1 Estimation of Channels Availability

Any algorithm that is used for the prediction of the channel availability with the usage of the past channel observations can be used in this step. The proposed CUCB-MAC protocol uses the renewal theory process for the prediction of channel availability [17,18].

Any channel  $i$  will be in one of two statuses either ON or OFF, the ON duration is represented by a random variable  $Y^i$ , while the duration of the OFF period is represented by a random variable  $X^i$ . So the probability distribution function (pdf) of the ON duration can be  $f_{TON}(Y)$ , and  $f_{TOFF}(X)$  can be the pdf of the OFF duration. Note that the ON and OFF durations are supposed to be independent and identically distribute (iid) random variables. The arrival of each PU is independent, each of these transition follow Poisson arrival process.

$$\begin{aligned}
 f_Y(t) &= \lambda_Y e^{-\lambda_Y t} \\
 f_X(t) &= \lambda_X e^{-\lambda_X t}
 \end{aligned} \tag{1}$$

where  $\lambda > 0$  is the parameter of the distribution

The utilization or the load of channel  $i$  is calculated as follows:

$$\mu^i = \frac{\lambda_{X^i}}{\lambda_{X^i} + \lambda_{Y^i}} = \frac{E[T_{ON}]}{E[T_{ON}] + E[T_{OFF}]} \quad (2)$$

where  $E[T_{ON}]$  and  $E[T_{OFF}]$  are the mean of the distribution.

$$E[T_{ON}] = 1/\lambda_{Y^i} \text{ and } E[T_{OFF}] = 1/\lambda_{X^i}$$

The renewal process is used to calculate  $\mu^i$  and  $\lambda_{X^i}$  as follows:

Assume a vector of  $r^i$  samples results from the sensing process of channel  $i$  for  $T_p^i$  duration:

$$Z^i = \{Z_{t1}^i, Z_{t2}^i, Z_{t3}^i, \dots, Z_{tr}^i\} \quad (3)$$

where  $Z_{tj}^i$  is the status of the link at time  $t_j$  ( $j = 1, 2, 3, \dots, r^i$ ), note that status of a link is either ON (1) or OFF (0)

Four types of transition probability based on ON (1) or OFF (0);  $0 \rightarrow 0$ ,  $0 \rightarrow 1$ ,  $1 \rightarrow 0$ ,  $1 \rightarrow 1$ . With the usage of the joint probability mass function, the probability of the four transitions can be calculated as follows:

$$\begin{aligned} P_{00}^i(t) &= (1 - \mu^i) + \mu^i e^{-(\lambda_{X^i} + \lambda_{Y^i})t} \\ P_{01}^i(t) &= \mu^i - \mu^i e^{-(\lambda_{X^i} + \lambda_{Y^i})t} \\ P_{11}^i(t) &= \mu^i + (1 - \mu^i) e^{-(\lambda_{X^i} + \lambda_{Y^i})t} \\ P_{10}^i(t) &= (1 - \mu^i) + (1 - \mu^i) e^{-(\lambda_{X^i} + \lambda_{Y^i})t} \end{aligned} \quad (4)$$

The Maximum Likelihood (ML) estimator  $\hat{\mu}^i$  and  $\hat{\lambda}_{X^i}$  can be calculated as follows:

$$\hat{\mu}^i = \frac{1}{r^i} \sum_{k=1}^{r^i} Z_{t_k}^i \quad (5)$$

$$\hat{\lambda}_{X^i} = -\frac{\mu^i}{T_p^i} \ln \left[ \frac{-B + \sqrt{B^2 - 4AC}}{2A} \right] \quad (6)$$

where  $A = (\mu^i - (\mu^i)^2) (r^i - 1)$   
 $B = -2A + (r^i - 1) - (1 - \mu^i) n_0 - \mu^i n_3$   
 $C = A - \mu^i n_0 - (1 - \mu^i) n_3$   
 $n_0, n_3$  denotes the numbers of occurrences of the  $0 \rightarrow 0$ ,  $1 \rightarrow 1$  transition respectively

- **At each time sample:**

For each channel the  $Z$  value will be changed based on the channel status recorded during the sensing process performed by the central spectrum manger. The  $n_s$  values will changed based on the channel status recorded during the sensing process performed by the central spectrum manger, and also on the previous channel's status.

- **At each time slot:**

The central spectrum manager calculates the possible probabilities  $P_{00}^i$  or  $P_{10}^i$  (equation 4) for each channel) using  $\hat{\mu}^i$ ,  $\hat{\lambda}_{X^i}$  and  $\hat{\lambda}_{Y^i}$  (-calculated at the time samples using equations 5, 6 and 2 respectively).

#### 4.2.2 Calculation of Probability of Channels Usage for Primary Users

For each channel the central spectrum manager has a separate stack with specific predefined length. This stack is used for reordering the PUs that previously used the channel for a certain period of time. In this step the channel status observations recorded for each channel in the previous subsection are used. But an extra checking is done in this process while recording the channel status, the central spectrum manger obtain the user ID if the channel is occupied by a PU. Then this observation is used to update the stack user of each channel as follows:

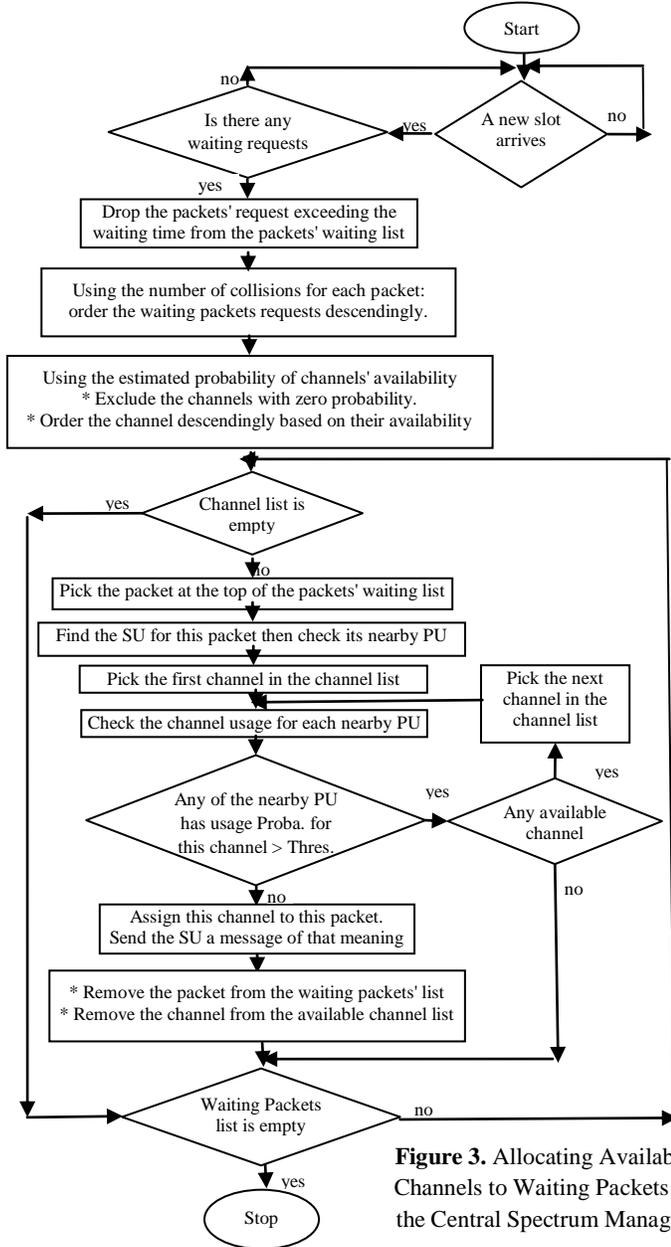
$$S_i \text{ (Primray User using Channel } i) = \begin{cases} PU_{id} & \text{If a PU is used Channel } i \\ 0 & \text{Otherwise} \end{cases} \quad (7)$$

Then; the channel usage probability is calculated for each PU at each time slot as follows:

$$\begin{aligned} \text{Channel } i \text{ Usage for Primary User } j &= \frac{\text{Number of Apperance of PUj in stack of channel } i}{\text{Stack Length}} \end{aligned} \quad (8)$$

#### 4.2.3 Allocation of Channels for Secondary Users

The central spectrum manger uses the collected number of collisions encountered from each SU packet, nearby PU list of each SU, the estimated



**Figure 3.** Allocating Available Channels to Waiting Packets at the Central Spectrum Manager

probability for each channel availability and the estimated probability for each channel usage by each PU; to assign the most appropriate channel for the waiting SUs packets.

Figure 3 illustrates a flow chart for allocating available channels to waiting packets done by the central spectrum manager at each slot.

## 5 EVALUATION OF THE PROPOSED CUCB-MAC PROTOCOL

Using “Java” a simulation program was built to develop, evaluate, test and compare the performance measurements of the proposed CUCB-MAC protocol with the original CB-MAC protocol. The built simulation program is divided into four parts; Packets’ creation, CB-MAC protocol, CUCB-MAC protocol and the calculation of the performance metrics for both protocols.

To achieve correct results that are comparable to reality, the packet creation process are done randomly. The same created packets have to serve as an input for both protocols to be able to obtain an accurate comparison between both protocols’ performance. Because of that the packet creation process is a separated function from the two compared protocols, the output of this creation process serve as an input for the two MAC protocols. As for the packet arrival function a negative exponential distribution [19] is used for the generation of the packets random arrival time, associated with random users’ number.

**Table 1.** Simulation Parameters

<i>Parameter</i>	<i>Value</i>
<b>PU Data Rate</b>	20 packets/sec
<b>Number of PUs</b>	20
<b>SU Data Rate</b>	30 packets/sec
<b>Number of SU</b>	20
<b>Packet Length</b>	4500 bytes
<b>Number of Channels</b>	4
<b>Sample Time</b>	5 msec
<b>Slot Time</b>	0.6 * Packet Transmission Time
<b>Dropping Time</b>	3 * Packet Transmission Time
<b>Channel Usage Threshold for each PU</b>	0.3
<b>Simulation Time</b>	10 sec

The used simulation parameters are listed in Table 1 [11,20]. These parameters are changed either up or down in various scenarios. This is done to test the proposed protocol upon several constrains and then prove its efficiency.

### 5.1 Performance Metrics

In this section the performance metrics used to evaluate and test the proposed CUCB-MAC protocol are illustrated. Five performance metrics are used; average throughput, average delay,

average number of PUs' packets collided, percentage of channel utilization and finally percentage of dropped packets.

### 5.1.1 Average Throughput

Average throughput is defined as the average rate of packets delivered successfully per one second. It's preferable to retain it as extreme as possible.

$$\text{Average Throughput} = \frac{\text{Number of packets reached their Destinations}}{\text{Simulation End Time} - \text{Simulation Start Time}} \quad (9)$$

### 5.1.2 Average Delay

Average Delay is defined as the average time taken for a packet to be transferred from the source to the destination. It's preferable to retain it as minimum as possible.

$$\text{Average Delay} = \frac{\sum_{\forall \text{ Packets}} (\text{Arrival Time} - \text{Sent Time})}{\text{Number of Packets}} \quad (10)$$

### 5.1.3 Average Number of Primary Users' Packets Collided

Collision occurs when a PU and a SU aim to use the same channel. It's preferable to retain it as minimum as possible.

$$\text{Average Number Of Collisions} = \frac{\sum_{\forall \text{ Packets}} (\text{Number of Collision it encounters for each PU})}{\text{Number of PUs' Packets}} \quad (11)$$

### 5.1.4 Percentage of Channel Utilization

Percentage Channel Utilization is defined as the percentage of how efficient the channels are being used. Or it can be defined as how much time the channel is being used from the beginning of the simulation till its end.

$$\text{Percentage of Channel utilization} = \frac{\sum_{\forall \text{ Channels}} \frac{\text{Time the channel is used}}{\text{Simulation End Time} - \text{Simulation Start Time}}}{\text{Number of Channels}} * 100 \quad (12)$$

In reality the aim is to retain the percentage of channel utilization as extreme as possible, as long as the packets are transferred safely from the first attempt. But when using a simulation program; where the same random packets' arrival act as an input for both the original and the proposed protocols, the protocol having less percentage of channel utilization is more efficient. As the

protocol with lower percentage of channel utilization can send more packets than the other one. So It's preferable to retain it as minimum as possible.

### 5.1.5 Percentage of Dropped Packets

Packets waiting in the SUs' buffer for a long time without being served due to the lack of channels are useless, so dropped. It's preferable to retain it as minimum as possible.

$$\text{Percentage of Dropped Packets} = \frac{\text{Number of Dropped Packets}}{\text{Total Number of Packets}} * 100 \quad (13)$$

## 5.2 Simulation Results

Four scenarios are used to prove the efficiency of the proposed CUCB-MAC protocol compared to the original CB-MAC protocol. In each scenario one simulation parameter takes different values to be able to see the effect of this change on both MAC protocols. The first three parameters used in the first, second and third scenarios are; data rate, time used to drop a packet and packet length respectively. The fourth scenario depends on changing the values of channel usage threshold to examine its impact on the proposed CUCB-MAC protocol; of course this parameter won't have any effect on the original CB-MAC protocol.

### 5.2.1 First Scenario: Changing Data Rate

In this scenario the effect of changing the SUs' data rate is shown in Figures 4 to 8. The SUs' data rate values vary from 10 packets to 50 packets per second.

Figure 4 shows that the average throughput of the proposed CUCB-MAC protocol is higher than that of the old CB-MAC protocol using various data rates, the throughput improvement increases with the increase of the data rate. As increasing the data rate means increasing number of packets per second, this will lead to increasing in the collision probability; so as the need to retransmit the collided packets, i.e. the time each packet will take from the source to the destination will

increase by the retransmission overhead, so the number of packets arriving per second (throughput) will decrease. This cannot be avoided using CB-MAC protocol, while the proposed CUCB-MAC protocol prevents some packets with high collision probability from being transmitted, so decreases the number of collision and some packets won't waste time in the retransmission process; thus retransmission overhead will be avoided; i.e. the time each packet will take from the source to the destination will not increase, leading to an increase in the number of packets arriving per second (throughput).

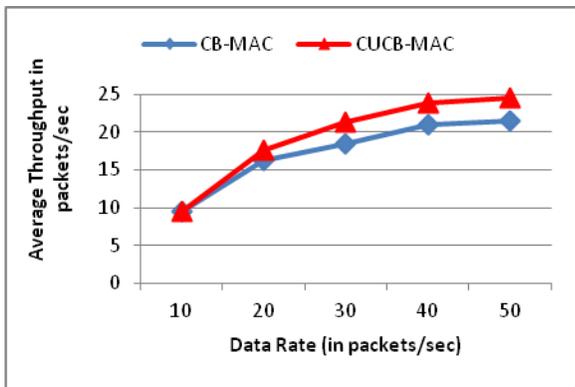


Figure 4. Average Throughput using Various Data rate

Figure 5 shows that the average delay of the proposed CUCB-MAC protocol is a bit lower than that of the original CB-MAC protocol for all used data rates. Also; it is clear that increasing the data rate will not increase the difference between the two averages delay got from applying both protocols. As increasing the data rate; i.e. increasing the number of packets per second, will increase the collision probability, so increase the packets retransmission process leading to a retransmission overhead, so increase in the time taken by a packet to reach its destination (delay). Using CB-MAC, the number of packets retransmission is high, so as the delay. While using CUCB-MAC, some of the retransmission process obtained using CB-MAC can be avoided, so lower delay.

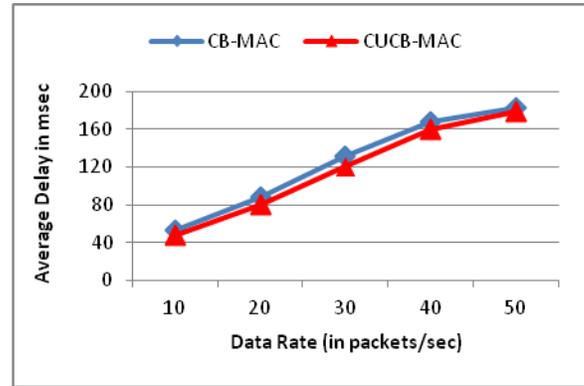


Figure 5. Average Delay using Various Data rate

Figure 6 shows that the average number of collided packets is much lower for the proposed CUCB-MAC protocol than that of the original CB-MAC protocol for various data rates. The difference between the values obtained using the two protocols highly increase with the increase of data rate. As an explanation for that, as the data rate increases, the number of packets per second increases which may be more than the channels

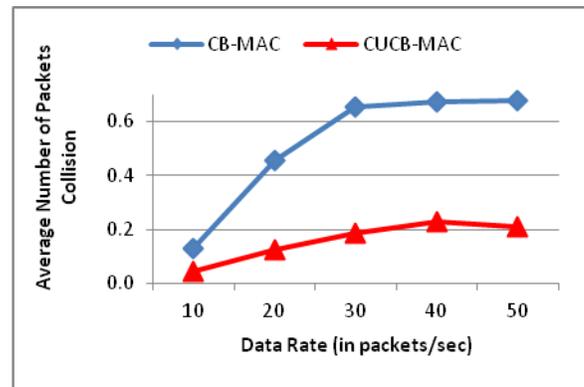


Figure 6. Average Number of Packets Collision using Various Data rate

can bear. Trying to send packets in spite of the probable happening congestion will lead to packets' collision. This can sometimes be avoided using CUCB-MAC, which is not the case using CB-MAC.

Figure 7 shows that the percentage of channel utilization of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol for various data rates. The difference between the values of channel utilization resulting from applying both protocols slightly increases

with the increase of data rate. Increasing the data rate means (increasing number of packets per second), i.e. increasing in the collision probability; so the packets' retransmission process will be performed more frequently. In case of applying the old CB-MAC protocol the time that each packet will take from the source to the destination will increase, so the channels will be used more often. While using the proposed CUCB-MAC protocol; the packets with high collision probability will be prevented from being transmitted, so it won't use the channels, and they will remain idle for sometimes.

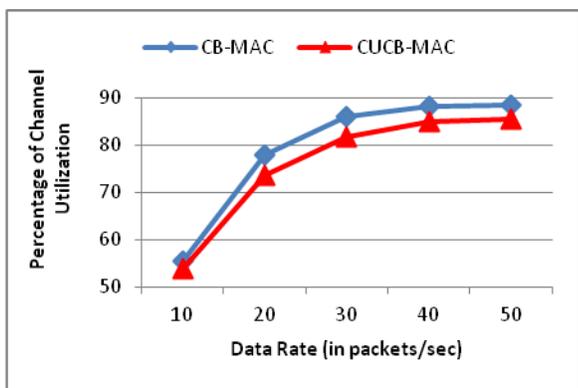


Figure 7. Percentage of Channel Utilization using Various Data rate

Figure 8 shows that the average number of dropped packets of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol for all used data rates. The difference between the number of dropped packets resulting from applying both protocols slightly increases with the increase of data rate. When the number of packets per second (data rate) increases, the probability that packets will collide increases, so the packets retransmission probability will increase, a packet may even needed to be retransmitted more than once, so the waiting time for these packets will increase. If this waiting time is too high, the packet will be dropped, this is the case using CB-MAC. But as using CUCB-MAC prevents highly probable packets' collision from happening, this will decrease the number of packets' retransmission; so as the packets' waiting time, which will eventually decrease their probability of being dropped.

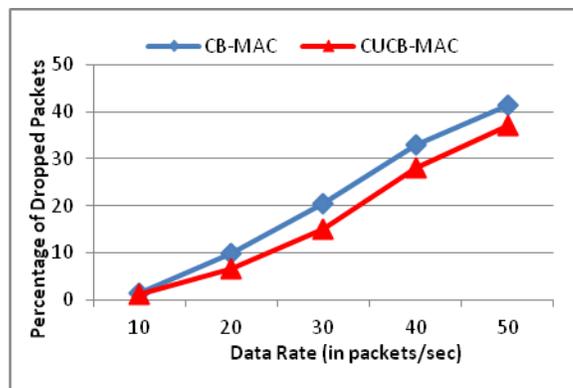


Figure 8. Percentage of Dropped Packets using Various Data rate

### 5.2.2 Second Scenario: Changing Packet Dropping Time

Some packets may be worthless to their destinations, due to the long time they have been waiting in their SUs' buffer; some of these packets may have collided before even more than once. So the best decision is to drop these packets instead of trying to use the spectrum to send a useless data. In this scenario the effect of changing the maximum time packets are allowed to wait in their SUs' buffer, on the performance metrics using both protocols is shown in Figures 9 to 13. The packet dropping time values varies from 1\*packet transmission time to 5\*packet transmission time.

Figure 9 shows that using the proposed CUCB-MAC protocol leads to higher average throughput than using the original CB-MAC protocol for various dropping time. The improvement of the throughput increases with the increase of the dropping time. Increasing the packet dropping time, meaning that the packets will have longer time to stay in the buffer, so it will have a larger chance to be served before they are dropped, this will increase the average throughput for both protocols. Using CB-MAC; although most of the packets are served at the end but they suffer from repeated collision, i.e. longer waiting time, so take a longer time to successfully reach their destinations, so the number of packets delivered per second (throughput) is small. In contraire; in case of using CUCB-MAC; as the number of collision is smaller, the waiting time is

smaller; so the number of packets delivered per second (throughput) is higher.

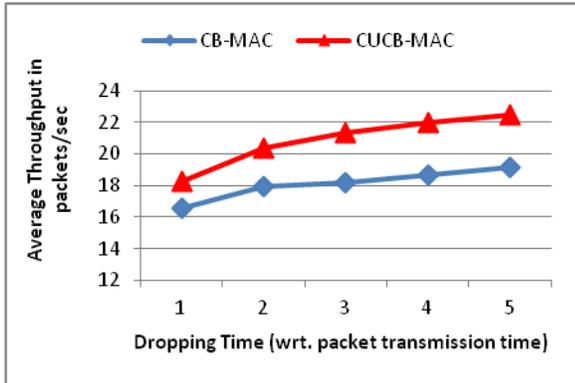


Figure 9. Average Throughput using Various Dropping Time

Figure 10 shows that for the average delay is almost the same using both MAC protocols when the packet dropping time is equal to the packet transmission time, but as increasing the packet dropping time the difference between the values resulting from applying the both protocols differs by very small values, but still the CUCB-MAC protocol gives less delay than CB-MAC protocol. Increasing the packet dropping time, means the packets can stay in the buffer for much longer time before it is dropped, so the average delay will be increased. Although increasing the packet dropping time will lead to high probability of the packets being successfully sent; but this may take a long time. As CB-MAC protocol suffers from high collision rate than CUCB-MAC protocol; so higher probability of packets' retransmission; i.e. longer waiting time, so longer time to successfully reach the destination (delay).

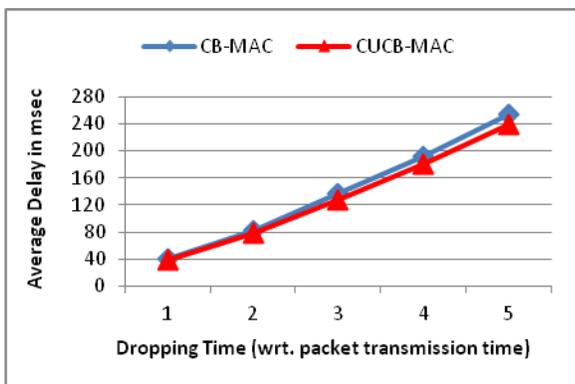


Figure 10. Average Delay using Various Dropping Time

Figure 11 shows that the average number of collided packets of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol while increasing packet dropping time value. Increasing the packet dropping time, means that the packet waiting time will increase, so the packets will be buffered for a longer time, i.e. the number of the packets staying in the SUs' buffers will increase, so the number of packets remaining in the networks and needed to be served increases, and as the spectrum is limited, the probability that packets collide will increase, some of these collisions are prevented using CUCB-MAC more than those using CB-MAC protocol.

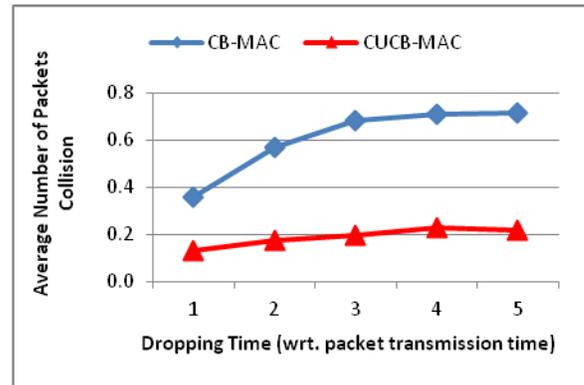
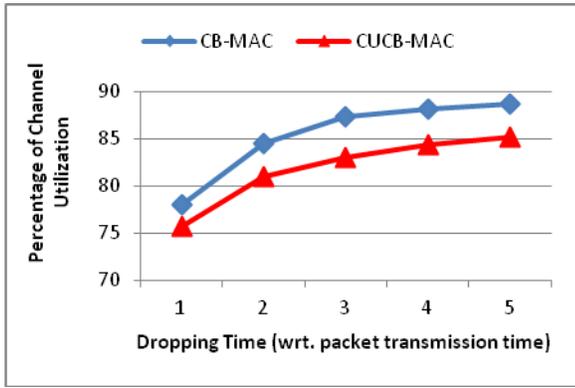


Figure 11. Average Number of Packets Collision using Various Dropping Time

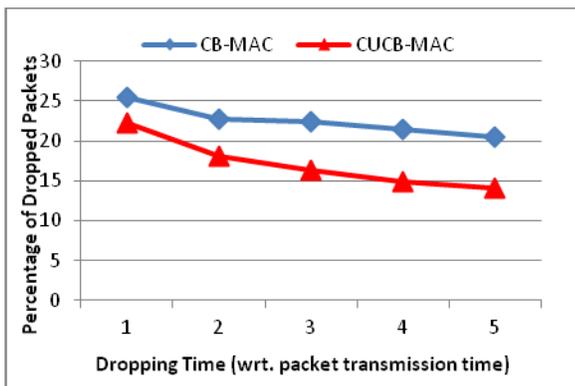
Figure 12 displays the percentage of channel utilization of both protocols while increasing the packet dropping time value. It is clear that the values resulting from applying the proposed CUCB-MAC protocol is lower than in case of applying the original CB-MAC protocol. The packet waiting time will increase when increasing the packet dropping time, so the packets will stay for longer time and will have a chance to be sent and not dropped, this means that the channels are being used more and more in other words the channel utilization increases. As CUCB-MAC prevents highly probable packets' collision from happening; in contrast to CB-MAC, so CUCB-MAC has lower number of packets' retransmission; i.e. lower channel utilization.



**Figure 12.** Percentage of Channel Utilization using Various Dropping Time

Figure 13 shows that the average number of dropped packets of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol, while increasing the packet dropping time value. Increasing the packet dropping time, increases the packet waiting time, so the opportunity that the packet will be sent before it is dropped will increase, i.e. the percentage of packet dropping will decrease. But as in CB-MAC, the number of collided packets is higher than in CUCB-MAC, so packets will stay longer time in case of using CB-MAC, this time may reach the maximum allowable waiting time, so they will be dropped in a higher rate than in case of using CUCB-MAC.

Noticing from Figure 13 that after a certain specific of the packet dropping time approximately 4\*packet transmission time, the percentage of dropped packets is decreasing by a small value. So the other performance metrics values either change by a small value or retain a constant value.



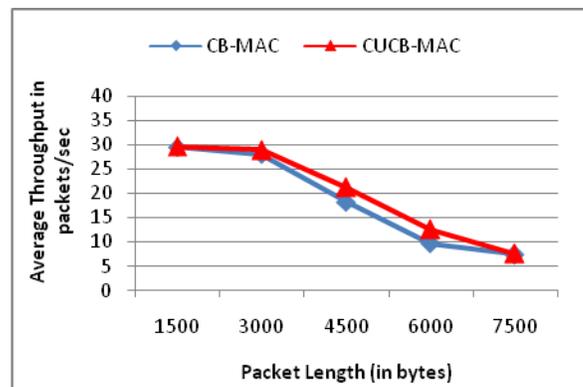
**Figure 13.** Percentage of Dropped Packets using Various Dropping Time

### 5.2.3 Third Scenario: Changing Packet Length

In this scenario the effect of changing the SUs' packet length from 1500 to 7500 bytes is shown in Figures 14 to 18.

It will be noticed in the next five figures that for medium packets length (3000, 4500 and 6000 bytes), the CUCB-MAC outperforms the CB-MAC. The best performance is always obtained when the packet length is 4500 bytes, increasing the packet length above that, will decrease the performance of both protocols. This because too long packets will have high probability to collide, which will lead to bad performance, but still CUCB-MAC outperforms CB-MAC by a little value.

Figure 14 shows that using the proposed CUCB-MAC protocol leads to slightly higher average throughput than using the original CB-MAC protocol for medium packet length. Increasing the packet length; means increasing the packet transmission time, which will lead to increasing the probability of packet being collided before its transmission. Increasing the number of collisions will lead to more retransmission so more retransmissions' overhead, i.e. more time to transmit a packet successfully, leading to low throughput. So it is more reasonable to use the proposed CUCB-MAC protocol that prevents highly probable packets' collision from happening, which will lead to higher throughput



**Figure 14.** Average Throughput using Various Packet Length

Figure 15 shows that the average delay of the proposed CUCB-MAC protocol is a bit lower than that of the original CB-MAC protocol for all used packet lengths. Also; it is clear that increasing the packet length will not increase the difference between the two averages delay got from applying both protocols. As increasing the packet length; will increase the collision probability, so increase the packets retransmission process which leads to a retransmission overhead, so increase in the time taken by a packet to reach its destination. Using CUCB-MAC, some of the retransmission process obtained using CB-MAC will be avoided, so this is will lead to lower delay.

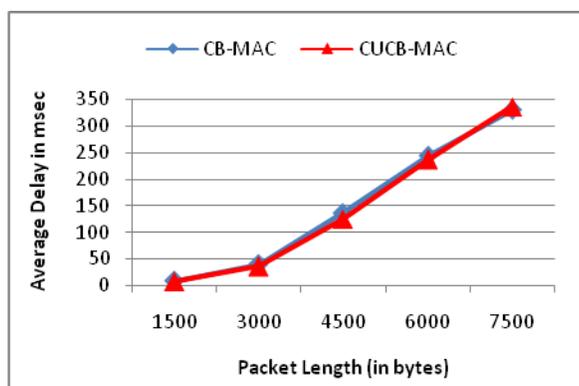


Figure 15. Average Delay using Various Packet Length

Figure 16 shows that the average number of collided packets is much lower using the proposed CUCB-MAC protocol than when using the original CB-MAC protocol for various packet lengths. The difference between the values obtained when using both protocols highly increase with the increase of packet length, till a medium value of 4500 bytes then the difference starts to decrease. This is because increasing the packet length, will lead to increasing the packet transmission time, which will increase the probability of a packet to be collided. So it is better to use the proposed CUCB-MAC protocol that avoids some collisions.

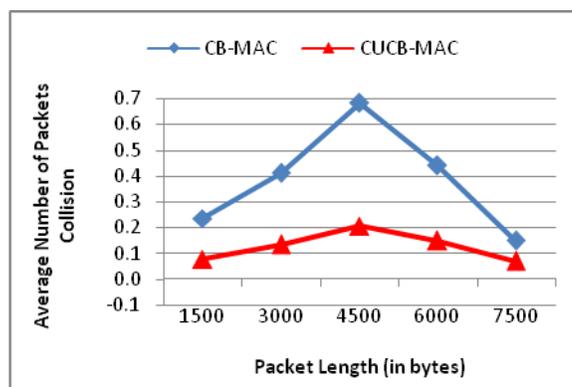


Figure 16. Average Number of Packets Collision using Various Packet Length

Figure 17 shows that the percentage of channel utilization of the proposed CUCB-MAC protocol is a bit lower than that of the original CB-MAC protocol while varying the packet length. Increasing the packet length will lead to increasing transmission time, i.e. increasing in the collision probability; so the packets' retransmission process will be needed more frequently. Using CUCB-MAC prevents some possible collision from happening; this means preventing more packets' retransmission and decreasing the overhead resulted from this process, which leads to lower channel utilization than CB-MAC protocol.

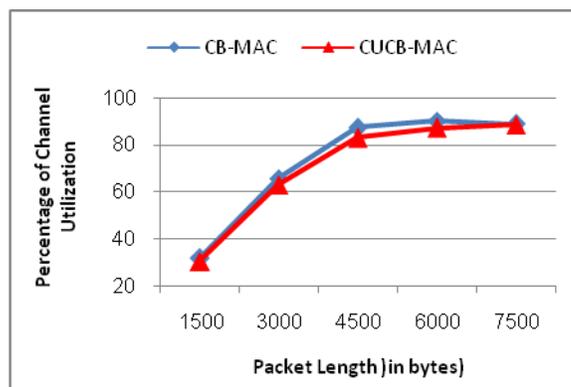


Figure 17. Percentage of Channel Utilization using Various Packet Length

Figure 18 shows that the percentage of dropped packets using the proposed CUCB-MAC protocol is lower than when using of the original CB-MAC protocol for medium packet lengths. Of course increasing the packet length will increase the probability of collision, i.e. increase the needs for packet retransmission (which may be done even more than once), so the waiting time for

these packets will increase. But as using CUCB-MAC protocol prevents highly probable packets' collision from happening, this will decrease its number of packets' retransmission, and the retransmission process overhead, which will eventually decrease their probability of being dropped.

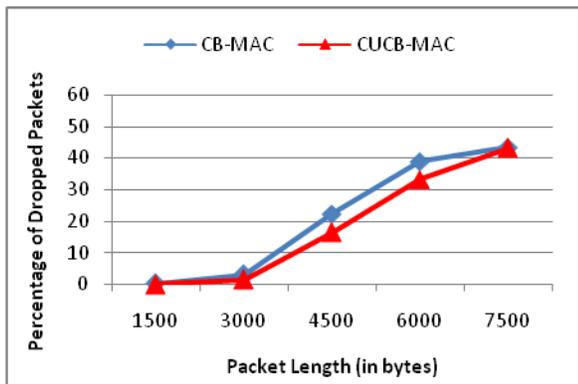


Figure 18. Percentage of Dropped Packets using Various Packet Length

#### 5.2.4 Fourth Scenario: Changing Channel Usage Threshold

One of the parameters used in the channel allocation process protocol for the proposed CUCB-MAC is the channel usage probability. This parameter represents the probability that a PU is expected to use a specific channel, it acts as a threshold in the proposed protocol; if the probability of channel usage by a PU exceeds this specific threshold, it means that this channel is expected to be used by a specific PU within the SU's range waiting for a free channel, so this channel is not allocated to this SU.

It is clear from Figure 19 that the average throughput of the proposed CUCB-MAC protocol is higher than that of the original CB-MAC protocol while increasing the channel usage probability threshold. Increasing the channel usage probability threshold used in CUCB-MAC, will allow packets with high probable collision to be sent, leading to collision occurrence so packet retransmission occurs, i.e. the time each packet will take from the source to the destination will increase by the retransmission overhead, so the

number of packets arriving per second (throughput) will decrease.

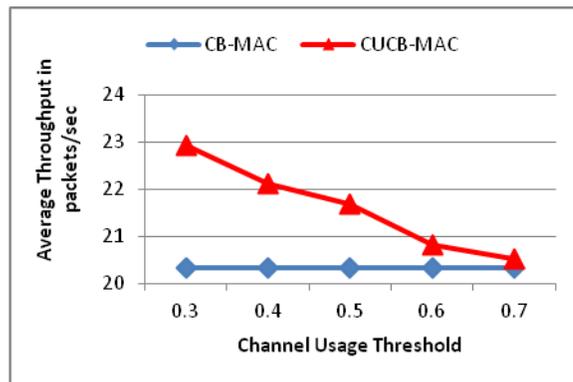


Figure 19. Average Throughput using Various Channel Usage Threshold

Figure 20 shows that the average delay of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol while increasing the channel usage probability threshold. It is clear that increasing the channel usage probability threshold used in CUCB-MAC; will allow more and more packets with high probable collision to be sent; so increase the collision probability, i.e. increase the packets' retransmission process leading to a retransmission overhead, so increase

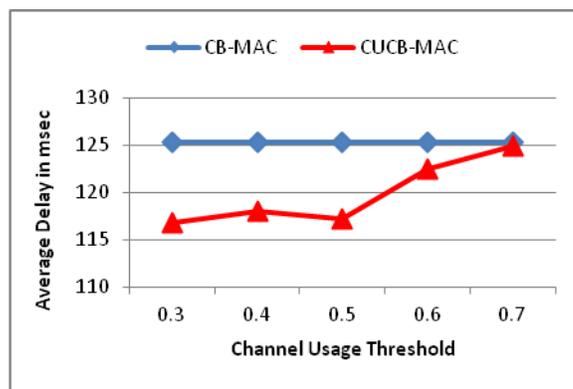


Figure 20. Average Delay using Various Channel Usage Threshold

in the time taken by a packet to reach its destination (delay).

Figure 21 shows that the average number of collided packets of the proposed CUCB-MAC protocol is a lower than that of the original CB-MAC protocol for all values of channel usage

probability threshold. Increasing the channel usage probability threshold used in CUCB-MAC, will allow packets with high probable collision to be sent; so collision occurs, i.e. more packets to be resent. The leads to the existence of larger number of packets in the network, and all of them need to use the spectrum, i.e. crowded network, so more and more collision.

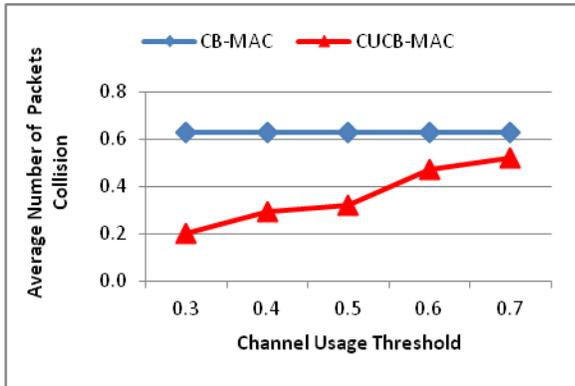


Figure 21. Average Number of Packets Collision using Various Channel Usage Threshold

Figure 22 shows that the percentage of channel utilization of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol for various channel usage probability

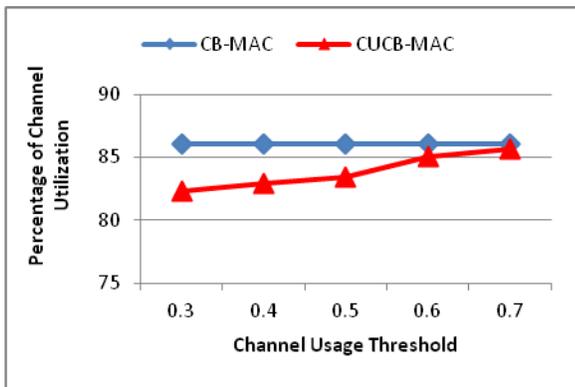


Figure 22. Percentage of Channel Utilization using Various Channel Usage Threshold

threshold. The increase of the channel usage probability threshold will increase the number of packets opportunity to be sent; rather than to be dropped; which will lead to increasing the number of packets using the channels, in other words the percentage of channel utilization will increase.

Figure 23 shows that the percentage of dropped packets of the proposed CUCB-MAC protocol is lower than that of the original CB-MAC protocol, for all the values used for the channel usage probability threshold. Increasing the threshold channel usage probability used in CUCB-MAC; will allow more packets to be sent (those that needed to be prevented), so the number of packets that wants to use the spectrum is increases and the network is more crowded, so more packets will be waiting in the buffer, and more packets will be dropped for exceeding their waiting time. In other word the percentage of dropped packets will increase.

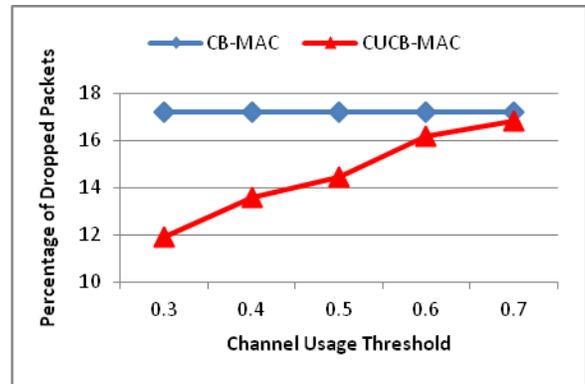


Figure 23. Percentage of Dropped Packets using Various Channel Usage Threshold

### 5.3 Summarized Results

The results of applying both the old and the proposed MAC protocols on various performance metrics using the three scenarios explained in section 5.2 are summarized in table 2. The average values for all performance metrics resulted from applying both protocols, together with the percentage of improvement obtained using CUCB-MAC are put in the table.

Table 2: Percentage of Improvement using the Proposed CUCB-MAC Protocol Compared to the Original CB-MAC

Changed Parameter	Performance Metric	Average value Obtained using CB-MAC	Average value Obtained using CUCB-MAC	Average Percentage of improvement Using CUCB-MAC

Data Rate	Average Throughput (pkts/sec)	17.31	19.32	11.6%
	Average Delay (msec)	124.45	117.14	5.9%
	Average No. of Packets collision	0.52	0.16	69.2%
	Perc. of Channel Utilization	79.19	75.94	4.1%
	Perc. of Dropped packets	21.21	17.64	16.8%
Dropping Time	Average Throughput (pkts/sec)	18.11	20.88	15.3%
	Average Delay (msec)	140.76	132.50	5.9%
	Average No. of Packets collision	0.61	0.19	68.7%
	Perc. of Channel Utilization	85.34	81.85	4.1%
	Perc. of Dropped packets	22.53	17.13	24.0%
Packet Length	Average Throughput (pkts/sec)	18.57	19.98	7.6%
	Average Delay (msec)	151.51	147.87	2.4%
	Average No. of Packets collision	0.38	0.13	66.8%
	Perc. of Channel Utilization	72.77	70.45	3.2%
	Perc. of Dropped packets	21.61	18.87	12.7%
Channel Usage Thres.	Average Throughput (pkts/sec)	20.33	21.62	6.3%
	Average Delay (msec)	125.34	119.91	4.3%
	Average No. of Packets collision	0.63	0.36	42.4%
	Perc. of Channel Utilization	86.03	83.88	2.5%
	Perc. of Dropped packets	17.22	14.58	15.3%

From table 5.2 it can be noticed that the average values of the performance metrics when applying the proposed CUCB-MAC protocol defeat those when applying the original CB-MAC protocol in all cases. Meaning that using CUCB-MAC improves all the performance metrics' values. The improvements are medium on the average throughput, the average delay and the percentage of channel utilization. While high improvements are obtained for the percentage of dropped packets and the average number of collided packets. As an important note we can notice the high improvement on the average number of collided PUs' packets. This is the most important metric as it affects the PU directly, which is a main aim for any cognitive radio network not to degrade the PUs quality of service.

Compared to the CB-MAC protocol, the proposed CUCB-MAC has some advantages in addition to those mentioned above: in the CB-MAC protocol, the packets are stored in the central control module buffer. If the buffer is overloaded, the packets are dropped. This is not the case in the proposed CUCB-MAC, the packets are stored each SU's buffer.

Also compared to the CB-MAC protocol, the proposed CUCB-MAC has some drawbacks: As any SU with a packet to send (in the proposed CUCB-MAC), needs to sense its surrounding area for the existing PUs in its range, then send a list of these PUs to the central control module together with the sent request. The central control module uses these lists to calculate each channel usage by each SU's nearby PUs. This process leads to the following:

- Consuming some energy of the SUs' battery.
- Extra buffering needed to store the list of PUs.
- Extra processing time needed by the central control module to calculate the channel usage, although it is small.

## 6 CONCLUSION AND FUTURE WORK

In this paper; a spectrum sharing technique for cognitive radio networks is proposed. This protocol depends on three parameters for the allocation of the channels to various SUs. Those parameters are: the number of collisions each packet encounters, the estimated probability for channel availability and the estimated probability of channel usage by each PU. So the proposed MAC protocol is named CUCB-MAC. A simulation program was built for comparing the proposed protocol to an old one named CB-MAC that uses only the first two parameters for the allocation process. The evaluation of the proposed CUCB-MAC protocol is done with the usage of three different scenarios. For each scenario a simulation parameter is changed either up or down to examine the impact of this change on both the proposed CUCB-MAC protocol and the original CB-MAC protocol.

From the results, it is concluded that the proposed CUCB-MAC protocol overcome the original CB-MAC protocol on all the measured performance metrics; average throughput, average delay, average number of PUs' packets collided, percentage of channel utilization and finally percentage of dropped packets.

As future work, <sup>1)</sup> Formulate a mathematical model to prove the values used as slot period, channel usage threshold and packet dropping time. <sup>2)</sup> Propose a decentralized MAC protocol that uses collision statistics. <sup>3)</sup> Use another collision statistics measure. <sup>4)</sup> Use a soft computing paradigm based on fitness optimization function to reach optimal best channel allocation process.

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