Contention Based Multichannel 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 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 to the available data channels and eventually their utilization by secondary users, with spectrum sensing part being handled by exclusive sensing nodes. We further introduce the provision of reservation of free channels by secondaries for extended periods to increase utilization without causing harmful interference to primaries. We demonstrate how such extended access to resources can be tuned to provide differential quality of service to the secondary users. The effectiveness of the protocol is evaluated by performing analysis and simulation. We use blocking probability, secondary usage of a secondary user and performance degradation caused to primary incumbents as performance metrics. We obtain the conditions for such extended access and try to gauge the resulting increase in utilization. Under optimal conditions, the proposed scheme enables the secondary network to utilize all available channels. The proposed scheme is shown to outperform the most sophisticated existing MAC schemes for distributed secondary networks.

Index Terms—Cognitive radio networks; secondary users; MAC protocol

1 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 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. Secondary users equipped with cognitive radio enabled devices will facilitate such dynamic spectrum access (DSA) where the cognitive radios continuously monitor the presence of primary users 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 decoupled 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 channels 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 secondary users contend among themselves to acquire those channels to be used for data transmission. Since there is no central entity to dictate which secondary users get what channels, the cognitive radios need to resort to some medium access control (MAC) protocol to decide on their share of the usable 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 with time because of dynamic 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 which channel(s) each must use.

1.1 Motivation

Designing efficient MAC protocols for distributed CRNs requires a tight coupling between the spectrum access module and the component responsible for managing spectrum availability. This requires the spectrum access module to be continuously aware of the surrounding

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physical environment. Conventionally, the existing body of work [4], [5], [6] assumes the secondaries to be sensing capable. However, recent research has shown that de-coupling sensing from secondary contention results in an improved primary channel usage. Moreover, the recent trend is more towards 'query and use' which is facilitated through radio environment maps [7], [8], [9] and spectrum databases [10]. Therefore, it is essential that cognitive routing protocols leverage such up-to-date spectrum information in building efficient and robust protocols. Also, with the increasing demand for low cost secondary nodes, it is imperative that sensing capability is de-coupled from regular secondary devices, thus motivating the need for spectrum repository look-ups. We seek to design a MAC protocol that not only achieves such de-coupling, but is also flexible enough to employ either the use of spectrum database or distributed spectrum sensing for spectrum availability information.

1.2 Contributions of This Work

We consider a cognitive radio based dynamic spectrum access network where stationary sensors are deployed solely for the purpose of gathering and sharing the spectrum usage statistics with the cognitive radios that are randomly scattered over the area of interest. With an aim to increase the channel usage efficiency, we design a contention based MAC protocol where the secondary nodes contend over a common control channel for data channel access. Such messaging through a common control channel is prevalent in cognitive MAC protocols [11], [12], [13]; the alternative being phase splitting [14], [15] when control messaging is performed during the precious channel idle time, thus reducing efficiency. Winning the contention allows the secondary nodes to gain access to the usable data channels. Our proposed MAC protocol empowers each secondary pair to greedily decide on a channel but also increases the overall secondary usage and idle channel utilization.

We analyze and simulate the performance of the proposed MAC protocol in terms of probabilities of blocked channels access attempt, idle channel grabbing, secondary usage, as well as primary quality of service (QoS) degradation. We introduce the provision of using the free channels for extended sessions by the contention winning secondary users provided prolonged absence of primaries on the channels. We also define conditions for unequal extensions to secondaries for their different QoS requirements. We demonstrate higher channel utilization achieved by such provision. We compare our scheme with two competitive multichannel MAC protocols [11] and [16] which are better performing than the other MAC schemes in literature. We compare the performance in terms of average secondary usage, system throughput, and primary degradation caused by misdetection. The key features and the benefits of the proposed MAC protocol are:

a) The data transmission phase is free from any collision among secondary nodes. It ensures a higher temporal utilization of available data channels as the contention takes place on a dedicated control channel. The gain in temporal utilization is 33 percent over that in [11] and 75 percent over that in [16] for best case scenarios.
b) An optimal length of contention window is obtained for maximum secondary usage.
c) It separates channel sensing from contention and channel access which increases secondary access probability.
d) It allows differential QoS provisioning for secondaries based on their demands.
e) It achieves near-complete utilization of channel idle time for both equal and differential QoS.
f) It limits the degradation to primary users' quality of service within a tolerable range.

1.3 Organization

The remainder of the paper is organized as follows. Section 2 presents some notable work in this field. In Section 3, we discuss the system model and state the assumptions. We present the multi-channel MAC protocol in Section 4. The performance of the proposed MAC protocol is presented in Section 5. The provision of multiple data-slots reservation by the secondary users and facilitating differential QoS needs are discussed in Section 6. Numerical study along with the results are presented in Section 7. Conclusions are drawn in the last section.

2 Related Work

There are several MAC protocols in the literature that are proposed for cognitive radio networks, broad classification of which can be found in [5]. According to the authors, MAC protocols can be broadly classified as those meant for distributed and centralized CRN. In a distributed CRN, the secondaries coordinate among themselves and access channels in a distributed manner without a central authority unlike the centralized CRNs. However, authors in [17] distinguished cognitive MAC protocols in two types: direct access based (DAB) and dynamic spectrum access. The former group consists MAC protocols where the secondaries try to access the unused spectrum without any global optimization. In such schemes, the sole purpose of each secondary pair is to maximize their own usage. Most of the these protocols are contention based namely HC-MAC [18], DOSS [13] and COMAC [19]. In HC-MAC [18], the authors propose a contention based DAB protocol that represents the sensing process as an optimal stopping problem in order to determine how long a cognitive radio should observe the wireless bands to optimize its expected throughput. Dynamic open spectrum sharing (DOSS) [13] uses a data band, a control channel, and a busy tone band that are exploited to manage communication, signaling, and contention, respectively. However, the effectiveness of DOSS is reduced due to the requirement of two separate bands (control channels) to manage busy tones and common information exchange. In COMAC [19], the secondary users contend for the access of the licensed bands but in underlay mode by limiting the interference caused. The main drawback of DAB MAC protocols is the lack of guarantee to protect primary incumbents. Failure to guarantee such provision by secondary standards will cause the primary network providers to create major roadblocks and reservations in the path of real implementation of such strategies.

On the other hand, DSA protocols are those that exploit optimization algorithms to achieve a global purpose. Various techniques have been adopted to optimize such global objectives, namely, graph theory based [20], [21], game theory based [22], [23], stochastic algorithms based [24], genetic algorithms based [25], and swarm intelligence based algorithms [6]. Below we discuss some notable work in this area. In [26], authors propose a CSMA/CA-based MAC protocol using statistical channel allocation to address the interoperability issue and achieve higher efficiency of spectrum utilization. In [27], a MAC protocol for distributed CRN was defined, which studied the effects of random sensing policy and negotiated sensing policy on the throughput of secondary users. However, how the co-ordination is maintained among the secondaries regarding channel sensing has not been discussed. In [11], the authors designed an opportunistic multi-channel MAC for QoS provisioning. In [16], the authors propose a multichannel MAC protocol by collaborative opportunistic spectrum sensing by the secondaries. The protocol ensures primary protection through secondary power control. Pawelczak et al. [28] presented different control channel implementations for multi-channel MAC protocols in CRN. Their performances were analyzed approximately and a comparison of efficiency were studied. Although all of the above mentioned MAC protocols make valid contributions, most of these work use spectrum sensing by the secondaries themselves thereby wasting precious primary inactivation time. We rather propose dedicated sensors to perform sensing resulting in better idle spectrum utilization shown both analytically and through simulation.

3 System Model and Assumptions

We consider a set of secondary users randomly scattered over a relatively small area of interest which can be considered as a cell. Due to their physical proximity, we assume that all nodes experience the same primary activities. Although secondary users' spectrum observation depends on the dynamism of the primary network and the size of the area under consideration, spectrum databases such as Google's [10] have shown that even in metropolitan downtown areas, vast areas (tens of square kilometers) have the same set of free channels. Similar single-cell analysis are used by some notable work in order to simplify the complex nature of inter-cell interference and focus on performance enhancement within the cell [29], [30]. As we mentioned before that the secondary users do not undergo the sensing process themselves, a centrally located dedicated sensor is used that continuously senses the primary activities. These sensors can also be dedicated nodes which periodically build/query a spectrum database or a radio environment map and update the current spectrum availability scenario. The sensor also periodically broadcasts beacons containing primary usage information on a common control channel similar to [12], [13]. These beacons contain time synchronization information for all secondaries under purview of the sensor. The beacons also contain binary vectors for each channel ID denoting if the channels are occupied or unoccupied which are heard by all the secondary users under the sensor. On hearing these beacons, the secondary users go through a contention process to acquire data channels before they can begin data transmissions. We make the following assumptions on the system settings:

1) *Time synchronization among secondaries*. We assume that all secondary users under a sensor are time synchronized. We argue that since the secondary nodes collect the channel status from the sensor nodes on regular intervals, re-synchronization from any drift can be practically possible. Such assumptions are not uncommon in distributed cognitive MAC protocols [14], [15], [31] where IEEE 802.11 type timer synchronization functions (TSF) are used.
2) *Channel propagation characteristics*. We assume that all the data channels have identical propagation characteristics and there is no preference for any particular channel. This is assumed for the simplicity of our analytical framework. Similar assumptions are made by notable work in the field of cognitive MAC protocols [11], [26]. We should mention that however, the proposed protocol works even if different channels exhibit non-identical radio propagation characteristics.
3) *Contention frequency*. We assume that each secondary user is allowed to contend for only one mini-slot. This avoids bandwidth/resource hogging and ensures long term fairness in terms of probability of winning the contention. Similar strategy is taken in IEEE 802.11 MAC standard [32].
4) *Winning incentive*. Upon successfully winning the contention, each secondary is allowed to grab only one channel per data transmission slot. This is to ensure fairness, assuming that all the users are of equal priority. However, we make provisions for extended usage of grabbed channels in case there is a low demand for channels by other secondaries.
5) *Number of radios*. To aid increased secondary user throughput, the secondary users can be equipped with two radios, one for contention and another for simultaneous data transmission. Availability of more than one transceivers has shown to increase secondary throughput [33]. Usage of multiple radios in secondary devices to increase utilization is also prevalent [13], [34].

Primary ON-OFF model. Availability of spectrum depends on the activity of the primaries. Though there is some evidence that the primary activities are heavy-tailed [35], [36], there are also references that show primary activities to be exponentially distributed [16], [37], [38], [39], [40]. We consider the commonly used primary activity ON-OFF model [41]. 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 duration 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

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

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

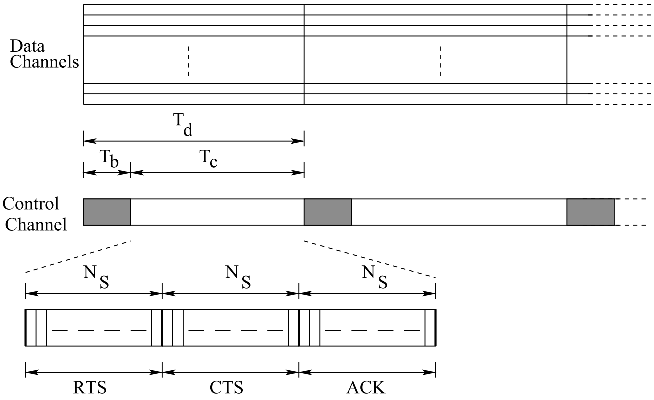

Fig. 1. MAC frame structure.

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

4 The Proposed MAC Protocol

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

4.1 The Frame Structure

We assume that there is one common control channel that is used for the beacon broadcasts by the sensor as well for the contention among the secondary nodes. 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 secondary nodes are assumed to be of fixed duration of one data slot.

4.2 The Contention Process

The secondary users 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, a secondary user 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, a RTS mini-slot is successful, if one and only one secondary user contends on that mini-slot, just like a successful transmission in slotted-ALOHA.

Upon receiving a successful RTS from a transmitting secondary user, the intended receiver transmits CTS in the *same mini-slot in 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 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. The NAV also contains the category of the secondary based on its priority/demand for multiple data-slots reservation discussed in Section 6.

Later this paper, we will show how the optimal length of the contention window, i.e., effectively N_S is determined by factors like probability of available channels, number of contending secondaries etc. If the optimal N_S is fixed for the lifetime of the network, then it can be easily programmed in the system. However, for more dynamic N_S, an estimated N_S can be designed and included in the beacons.

4.3 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, where N_A is defined as the number of available 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 informs others 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., they run out of data channels). After the data channels are grabbed, the secondary transmitters start transmission on the channel grabbed in the next data slot.

4.4 Mode of Operation

The design of the MAC protocol 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 mode depends on the traffic of secondary users contending for mini-slots. Further insight on the mode selection is given in Section 4.5. However, a secondary user transmitting through multiple data slots needs to listen to the beacons following every data slot in order to make sure the channel is still free from primary activity. If a primary arrives on a data channel *during an ongoing secondary transmission*, then the secondary user 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.

We assume, the structure of control frames is derived from the typical RTS/CTS/ACK frame structure used in IEEE 802.11 MAC. A 20 byte long RTS frame and 14 bytes long CTS frame are similar to typical 802.11 MAC structure. Only the ACK frame has an extra byte to denote the channel ID to make it 15 bytes long.

4.5 Design Optimizations

So far, the discussion on the design of the MAC protocol has been on its working principle. To achieve the best performance, some of the protocol design parameters need to be optimized, which are discussed here.

Length of contention window. The length of the contention window (effectively $3N_S$) is determined by the number of mini-slots N_S when we assume that each mini-slot duration is fixed. It is easy to see that, if the length of contention window is too small, then the RTS contention probability will be high, thus adversely affecting the number of winning secondaries thereby decreasing the secondary utilization. However, longer contention window will waste the available channels for longer periods and increase the probability of primary arrival. Thus an optimal N_S is required considering several system variables and optimizing either secondary usage or primary interference or both.

One versus multiple data slots. Once a data channel is successfully acquired and transmission begins, the question that arises is whether the transmitting node should relinquish the channel after one data slot or should use the same channel for multiple successive data slots. If multiple data slot transmission is allowed, then how many can be reserved at a time? The answer is a determinant of the net utilization of the available channels. It is intuitive that low secondary activity would allow longer retention of the data channels. With increase in secondary activity, the number of data slots that can be reserved should decrease. However, later we will observe that there exists a convexity of the probability of winning the contention with the number of contenders. Therefore, with very high secondary activity, the number of contention winners becomes less and less number of data slot reservation will lead to inefficient utilization in such cases. Thus, the number of data slots reservation should be a function of the number of secondary users winning the contention.

5 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.

Definition 1 (RTS Success Probability). *This is the probability of successfully winning a RTS mini-slot by any secondary node.*

Definition 2 (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).*

Definition 3 (Blocking Probability). *The blocking probability is defined as the probability that a contending secondary will be deprived of a channel even after winning the contention. This is calculated as the ratio of total deprived or blocked winners to the total number of contending secondaries in the contention window.*

Definition 4 (Secondary usage). *Secondary usage is the number of channels that are successfully utilized by the secondary users without any interruption from primary nodes for at least one data transmission slot.*

Definition 5 (PU QoS degradation). *We define PU QoS degradation as the amount of time the primary user experiences interference from any secondary node either continuously or intermittently, i.e., the time after which the primary does not perceive any interference from secondaries whatsoever.*

TABLE 1
Notations Used

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
N_{DS}	Number of consecutive data-slots reserved by a winning SU
$\bar{t}_{ON}$	Average PU ON time per contention window ($=1/\lambda_p$)
$\bar{t}_{OFF}$	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 secondaries contending per RTS window

5.1 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. As already mentioned, the ON and OFF duration are exponentially distributed random variables. Using the Gilbert-Elliott 2-state classical Markov model, we get,

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

Therefore, the average number of available channels in the system N_A is expressed as $N_A = p_{idle} \times N_T$, where N_T is the total number of channels in the system.

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

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

The commonly used notations are shown in Table 1.

5.2 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 during a slot. With secondary users generating request at a rate of λ_s per RTS mini-slot, the RTS success probability is given by $p_s = \lambda_s e^{-\lambda_s}$, where $\lambda_s = \frac{\Lambda}{N_S}$.

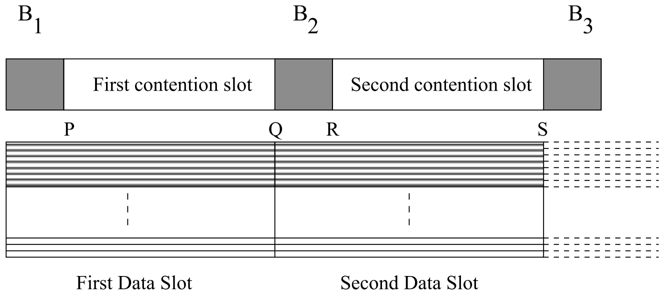

Fig. 2. Consecutive data and contention slots.

In order to find the condition for maximum number of contention winners, we equate the derivative of success probability to 0, i.e., $e^{-\lambda_s}(1-\lambda_s)=0$, resulting in $\lambda_s=1$ Therefore, the maximum success probability is achieved when $\Lambda = N_S$.

5.3 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.

$$N_{SW} = N_S \times p_s. \tag{5}$$

Therefore, the expected number of channels grabbed by the secondaries in a contention window (N_{CG}) is the minimum of N_{SW} and N_A. Thus,

$$\text{E[Idle channel grabbing]} = N_{CG} = \begin{cases} N_{SW} & \forall\, N_{SW} \leq N_A, \\ N_A & \text{otherwise.} \end{cases} \tag{6}$$

5.4 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 expected number of slot winners is N_{SW}. When $N_A \geq N_{SW}$, then blocking probability is 0 as all N_A winners are bound to grab channels. However, for $N_A < N_{SW}$, only the first N_A winners will grab channels and the remaining $N_{SW} - N_A$ winners will be blocked. Therefore the average blocking probability of the system is,

$$\text{BP} = \begin{cases} 0 & \forall\, N_A \geq N_{SW}, \\ \frac{N_{SW}-N_A}{\lambda_s \times N_S} & \text{otherwise.} \end{cases} \tag{7}$$

TABLE 2
PU Arrivals and Corresponding Channel Grabbing and Secondary Usage

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

5.5 Secondary Usage

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 secondary user. 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 2, 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 secondary usage. We also point out the idle channel grabbing and possible usage in such scenarios.

The probability of no primary interruption from the start of the second data slot (time Q) till the end of that slot (time S), P', is given by,

$$P' = \text{Prob}\{\text{Case 5}\} + \text{Prob}\{\text{Case 6}\}. \tag{8}$$

Detailed calculation of P' can be found in Appendix.

Therefore,

$$\text{E[Secondary usage]} = N_{CG} \times P'. \tag{9}$$

Later in Section 7, we use Eq. (9) to evaluate the optimal N_S in order to maximize the utilization. Possible values of N_S and other design variables are also evaluated.

5.6 PU QoS Degradation

When a PU initiates transmissions on its licensed channel, there can be two arrival scenarios for the PU: either during a contention slot or during a data slot. These scenarios lead to different degradation depending on the presence of secondary nodes on that channel. We illustrate the PU degradation scenarios using Fig. 2.

Case 1. PU arrives during the contention slot between P and Q in Fig. 2. In such a case the PU will find the channel to be free as contention for that channel is going on among the secondary nodes. However, depending on the result of contention, the channel may be used by a secondary for T_d duration (from Q to S) causing PU degradation (average value $\frac{T_c}{2}+T_d$) or may not be used at all with no PU degradation. It is to be noted that such PU arrival will be reflected in beacon B_2 resulting the channel being vacated by secondary beyond S.

Case 2. PU arrives at any time during the data slot (between Q and S in Fig. 2). The channel can be either free or busy resulting in no or some degradation (average value $\frac{T_d}{2}$) respectively.

In order to evaluate the expected PU QoS degradation (D_{PU}), we first calculate the probabilities of the above two scenarios. The probability of PU arriving between P and Q is given by,

$$\begin{aligned} P_{PU}^{P\to Q} &= \text{Prob}\{\text{z} \leq T_c\} \\ &= 1 - \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)}. \end{aligned} \tag{10}$$

Similarly, the probability of PU arriving between Q and S is given by,

$$P_{PU}^{Q\to S} = 1 - \frac{\lambda_p e^{-\mu_p T_d} - \mu_p e^{-\lambda_p T_d}}{(\lambda_p - \mu_p)}. \tag{11}$$

As degradation occurs only when a secondary nodes grabs the PU channel, we need to find the probability of a secondary node grabbing such a channel (either Case 1 or 2). The events of PU arrival on a channel and secondary node winning the contention and grabbing the same channel are mutually independent. Thus,

Prob{Secondary grabbing a channel | PU arrival on the same channel} = Prob{Secondary grabbing a channel}. Therefore probability of secondary grabbing a channel (P_{SU}) is expressed as,

$$\begin{aligned} P_{SU} &= \text{Prob}\{\text{SU winning any slot } k\} \times \text{Prob}\{k \leq N_A\} \\ &= p_s \times \begin{cases} 1 & \forall N_A > N_S, \\ \sum_{k=1}^{N_A} \binom{N_A}{k} \left(\frac{1}{N_S}\right)^k \left(1 - \frac{1}{N_S}\right)^{N_A - k} & \text{otherwise.} \end{cases} \end{aligned} \tag{12}$$

Therefore, the expected PU QoS degradation D_{PU} is expressed as,

$$\begin{aligned} D_{PU} &= \text{E[PU deg. for Case 1]} \times P_{PU}^{P\to Q} \\ &\quad + \text{E[PU deg. for Case 2]} \times P_{PU}^{Q\to S} \\ &= \big[\text{E[PU deg. when ch. is grabbed]} \times P_{SU} \\ &\quad + \text{E[PU deg. when ch. is free]} \times (1 - P_{SU})\big] P_{PU}^{P\to Q} \\ &\quad + \big[\text{E[PU deg. when ch. is grabbed]} \times P_{SU} \\ &\quad + \text{E[PU deg. when ch. is free]} \times (1 - P_{SU})\big] P_{PU}^{Q\to S} \\ &= \left[\left(\frac{T_c}{2} + T_d\right) \times P_{SU} + 0 \times (1 - P_{SU})\right] P_{PU}^{P\to Q} \\ &\quad + \left[\frac{T_d}{2} \times P_{SU} + 0 \times (1 - P_{SU})\right] P_{PU}^{Q\to S} \\ &= P_{SU}\left[\left(\frac{T_c}{2} + T_d\right) \times P_{PU}^{P\to Q} + \frac{T_d}{2} \times P_{PU}^{Q\to S}\right]. \end{aligned} \tag{13}$$

5.7 Effects of Sensing Error

When a sensor node fails to detect the presence PU on a channel, the channel is denoted as free in the subsequent beacon to the SUs. Failure to detect primaries on a channel might result in interference with the primaries if secondaries were to start transmission on that channel. To measure to what extent primary QoS is degraded, we assume p_{err} to be the probability of primary detection failure. We assume this to be same for all the channels. Such a sensing error leads to a collision between primary and secondary transmission only if that particular channel is grabbed by a SU transmitter-receiver pair and the PU continues to use the channel beyond the contention window following the beacon. We define P_{int} as the probability of interference caused to an ongoing PU transmission by SUs due to sensing error. Therefore,

$$\begin{aligned} P_{int} &= p_{err} \times \text{Prob}\{x > T_d\} \times P_{SU} \\ &= p_{err} \times e^{-\lambda_p T_d} \times P_{SU.} \end{aligned} \tag{14}$$

Expected PU degradation on a channel due to sensing error assuming there is always a SU communication on that channel is expressed as,

$$\begin{aligned} D_{PU}^{err} &= p_{err}(\text{Prob}\{\text{PU leaves before SU starts}\}\text{E[PU deg.]} \\ &\quad + \text{Prob}\{\text{PU stays beyond SU starts}\}\text{E[PU deg.]}) \\ &= p_{err}(\text{Prob}\{x \leq T_d\} \times 0 + \text{Prob}\{x > T_d\} \times T_d/2) \\ &= p_{err} \times e^{-\lambda_p T_d} \times T_d/2. \end{aligned} \tag{15}$$

6 Differential QoS through Multiple Slots Reservation

In this section, we determine the relation between the number of contention winning secondary users and the number of successive data-slots to be reserved by each winning secondary user. Utilization of an idle channel is evaluated for both single and multiple data-slots reservation scenarios.

6.1 Multiple Data-Slots

The secondary users always have to resort to the content process irrespective of their traffic intensity. For low loads, i.e., when there are plenty of data slots for the contending secondary users, it does not make sense for the secondary users to contend for each and every data slot. The possibility of reserving consecutive data slots by a secondary user eradicates the need for slot by slot contention. In terms of utilizing channel idle time, such reservation ensures utilization for at least that many data slots. The number of data slots to be reserved depends on the number of secondary users that have won the contention rather than the total number of contending secondaries. A secondary user can easily gauge the number of winners in a contention window by the number of NAVs received in the ACK window. Using number of contenders as a metric to reserve multiple slots can be misleading as higher number of contenders does not necessarily mean higher number of winners. It is the winners who have the prerogative of utilizing the idle channels.

The designed multiple slot reservation scheme serves three purposes: it is fair to the contention winners,

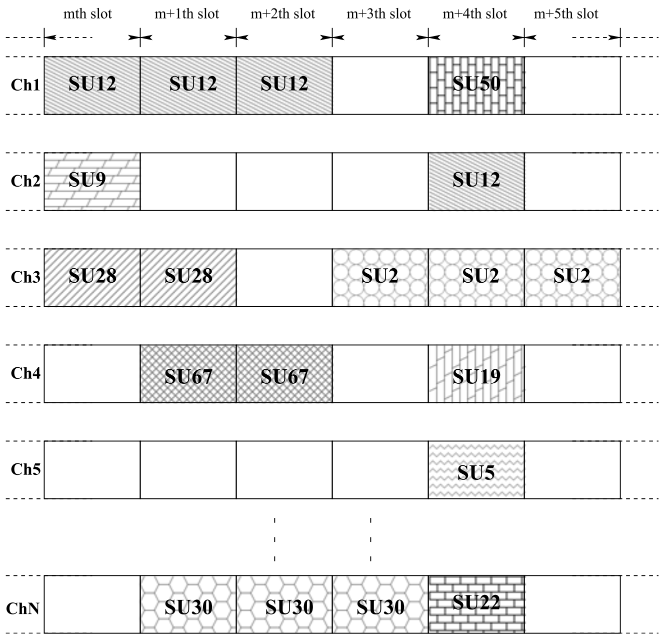

Fig. 3. A scenario with multiple data-slots reservation.

maximizes idle channel utilization and minimizes signaling overhead. A slotted ALOHA like contention process incurs such signaling overhead when the secondary users have to resort to contention irrespective of their load/traffic intensity. By allowing secondaries to reserve channels for multiple data slots we save multiple such contentions, thereby saving signaling overhead.

When $N_{SW} \geq N_A$, the number of winners are more than the number of channels available. Therefore, not all the contention winners get channels, i.e., only the first N_A winners are allowed to grab channels. In such cases, to ensure fairness, the winning secondary users are allowed to use the free channels only for one data slot. The right to use the channels for the next data slot is determined by another contention.

In case of $N_{SW} < N_A$, i.e., when there are less winners than available channels, each winner is allowed to reserve channel for $\lfloor N_A/N_{SW} \rfloor$ slots. Therefore, the number of data slots reserved by a winning secondary, N_{DS} is given by,

$$N_{DS} = \begin{cases} 1 & \forall\ N_{SW} \geq N_A, \\ \left\lfloor \frac{N_A}{N_{SW}} \right\rfloor & \text{otherwise.} \end{cases} \tag{16}$$

6.2 Differential QoS

Sometimes it is required to allow unequal share of the idle channels to different secondary users. Such differential QoS is necessitated when secondaries have different bandwidth requirements. In our proposed MAC protocol such differential QoS is manifested through reservation of data channels for multiple slots rather than allowing secondaries reserve multiple data channels. However, unlike allowing all the winning secondaries to reserve same number of channels (i.e., concept discussed in Section 6.1), we allow the secondaries to reserve slots according to their demands or priorities.

Let us assume that there are k classes of secondaries in the system with $w_1, w_2, \ldots w_k$ being their priorities/demands based on the MAC design. Our work is flexible to such categorization; these k classes along with their priorities can be either pre-determined or dynamic and based on the demand of the winning secondaries. In the latter case, the winning secondaries advertise their demands (w_i) in the NAVs. We assume that the number of winners in class i is n_i, i.e., $\sum n_i = N_{SW}$. The number of data slots reserved by a winning secondary in class i, is given by,

$$N_{DS}^i = \begin{cases} 1 & \forall\ N_{SW} \geq N_A, \\ \left\lfloor N_A \times \frac{w_i}{\sum w_i n_i} \right\rfloor & \text{otherwise.} \end{cases} \tag{17}$$

The relation between Equations (16) and (17) is given as,

$$N_{DS} = \frac{\sum N_{DS}^i}{N_{CG}}. \tag{18}$$

Fig. 3 shows an illustrative example with multiple data slots reservation provisioning. We see that in the mth data slot there are three winners who grabbed channels. However, due to differential QoS provisioning, $SU12$, $SU28$ and $SU9$ reserve three, two and one data slots respectively. In the $(m+1)$th data slot we see $Ch4$ and ChN are grabbed by new winners of the previous (mth) contention slot and are allowed to reserve the channel for different duration. In $(m+4)$th slot, there are more winners in comparison to previous slots and $N_{SW} \geq N_A$ condition is satisfied. Therefore, all the channels are grabbed by secondaries and each is allowed to use the channel for only a single slot. However, $SU2$ is allowed to continue using $Ch3$ for the duration reserved in $(m+3)$th slot.

6.3 Idle Channel Utilization

Idle channel utilization is defined as percentage of the channel idle time that is utilized by a secondary. Therefore, the steady state idle channel utilization is the number of data slots reserved as a fraction of total available channels, i.e.,

$$\text{E[Idle Channel Utilization]} = \frac{N_{DS} \times N_{CG}}{N_A}. \tag{19}$$

We compare idle channel utilization for both single and multiple slot reservation scheme in Section 7 and show almost 100 percent utilization through multiple slots reservation.

It is to be noted that the proposed MAC protocol also ensures fairness among the contending SUs. If classes of SUs are not considered, then all the SUs are subject to the same environment and in the long run, all will observe the same success rate. When classes are considered, the higher classes are allocated multiple data slots *only when the load is low*, i.e., multiple slots are not allocated by sacrificing others. Also, the differential QoS provisioning categorizes the SUs according to their demands. More successive data slots are given to only those winners who ask for more. Therefore, the MAC does not treat any contending SU unfairly or preferentially.

7 Performance Evaluation

We conduct numerical simulation in MATLAB to evaluate the proposed MAC protocol. We then compare our results against selected state of the art cognitive MAC protocols. As inputs, we assume $N_T = 30$, $T_b = T_c/100$ unless stated otherwise. We vary p_{idle} from 0.3 to 0.9 and

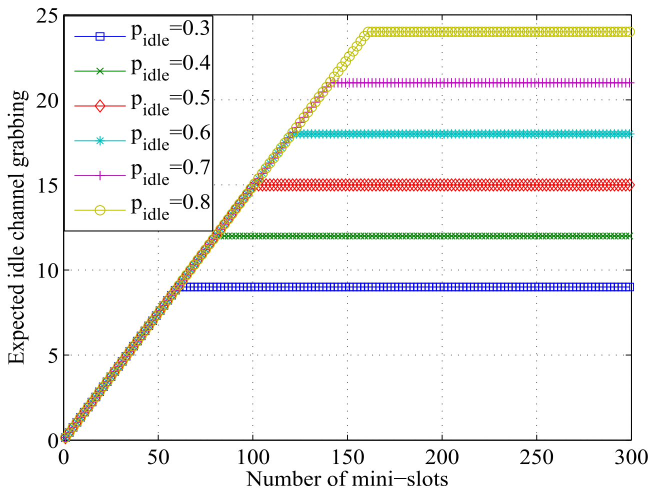

Fig. 4. Idle channel grabbing characteristics, with $N_T = 30$ and $\lambda_s = 3$.

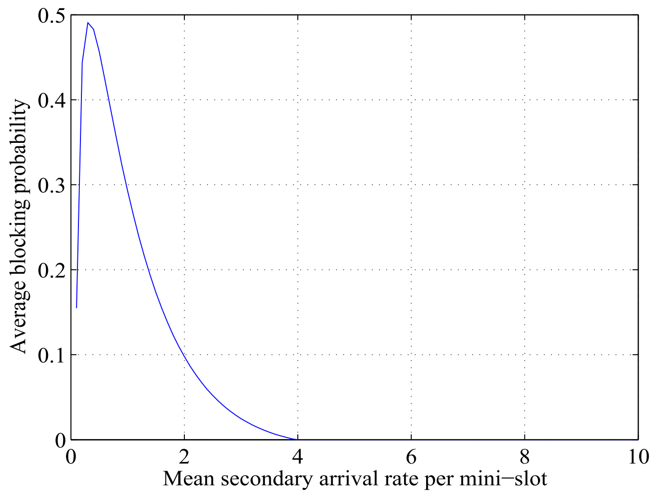

Fig. 6. Average blocking probability with $N_T = 30$, $N_S = 200$, $p_{idle} = 0.5$.

assume varied range of λ_s to emulate low and high density of secondary contenders.

Channel grabbing. It is intuitive that channel grabbing and secondary usage will be maximum at peak value of the number of contention winners. Therefore, for the aforementioned performance metrics, we simulate their characteristics at a non-peak value of p_s, i.e., at $\lambda_s \neq 1$.

In Fig. 4, we investigate the nature of expected idle channel grabbing against the number of mini-slots for 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. 5, we show how idle channel grabbing varies with the rate of secondary contention per mini-slot. The nature mimics typical slotted-ALOHA throughput curve. Higher probability of p_{idle} results in higher peak value of N_{CG}. Here we keep N_S fixed at 100.

Blocking probability. The nature of average blocking probability with mean secondary arrival rate, λ_s, is shown in Fig. 6. We see that the convexity mimics the nature of exponential distribution with average blocking probability peaking at a certain λ_s and then exponentially decreasing. This characteristic can be attributed to the fact that for a certain number of N_A, when the total number slot winner N_{SW} reaches the peak, blocking probability is also has the maxima at that point as maximum number of winners are blocked at that λ_s. However with more contending secondaries, we have less winners due to contention resulting in a sharp decline in average blocking probability.

In Fig. 7, 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 value is zero as *all* the winning secondaries are able to grab channels. After a certain N_S, when total number of winning mini-slots go beyond N_A (for a particular p_{idle}), average blocking probability becomes non-zero. The average blocking probability continues to increase with N_S till it reaches the saturation point when most of the winning secondaries are blocked. With higher p_{idle}, such saturation point for average blocking probability is reached at a higher N_S and also has a lower peak value as an increased N_A results in more winning secondaries to grab channels.

Secondary usage. Nature of secondary usage with number of mini-slots is demonstrated in Fig. 8. We see that with the

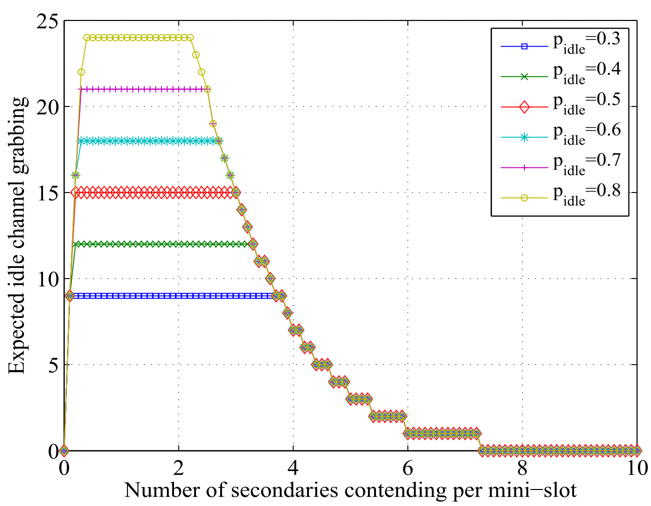

Fig. 5. Idle channel grabbing characteristics with $N_T = 30$ and $N_S = 100$.

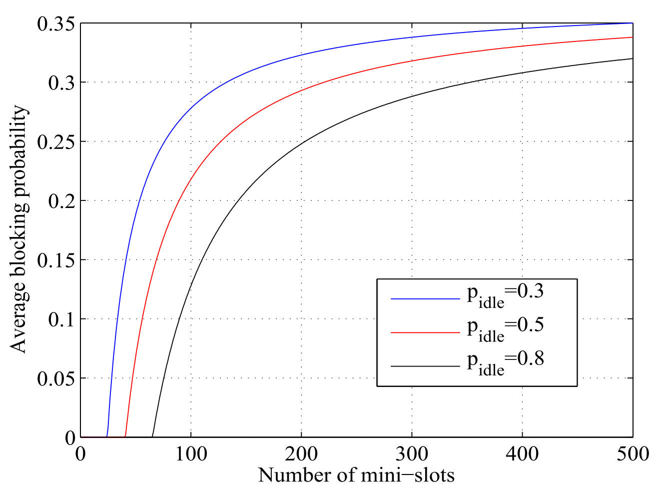

Fig. 7. Average blocking probability with $N_T = 30$, $\lambda = 1$.

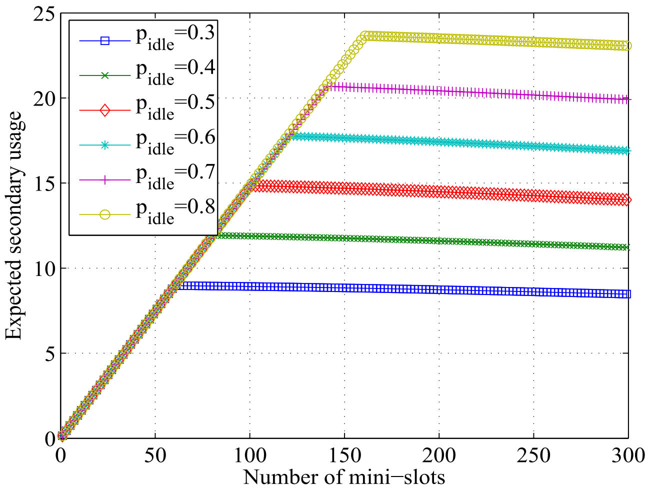

Fig. 8. Average secondary usage with $N_T = 30$ and $\lambda_s = 3$.

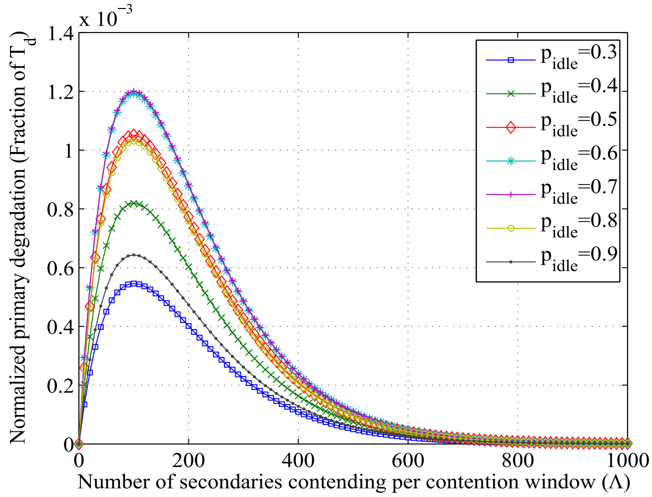

Fig. 10. Expected PU degradation with $N_T = 30$ and $N_S = 100$.

increase in number of mini-slots, the usage increases linearly till it reaches the inflection point. The existence of the maxima for a particular p_{idle} is a measure of the optimal number of slots for the system. Such convexity exists because larger contention window leads to higher probability of primary arrival (higher value of $\bar{P}_{PU}^{P\rightarrow S}$)and thus less usage. For example, when $p_{idle} = 0.6$, the optimal N_S is around 120 for maximum secondary usage.

In Fig. 9, we see that the nature of secondary usage with varying number of secondaries is similar to that of channel grabbing in Fig. 5. However the peak value of average secondary usage for each p_{idle} is less than that of average channels grabbed as some channels will encounter interference from primaries.

Primary degradation. In Fig. 10, we show how PU QoS degradation varies with number of secondary users contending per contention window. We see that the normalized peak value of the degradation is very small. We also notice that the maxima are obtained at $\Lambda = N_S = 100$ for all values of p_{idle}. At $\Lambda = N_S$, we have maximum RTS success. This signifies maximum channel grabbing and eventual peak usage resulting peak PU degradation.

In Fig. 11, we see that with varying number of mini-slots the average PU degradation increases linearly and then slowly starts to decrease. We notice the peak value for all p_{idle} values occurring at the same value of N_S. However, this critical value of N_S is much higher that the optimal N_S obtained from Fig. 8 for maximum utilization.

Effect of sensing error. Effects of sensing error on probability of interference to ongoing PU transmission is shown in Fig. 12. The figure shows the nature of P_{int} from Eq. (14) with varying p_{err}. We observe than even with relatively high probability of sensing error 0.1, the chances of a secondary interfering with an ongoing primary communication is relatively small (in the order of $10^{-}3$). Later in Fig. 17, we will show how ensuing quantitative PU degradation fares with other state of the art MAC protocols.

Multiple slots reservation. Consequences of multiple data slots reservation are demonstrated in Figs. 13 and 14. In Fig. 13, the number of data slots reserved N_{DS} by each winning secondary is shown for different λ. The magnified section (values 0-10) shows that for $\Lambda < 10$, each winning SU is allowed to reserve more than one data slots. This is because in this case $N_{SW} < N_A$. However for the region $10 \leq \Lambda < 400$, $N_{SW} < N_A$ and therefore each winning SU is given only one data slot. Beyond $\Lambda = 400$, because of large number of average contending SUs per mini slot, the

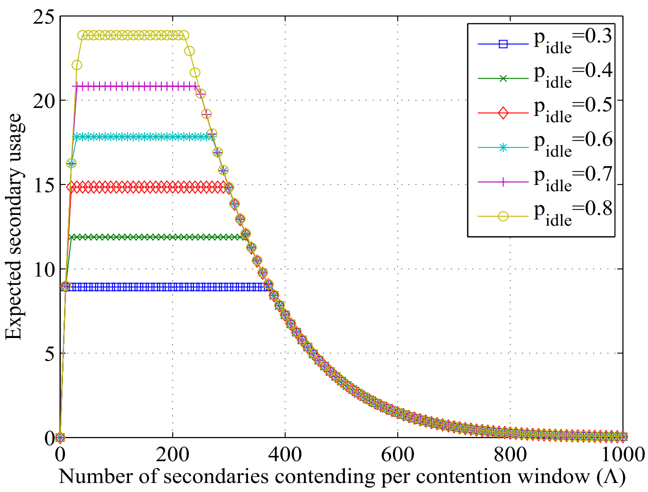

Fig. 9. Average secondary usage with $N_T = 30$ and $N_S = 100$.

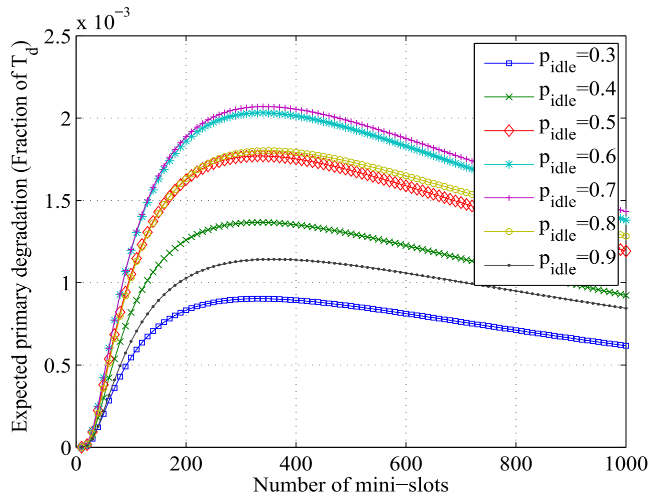

Fig. 11. Expected PU degradation with $N_T = 30$ and $\Lambda = 100$.

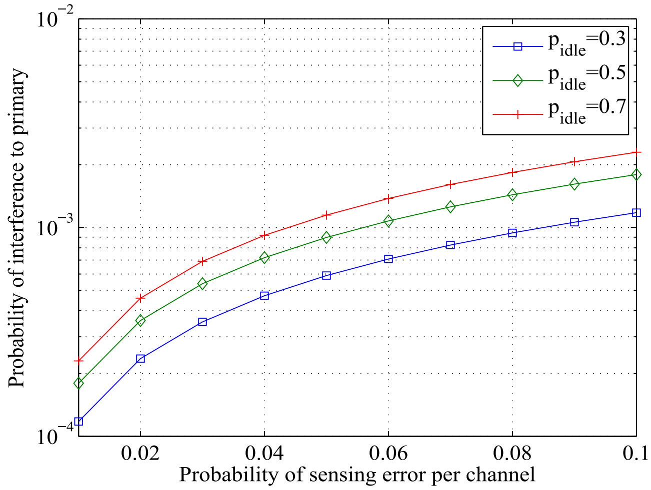

Fig. 12. Probability of interference to ongoing PU transmission due to sensing error with $N_T = 30$ and $N_S = 100$.

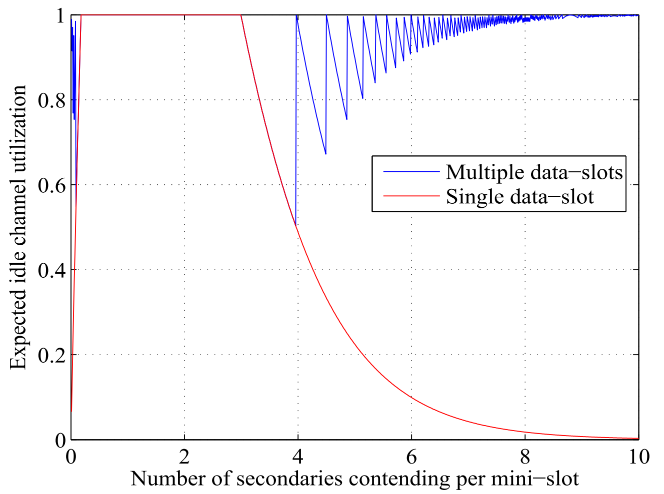

Fig. 14. Average idle channel utilization for single and multiple data-slots with $N_T = 30$ and $N_S = 100$.

expected number of contention winner N_{SW} comes sharply below N_A and each winning SU is given more data slots.

Comparison between idle channel utilization for single and multiple data slot reservation schemes is shown in Fig. 14. We see that multiple slot is either better or same in terms of utilization for all the values of λ_s and therefore λ as well. Single slot scheme looses ground when there are too many contenders and therefore less winners. However, multiple slots scheme ensures almost 100 percent utilization for all values of λ. The instances where utilization is lower is because of the floor function in Eq. (16). Although theoretically multiple slots should ensure complete utilization, we are wasting some idle channel time for indivisibility of data channels.

Performance comparison. We compare the performance of our proposed scheme with two of the latest MAC schemes, opportunistic sensing based MAC (OS-MAC) [16] and OMC-MAC [11]. Both these work consider common control channels for control messaging and claim better performance than other existing schemes in the literature. For the comparison, we keep $p_{idle} = 0.5$ for all schemes and $N_S = 100$.

In [16], the authors evaluated the performance of their proposed scheme through implementing the OS-MAC in their simulation environment. In Fig. 15, we compare the steady state throughput of our proposed scheme with that of OS-MAC shown in [16, Fig. 8]. For fairness of comparison, we assumed $N_T = 40$, $\bar{t}_{ON} = \bar{t}_{OFF} = 300\,\text{s}$, and transmission rate for data channel to be 1 Mbps. These values are same as what were used in [16]. The figure shows that the proposed scheme clearly outperforms OS-MAC in terms of steady state throughput.

In Fig. 16, we compare the average secondary usage of our proposed scheme with OMC-MAC against different number of secondary users contending per contention window. For OMC-MAC, we used the values of T_{BI}, t_{DIFS}, t_{SIFS}, σ, P_t, T_{spc} and T_{con} equal to the values used in [11]. We compare our results with OMC-MAC having variable T_{DT} as that is proved to be better performing than fixed T_{DT}. We see that for different values of N_T, our proposed scheme performs better than OMC-MAC not only in terms of number of channel utilized, but also OMC-MAC has higher decay with more channels in the system. This happens because in OMC-MAC, sensing of channels is performed in

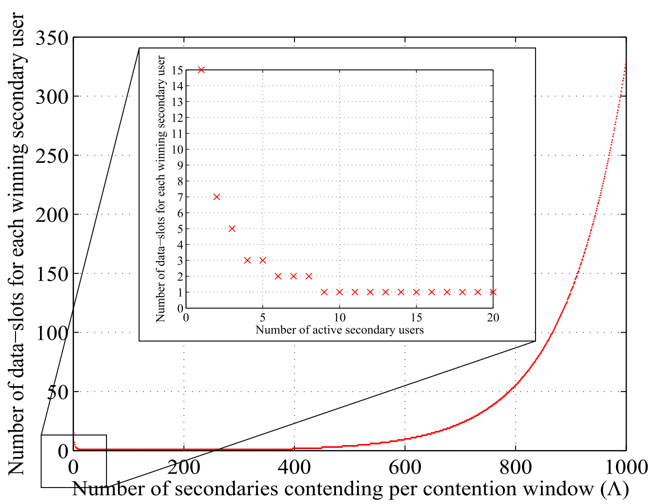

Fig. 13. Number of successive data-slots reserved by winning SUs with $N_T = 30$ and $N_S = 100$.

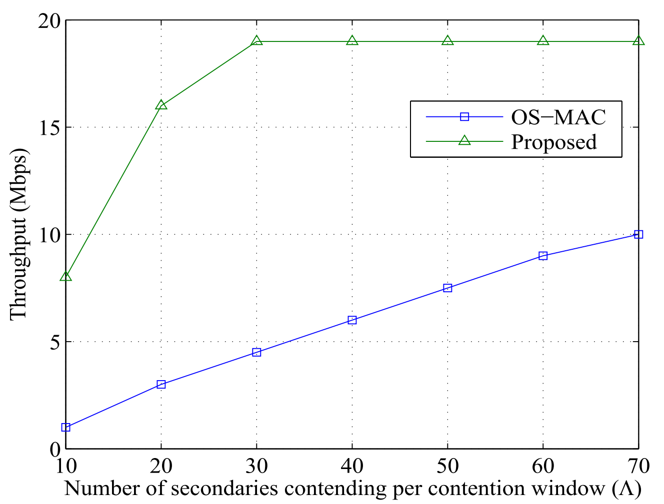

Fig. 15. Throughput comparison with OS-MAC with $p_{idle} = 0.5$, $N_T = 40$ and $N_S = 100$.

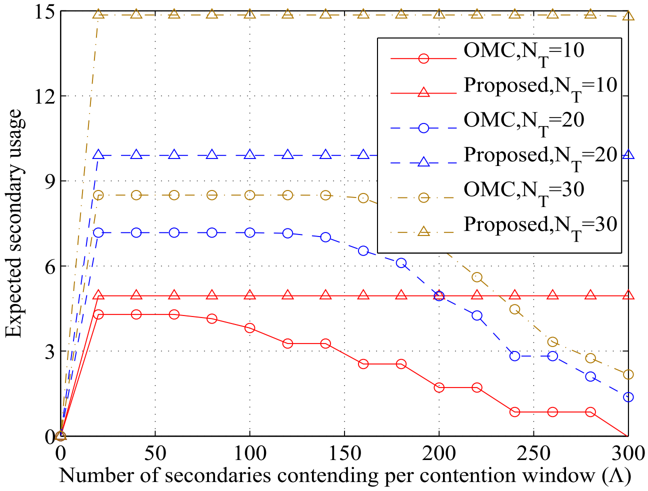

Fig. 16. Expected secondary usage comparison with OMC-MAC with $p_{idle} = 0.5$ and $N_S = 100$.

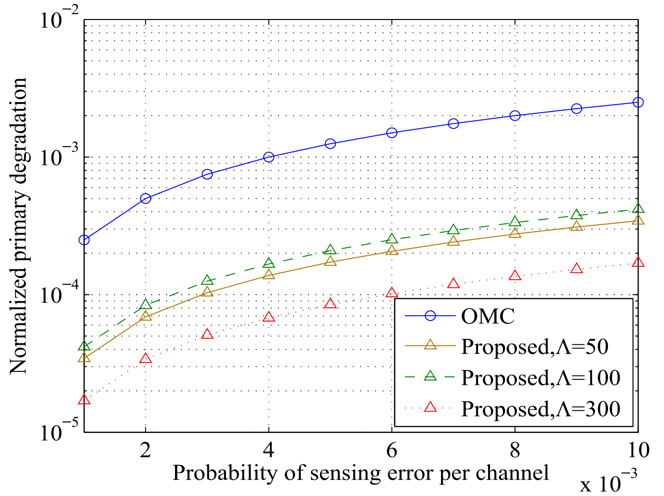

Fig. 17. Normalized primary degradation comparison with OMC-MAC with $p_{idle} = 0.5$, $N_T = 25$ and $N_S = 100$.

the same cycle of beacon interval with contention and transmission. Such serialization takes its toll on the average secondary usage when there are more channels to scan as the sensing takes up considerable time from beacon interval duration.

Fig. 17 compares the proposed MAC protocol with OMC-MAC in terms of normalized primary degradation against varying probability of sensing error. Primary degradation in our proposed MAC is a function of Λ, whereas, OMC-MAC is not. Therefore, we show the nature of primary degradation for different Λ values. We observe that although the degradation in OMC-MAC does not depend on Λ, the normalized primary degradation in our proposed scheme for different Λ values is much less than that of OMC-MAC. Therefore, our proposed MAC outperforms OMC-MAC in terms of primary degradation caused by sensing error.

To summarize, the results section showed the nature of channel grabbing, blocking probability, and secondary usage with N_S. We have shown how optimal N_S can be evaluated by maximizing secondary usage and minimizing primary degradation. The effect of sensing error on probability of interference to primaries is also shown. We also demonstrated how the proposed protocol performs better than state of the art MAC protocols in terms of secondary usage and primary degradation.

8 Conclusions

In this paper, we present a MAC protocol for secondary users in a distributed cognitive radio networks who contend among themselves for accessing data channels not being used by the primaries. We de-couple the sensing mechanism from reception and transmission by having fixed dedicated sensors that are responsible for detecting presence of primaries in various channels and broadcasting that information to secondary users. The proposed protocol is flexible enough to use either distributed spectrum sensing or referring to a spectrum map/databse for such primary detection. Through a contention-based signaling comprising RTS, CTS, and ACK, the users get access to available data channels. The proposed protocol is flexible enough to allow multiple classes of secondary users and takes into consideration, different QoS criteria, which include primary user service interruption rate, secondary user interruption rate, and blocking probability. Through simulation experiments, we show that the proposed scheme outperforms existing MAC schemes in terms of system throughput and average channel utilization. The proposed MAC protocol is also more robust to misdetection of primaries than other popular MAC schemes.

Appendix

$$
\begin{aligned}
P' &= \text{Prob}\{\text{Case V}\} + \text{Prob}\{\text{Case 6}\} \\
&= \text{Prob}\{\text{PU arrives after P and leaves before Q}\} \\
&\quad + \text{Prob}\{\text{PU does not arrive between Q and S}\} \\
&= \text{Prob}\{\text{PU arrival} + \text{ON duration} \le T_c\} \\
&\quad + (1 - \text{Prob}\{\text{PU arrival} \le T_d\}) \\
&= \text{Prob}\{\text{z} + \text{x} \le T_c\} + (1 - \text{Prob}\{\text{z} \le T_d\}) \\
&= \int_0^{T_c} \frac{\lambda_p \mu_p}{\lambda_p - \mu_p} [e^{-\mu_p z} - e^{-\lambda_p z}] \int_0^{T_c - z} \lambda_p e^{-\lambda_p x} dx dz \\
&\quad + \left(1 - \int_{-\infty}^{T_c} \frac{\lambda_p \mu_p}{\lambda_p - \mu_p} [e^{-\mu_p z} - e^{-\lambda_p z}] dz\right) \\
&= \frac{\lambda_p \mu_p [e^{-\lambda_p T_c} - e^{-\mu_p T_c}]}{(\lambda_p - \mu_p)^2} - \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)} \\
&\quad + \frac{\lambda_p \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)} + \frac{\lambda_p e^{-\mu_p T_d} - \mu_p e^{-\lambda_p T_d}}{(\lambda_p - \mu_p)}.
\end{aligned}
$$

Acknowledgments

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