Contention based Multi-channel MAC Protocol for Distributed Cognitive Radio Networks

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***Abstract*—Design of an efficient medium access control protocol is critical for proper functioning of a distributed cognitive radio network and better utilization of the available channels not being used by primary users. In this paper, we design a contention based distributed medium access control (MAC) protocol for the secondary users' channel access. The proposed MAC protocol allows collision-free access of the available channels and eventual utilization by secondary users, with spectrum sensing part being handled by exclusive sensing nodes. The effectiveness of the proposed MAC protocol is evaluated analytically and also through empirical simulations. We show how the protocol performs with respect to blocking probability, channel grabbing, and channel utilization[1].**

I. Introduction

Radio spectrum allocation and management have traditionally followed a 'command-and-control' approach where chunks of spectrum are allocated for specific services under restrictive licenses. The restrictions specify the technologies to be used and the services to be provided, thereby constraining the ability to make use of new technologies and the ability to redistribute the spectrum to higher valued users. There have been experimental studies that reveal that the spectrum utilization is time and space dependent and that most parts of radio spectrum are highly underutilized. These limitations have motivated a paradigm shift from static spectrum allocation towards a notion of dynamic spectrum management where secondary networks users (SUs) (non-license holders) can 'borrow' idle spectrum from the primary network users (PUs) (license holders) without causing harmful interference to the latter. SUs equipped with cognitive radio enabled devices will facilitate such dynamic spectrum access (DSA) where the cognitive radios continuously monitor the presence of PUs and opportunistically access the unused or under-utilized licensed bands [1].

The cognitive radios undergo sensing, channel contention, data transmission, and reception. Depending on the granularity of the channels being sensed, the radios might need considerable amount of duty-cycle for the sensing process itself. Therefore, oftentimes the sensing process is de-coupled from the other functions of cognitive radio where dedicated sensors are used solely for the purpose of spectrum sensing. Such sensors continuously scan the spectrum usage (i.e., identify which ones are currently being used and which channels can potentially be used) and broadcast the usage statistics to the other cognitive radios. With the knowledge of the usable channels, the SUs contend among themselves to acquire those channels to be used for data transmission. Since there is no central entity to dictate which SUs get what channels, the cognitive radios need to resort to some medium access control (MAC) protocol to decide on their share of the channels.

The absence of any central entity or a repository containing up-to-date information about usable channels necessitates the need for a contention based MAC protocol where there cannot be any presumption on node-to-node coordination. Though there have been MAC protocols developed for single channel [2] and multi channels [3], [4] for distributed ad hoc and sensor networks, they are not directly applicable to the cognitive radio networks (CRNs) because of two reasons: i) the set of available channels for communication is always changing because of primary activity, and ii) the set of available channels for every node could be different based on their spatial location. The cognitive radios either can simply choose to transmit data packets on some channel hoping that there would not be any collision, or they can choose to go through a contention phase where the nodes first agree on what channel each must use.

There have been some MAC protocols proposed for CRNs. In [5], the authors proposed a broad classification of the MAC protocols where they classified the protocols into different genres which include protocols for ad hoc CRNs and centralized CRNs. In [6], a MAC protocol for ad hoc CRNs was defined, which studied the effects of random sensing policy and negotiated sensing policy on the throughput of SUs. However, how the co-ordination is maintained among the secondaries regarding channel sensing is not discussed. In [7], the authors designed an opportunistic multichannel MAC for quality of service (QoS) provisioning. Authors in [8] discuss different control channel implementations for multichannel MAC protocols in CRNs. Performance of the protocol is analyzed and a comparison of efficiencies is put forth. To the best of our knowledge, none of these work have considered exclusive sensing devices that work independently. Separating sensing from secondary contention and transmission is expected to result in better access of the channels while they are unused, thus increasing the idle channel utilization.

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In this paper, we consider a cognitive radio based DSA network where stationary sensors are deployed solely for the purpose of gathering and sharing the spectrum usage statistics with the SUs that are randomly scattered over the area of interest. We design a contention based MAC protocol where the SUs contend over a common control channel for data channel access. Winning the contention prompts the SUs to gain access to the usable data channels. We analyze and simulate the performance of the proposed MAC protocol in terms of probabilities of blocked channel access attempts, idle channel grabbing, and idle channel utilization. The key features of the proposed protocol are:

(a) It separates channel sensing from contention and channel access which increases secondary access probability.
(b) It ensures a higher temporal utilization of available data channels as the contention takes place on a dedicated control channel.
(c) The data transmission phase is free from any collision among SUs.
(d) It provides optimal length of contention window for maximum idle channel utilization.

The remainder of the paper is organized as follows. In section II, we discuss the system model and state the assumptions. We present the multichannel MAC protocol in section III. The performance of the proposed protocol is analyzed in section IV. Numerical study along with the results are presented in section V. Conclusions are drawn in the last section.

II. System Model and Assumptions

We consider a set of SUs randomly scattered over a relatively small area of interest. Due to their physical proximity, we assume that all nodes experience the same primary activities. As the SUs do not undergo the sensing process themselves, a centrally located dedicated sensor is used that continuously senses the primary activities. The sensor also periodically broadcasts beacons containing primary usage information on a common control channel. These beacons (i.e., binary vectors showing if channels are occupied or unoccupied) are heard by all the SUs. On hearing these beacons, the SUs go through a contention process to acquire data channels before they can begin data transmissions.

Assumptions: We make the following additional assumptions on the system settings:

1) A sensing node is able to distinguish between primary transmission and secondary transmission on any data channel through some preamble that primaries usually use. A channel is designated as occupied only when there is an ongoing primary transmission on that channel.
2) SUs rely on the beacons from the sensor node for channel occupancy information.
3) All SUs are time synchronized; this is achieved through the same sensing beacons.
4) All channels have identical propagation characteristics and there is no preference for any particular channel.
5) Relatively small size of area of interest implying no spectrum reuse among the SUs.
6) To aid increased SU throughput, the SUs can be equipped with two radios, one for contention and another for simultaneous data transmission.

Primary ON-OFF Model: Availability of spectrum depends on the activity of the PUs. We consider the commonly used primary activity ON-OFF model [9]. According to this model, every channel has two states: ON (channel busy) and OFF (channel idle) depending on primary user activity. ON and OFF period durations are independently exponentially distributed with parameters λ_p and μ_p. Thus, for any channel, the duration of ON period x is an exponentially distributed random variable with mean $\frac{1}{\lambda_p}$ and is given by

$$f_1(x) = \begin{cases} \lambda_p e^{-\lambda_p x} & \forall\ x \geq 0 \\ 0 & \forall\ x < 0 \end{cases} \quad (1)$$

Similarly, the duration of OFF period denoted by the random variable y with mean $\frac{1}{\mu_p}$ has the distribution,

$$f_2(y) = \begin{cases} \mu_p e^{-\mu_p y} & \forall\ y \geq 0 \\ 0 & \forall\ y < 0 \end{cases} \quad (2)$$

III. The proposed MAC Protocol

We propose the MAC protocol by describing the frame structure, channel access method, mode of operation and design optimization.

A. The frame structure

We assume that there is one common control channel that is used for the beacon broadcasts by the sensors as well for the contention among the SUs. The sensor sends a beacon periodically every T_c seconds indicating the channels that are idle at that point of time. The beacon duration is T_b. The time between two beacons (i.e., T_c) is divided into three equal sized windows for RTS, CTS, and ACK as shown in Fig. 1. The RTS, CTS, and ACK windows are further divided into N_S mini-slots each. The time-slotted data channels are synchronized with the common control channel. Nodes acquiring data channels after winning contentions get to transmit during the *next* data slot which is of duration $T_d = T_c + T_b$. The packets transmitted by the SUs are assumed to be of fixed duration of one data slot.

B. The contention process

The secondary nodes that want to transmit data must go through the contention process to acquire data channels. All such contending nodes randomly pick one of the N_S mini-slots in the RTS window. In that mini-slot, the secondary node transmits its intention of transmission and who the intended receiver is. Of course, more than one secondary node might decide to transmit during the same mini-slot. In such cases of RTS collisions, the colliding nodes try again in the next RTS window. Also, there might be RTS mini-slots that are chosen by none; those RTS mini-slots go idle. Thus, an RTS mini-slot is successful, if one and only one secondary node contends

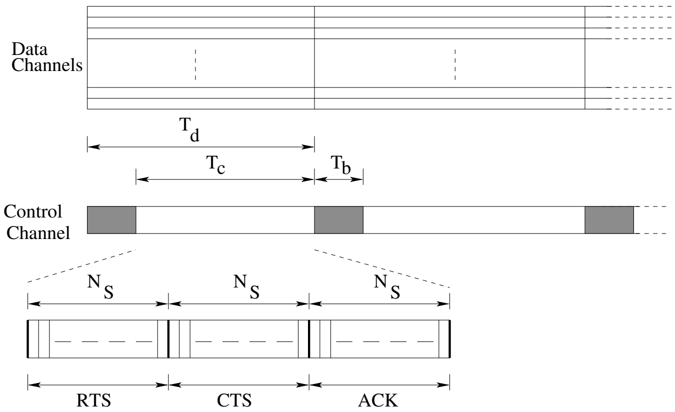

Fig. 1. MAC frame structure

on that mini-slot. Upon receiving a successful RTS from a transmitting secondary node, the intended receiver transmits CTS in the same mini-slot of the CTS window. Thus, only the successful RTS mini-slots would have their corresponding CTS mini-slot transmissions. Once the transmitter receives the CTS, it responds in the same mini-slot of the ACK window confirming which particular channel is to be used among the usable channels. The ACK also contains a network allocation vector (NAV) specifying the duration for which the chosen channel will be in use so that (i) no other node tries to use that data channel, and (ii) the sensor node is aware of the data channel being used by a SU transmitter-receiver pair.

C. Data channel grabbing and transmissions

The outcome of the contention process marks each mini-slot as either 'successful' or 'unsuccessful'. The winners of the contention grab the available data channels in a sequential manner. Thus, the winner of the first successful mini-slot gets to pick one of the N_A channels. The ACK contains the information of the channel grabbed; thus the remaining winners refrain from grabbing that channel. The second winner gets to pick next and lets other know about the channel grabbed through the ACK. Thus, as long as the number of winners is less than or equal to N_A, all winners are guaranteed to grab a data channel. If N_A is less than the numbers of winners, then the first N_A winners will get one data channel each. The remaining winners will be blocked (i.e., the system runs out of data channels for the SUs). After the data channels are grabbed, the secondary transmitters are ready to start transmission on the grabbed channel in the next data slot.

D. Mode of operation

The design of the MAC is flexible enough to support two modes of operation: i) transmission on the next data slot only, and ii) transmission on multiple successive data slots. Choice of the modes depends on the traffic of SUs contending for mini-slots. Further insight on the mode selection is given in Section III-E. However, a SU transmitting through multiple data slots always needs to listen to the beacons following every data slot in order to make sure the channel is still free from primary activity. If PU arrives on a data channel *during an ongoing SU transmission*, then the SU has to relinquish that channel at the end of the data transmission slot. Thus, the duration T_d is suitably chosen to keep the interference caused to primary within a tolerable range.

E. N_S Optimization

So far, the discussion on design of the MAC protocol has been on its working principle. As far as achieving the best performance is concerned, the number of mini-slots for RTS contention (N_S) needs to be optimized. Such optimization must consider several system variables like the number of active SUs and the number of available channels. It is easy to see that, if N_S is small compared to the number of secondary nodes then the RTS contention probability will be high. Also, since a successful RTS mini-slot can result in acquiring one data channel, the value of N_S must allow the provision of potentially using all available data channels. We discuss optimal N_S in section V.

IV. Analysis of the Proposed MAC Protocol

We analyze the performance of the proposed MAC protocol in terms of some of the commonly used metrics. First, we provide their definitions in our context.

RTS Success Probability: This is the probability of successfully winning a RTS mini-slot by any secondary node.

Blocking Probability: The blocking probability at jth mini-slot is defined as the probability that a request for free channels at the jth mini-slot by any secondary transmitter-receiver pair will be blocked due to the reason that other secondary transmitter-receiver pairs in the previous $(j-1)$ mini-slots have already grabbed all the available channels. This is preconditioned to successfully winning a RTS mini-slot.

Idle Channel Grabbing: This is a measure of how many channels the secondary nodes have grabbed among the idle channels after successfully winning the contention. It is calculated by the expected number of channels successfully grabbed through the contention slot (regardless of their eventual utilization in the data transmission slot).

Idle Channel Utilization: Idle channel utilization is the number of channels that are successfully utilized by the secondary users without any interruption from primary nodes during the data transmission slot.

A. The primary ON-OFF model

The probability of any channel being idle in the contention window (p_{idle}) is the steady state probability of that channel in OFF state. We have already mentioned that we consider the ON and OFF durations are exponentially distributed random variables. Using the Gilbert-Elliott 2-state classical Markov model, we get,

$$\begin{aligned} p_{idle} &= Prob\{\text{a channel is in OFF state}\} \\ &= \frac{\bar{t}_{OFF}}{\bar{t}_{ON} + \bar{t}_{OFF}} = \frac{1/\mu_p}{1/\lambda_p + 1/\mu_p} = \frac{\lambda_p}{\lambda_p + \mu_p} \end{aligned} \quad (3)$$

N_T	Number of total channels in the spectrum of interest
N_S	Number of mini-slots in RTS contention window
N_A	Number of available channels in the spectrum of interest
N_{SW}	Number of mini-slots won in RTS window
N_{CG}	Number of channels grabbed in a contention slot
N_{CU}	Number of channels utilized in a data slot
t_{ON}	Average PU ON time per contention window ($= 1/\lambda_p$)
t_{OFF}	Average PU OFF time per contention window ($= 1/\mu_p$)
λ_s	Secondary rate of contention per mini-slot (Poisson)
T_c	Duration of contention window
T_d	Data transmission slot duration
T_b	Beacon duration
p_s	Probability of a successful RTS contention
p_c	Probability of selecting a free channel
p_{idle}	Probability of a channel being idle
Λ	Number of SUs in the network

TABLE I
NOTATIONS USED

Therefore, the average number of available channels in the system N_A is expressed as $N_A = p_{idle} \times N_T$. The commonly used notations are shown in Table I.

We seek to find the distribution of inter-arrival times of the ON/OFF periods from traditional ON-OFF model for further calculating idle channel utilization in Section IV-E. The random variable representing the primary inter-arrival time **z** is the sum of two independent random variables for ON and OFF periods **x** and **y** respectively, i.e., $\mathbf{z} = \mathbf{x} + \mathbf{y}$. Therefore, the distribution of **z** is obtained as:

$$\begin{aligned} f_Z(z) &= f_X(x) * f_Y(y) \\ &= \int_{-\infty}^{+\infty} f_X(z-y) f_Y(y) dy \\ &= \frac{\lambda_p \mu_p [e^{-\lambda_p T_c} - e^{-\mu_p T_c}]}{(\lambda_p - \mu_p)} \end{aligned} \tag{4}$$

B. RTS success probability

Winning a RTS mini-slot is just like transmissions in a slotted ALOHA system where a successful transmission occurs if and only if there is one node transmitting a packet during a slot. With SUs generating request at a rate of λ_s per RTS mini-slot, the RTS success probability is given by $p_s = \lambda_s e^{-\lambda_s}$.

C. Blocking probability

Successfully winning a RTS mini-slot does not necessarily mean that the winner will get a data channel. This is because, the RTS mini-slot winners claim data channels in a sequential manner starting with the winner of the first mini-slot. By the time the winner of the jth mini-slot tries to claim a data channel, there might not be any channel available, as the previous ones (i.e., the winners of mini-slots 1 through $(j-1)$) could grab all the available data channels N_A. However, if the number of available channels N_A is more than the number of mini-slots N_S, then all the winners grab channels and there is no blocking.

Since each RTS mini-slot is won independently of each other, each with probability p_s, the probability that there will be j winners ($0 \le j \le N_S$) is,

$$\binom{N_S}{j} (p_s)^j (1-p_s)^{N_S - j} \tag{5}$$

When $N_A \ge N_S$, then blocking probability is 0 as all N_A winners are bound to grab channels. However, for $N_A < N_S$, only the first j winners will grab channels and the remaining $j - N_A$ winners will be blocked. Therefore the average blocking probability of the system is,

$$\text{E[BP]} = \begin{cases} 0 & \forall\ N_A \ge N_S \\ \displaystyle\sum_{j=N_A+1}^{N_S} \binom{N_S}{j} (p_s)^j (1-p_s)^{N_S-j} & \text{otherwise} \end{cases} \tag{6}$$

D. Idle channel grabbing

Getting hold of idle channels by the secondary nodes during the ACK window depends on how many mini-slots have been successfully won by the secondaries in the RTS window. Successfully winning a mini-slot means that only one secondary has selected that mini-slot. We define N_{SW} as the expected number of successful mini-slots won by the secondaries in the RTS window.

$$N_{SW} = N_S \times p_s \tag{7}$$

If the secondaries are allowed to grab only one channel, then the expected number of channels grabbed by the secondaries in a contention window (N_{CG}) is the minimum of N_{SW} and N_A. Therefore,

$$\text{E[Idle channel grabbing]} = N_{CG} = \begin{cases} N_{SW} & \forall\ N_{SW} \le N_A \\ N_A & \text{otherwise} \end{cases} \tag{8}$$

E. Idle channel utilization

We argue that in order to utilize an idle channel, winning the contention and grabbing the channel is not enough. A grabbed channel is defined to be utilized if that secondary is allowed uninterrupted access (i.e., without any primary activity) on that channel in the following data transmission slot. Therefore, any grabbed channel needs to be free from any primary activity from the start of the next transmission slot till the end of that slot (i.e., T_d duration) to be successfully utilized by a SU. Interestingly, the PU can even arrive during the contention slot (duration T_c) when that idle data channel is being contested for. But the channel will only be utilized if the PU vacates the channel before start of the following data transmission slot.

Through Fig. 2 and Table II, we show all the different cases of primary arrivals and departures within two inter-beacon periods (i.e., two data-transmission periods) with respect to idle channel utilization. We also point out the idle channel grabbing and possible utilization in such scenarios.

We define, $P_{PU}^{P \to S}$ as the probability of primary to arrive anytime from the start of the first contention slot (time P) till

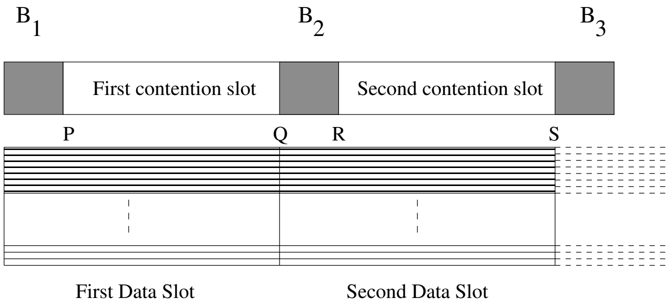

Fig. 2. Consecutive data and contention slots

Cases	Primary Arrival	Primary Departure	Grabbing in 1st cont. slot	Utilization in 2nd data slot
I	Before B_1	Before B_2	NO	NO
II	Before B_1	After B_2 & Before B_3	NO	NO
III	After B_1 & Before B_2	After B_2 & Before B_3	YES	NO
IV	After B_1 & Before B_2	After B_3	YES	NO
V	After B_1 & Before B_2	Before B_2	YES	YES
VI	After B_2 & Before B_3	After B_3	YES	YES

TABLE II
PU ARRIVALS AND CORRESPONDING CHANNEL GRABBING AND UTILIZATION

the end of the second data slot (time S). Then the probability of no primary arrival during this time is given by,

$$\begin{aligned} 1 - P_{PU}^{P\to S} &= \text{Prob}\{\text{Case V}\} + \text{Prob}\{\text{Case VI}\} \\ &= \text{Prob}\{\text{PU arrival+ ON duration} \le T_c\} \\ &+ \text{Prob}\{\text{OFF duration} > T_d\} \\ &= \text{Prob}\{\text{z+x} \le T_c\} + \text{Prob}\{\text{y} > T_d\} \\ &= 1 + e^{-\mu_p T_d} + \frac{\lambda_p \mu_p [e^{-\lambda_p T_c} - e^{-\mu_p T_c}]}{(\lambda_p - \mu_p)^2} \\ &- \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)} + \frac{\lambda_p \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)} \end{aligned} \quad (9)$$

Therefore,

$$\text{E[Idle channel utilization]} = N_{CG} \times (1 - P_{PU}^{P\to S}) \quad (10)$$

From Eqn. (10), we evaluate the optimal N_S in order to maximize the utilization. Possible values of N_S and other design variables are also evaluated.

V. SIMULATION MODEL AND RESULTS

We conduct simulation experiments in MATLAB to find the empirical results of the proposed MAC protocol. As input to the simulation model we kept $N_T = 30$, $T_c = 30\mu s$, and $T_b = T_c/100$ unless stated otherwise.

RTS Success Probability: We show the characteristics of RTS success probability with the number of active secondaries in Fig. 3. It shows the typical nature of slotted ALOHA throughput with the peak success probability of 0.37. With more mini-slots, the peak value is reached with more secondaries in the system contending per mini-slot, λ_s.

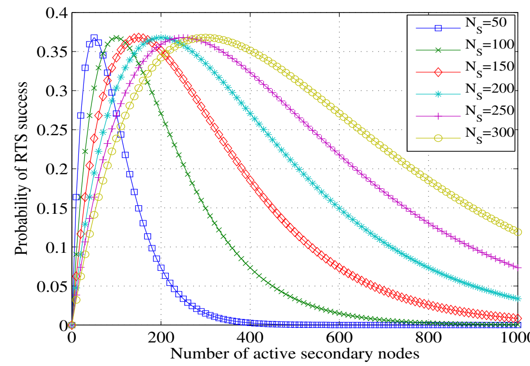

Fig. 3. RTS success probability.

Blocking Probability: In Fig. 4, we show how the average blocking probability varies with number of mini-slots in each contention window. We notice that for low values of N_S, average blocking probability is 0 as all the winning secondaries are able to grab channels. At a certain N_S, when total number of winning mini-slots go beyond N_A (for a particular p_{idle}), average blocking probability becomes finite. It continues to increase with N_S till it reaches almost 1 where most of the mini-slots winning secondaries are blocked. With higher p_{idle}, such saturation point is reached at a higher N_S as the increased N_A results in more secondaries to grab channels.

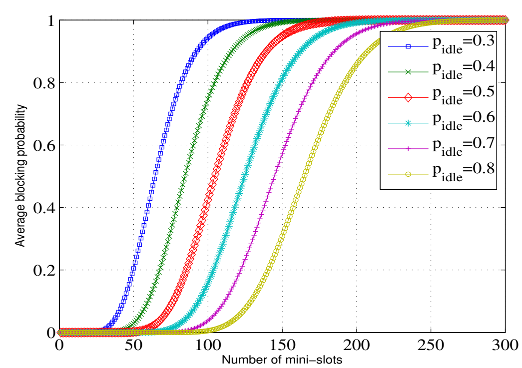

Fig. 4. Average blocking probability, with $N_T = 30$.

Channel Grabbing: We investigate the nature of expected idle channel grabbing against the number of mini-slots at different values of p_{idle}. N_{CG} shows steady increase with number of slots grabbed N_{SW} till it reaches the point where N_{SW} crosses the number of available channels N_A, which becomes the steady state value. For higher values of p_{idle}, the value of N_A increases and so does the steady state value.

In Fig. 6, we show how idle channel grabbing varies with the rate of secondary contention per mini-slot where we kept $N_S = 100$. The nature mimics typical slotted-ALOHA throughput curve. A higher probability of p_{idle} results in a higher peak value of N_{CG}.

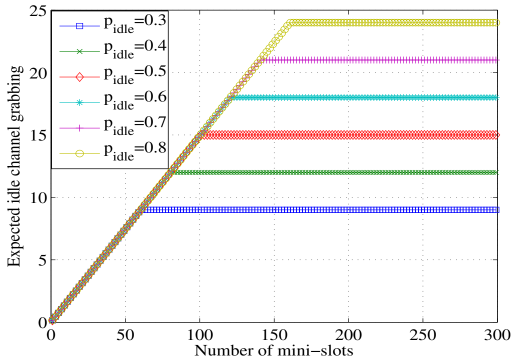

Fig. 5. Idle channel grabbing characteristics, with $N_T = 30$ and $\lambda_s = 3$.

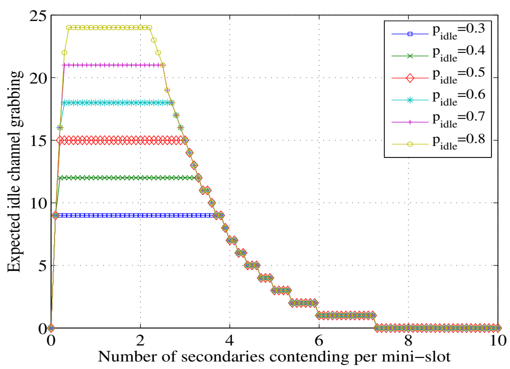

Fig. 6. Idle channel grabbing characteristics with $N_T = 30$ and $N_S = 100$

Channel Utilization: The nature of idle channel utilization with number of mini-slots (N_S) is demonstrated in Fig. 7. We see that, with the increase in N_S, the utilization increases linearly till it reaches an inflection point. The existence of the maxima is a measure of optimal number of contention mini-slots (N_S) for the system. Such convexity exists because a larger contention window leads to more probability of PU arrival (higher value of $\bar{P}_{PU}^{P \to S}$) and thus less utilization. For example when $p_{idle} = 0.6$, the optimal N_S is around 120 for the maximum idle channel utilization.

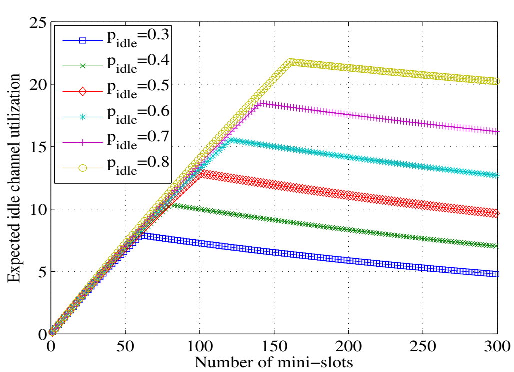

Fig. 7. Idle channel utilization with $N_T = 30$ and $\lambda_s = 3$

In Fig. 8, we see that the nature of channel utilization with varying number of secondaries is similar to that of channel grabbing in Fig. 6. However the peak value of average channel utilized for each p_{idle} is less than that of average channels grabbed as some channels will encounter interference from PUs.

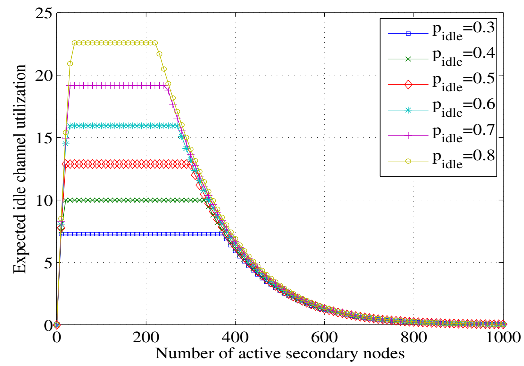

Fig. 8. Idle channel utilization with $N_T = 30$ and $N_S = 100$

VI. Conclusions

In this paper, we proposed a contention based MAC protocol where for secondary cognitive radio networks where sensing is de-coupled from the communicating SUs. The sensors gather and distribute the channel occupancy reports to the SUs who then engage in a contention process using a common control channel. Winners of the contention get to access and use the data channels. The protocol is flexible to allow multiple classes of SUs. Our evaluation measures take into consideration different QoS criteria, which include contention blocking probability and utilization of idle channels.

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