Stochastic Model Based Opportunistic Channel Access in Dynamic Spectrum Access Networks

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Abstract—We present a stochastic model-based opportunistic channel access and transmission scheme for cognitive radio enabled secondary users for single data channel. We refer to this scheme as Residual Idle Time Distribution based Scheme (RIBS). In this scheme, the SU randomly senses the channel and if the channel is sensed idle, then it uses residual idle time distribution to estimate its transmission duration such that the probability of its interference with PU is below a predefined threshold. We derive analytical formulae for various performance metrics of SU and validate them through simulations. Simulation experiments are conducted for two different scenarios. In the first scenario, we use synthetically generated channel occupancy data due to PU transmissions using two standard distributions (2-phase Erlang and Uniform distribution). In the second scenario, we use data collected by simulating a TDMA-based PU network that runs realistic applications (VoIP and Web browsing). A pair of sender and receiver SU uses RIBS to opportunistically transmit on the channel. Our simulation experiments show that SU can use RIBS to opportunistically transmit on the channel without violating the interference probability constraint. We also list some of the challenges in using RIBS in realistic scenarios, and provide a comprehensive methodology to use RIBS in such scenarios.

Index Terms—Dynamic spectrum access, opportunistic spectrum access, cognitive radio, MAC

1 Introduction

Dynamic Spectrum Access (DSA) has emerged as a promising spectrum sharing paradigm to efficiently utilize the electromagnetic spectrum. In this approach, the unlicensed users (also referred to as Secondary Users or SUs) can dynamically use licensed spectrum band to increase spectrum utilization. One important category of DSA is *interweave* mode (see [1], [2] for complete categorization of DSA models). In interweave mode, which is also known as *opportunistic spectrum access* (OSA), SU uses the spectrum band when PU is absent and vacates it when PU appears on the band. The SUs must also abide by certain Interference Management (IM) policy, which specifies an upper bound on the interference that a PU can tolerate due to SU transmissions. The IM policy should be known *a priori* to both SUs and PUs.

Channel occupancy models (i.e., channel idle and busy time distributions) due to Primary User traffic have recently been used to devise opportunistic channel access schemes for secondary networks. Several authors (for example, [3], [4]) have proposed opportunistic channel access schemes in which SU keeps track of the amount of idle time that has elapsed from the start of current idle cycle in which SU has sensed the channel. It computes the probability of successful transmission of its next frame using the channel idle time distribution, conditioned on the elapsed idle time. The main limitation of such schemes is that the SU needs to continuously sense the channel (irrespective of whether it has frames to transmit or not) in order to keep track of the start of each idle cycle. Continuous sensing of the channel significantly drains the energy of SU over long run, and is not suitable for energy-constrained SU devices. In this paper, we propose a stochastic model based opportunistic spectrum access scheme which can be used by SUs to access primary channel such that the impact on PU is within acceptable limits. There are two main motivations for our work : (1) To increase the utilization of a primary channel by having SUs use the channel within acceptable limits of interference with PU and (2) to reduce the channel sensing overhead of SUs so that the channel access scheme can also be used by energy-constrained secondary networks such as cognitive sensor networks [5], or battery-operated low end wireless devices. The proposed channel access scheme is called Residual Idle Time Distribution based Channel Access Scheme (RIBS). RIBS uses channel's residual idle time distribution to compute transmission duration for an SU such that the probability of interference of SU with PU is below a predefined threshold. The residual idle time distribution is obtained using the known idle time distribution for the channel. RIBS is a non-persistent carrier sensing scheme in which SU does not continuously sense the channel if the channel is busy. Further, RIBS does not require the SU to continuously sense the channel to keep track of start of each idle cycle. Details of RIBS are presented in Section 5.

The main contributions of this paper are as follows:

1) We propose an opportunistic channel access scheme that is based on residual idle time distribution of the channel.

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2) The proposed scheme does not require the SU to continuously sense the channel and also ensures that the probability of interference of SU transmissions with PU is below a predefined threshold. It has low sensing overhead and hence energy efficient.
3) We provide a methodology for opportunistic spectrum access when on-off traffic of PU can be of any general distribution.
4) We use simple backoff scheme to access channel idle periods and specify guidelines in choosing the backoff parameter in different operating scenarios.

2 Related Work

Research in the area of DSA, specifically in interweave mode, got major initial impetus from neXt Generation Communications (XG) program of DARPA [6] and initiatives of Ofcom (spectrum regulatory body in the U.K.) [7]. A number of prior research works have proposed access schemes based on primary channel occupancy models. In [8], authors assume that opportunistic transmission of an SU spans N primary channels and model the complete system state due to operation of PUs as 2^N-state Continuous Time Markov Chain (CTMC). The authors derive the distribution of transmission opportunity (TO) for an SU using lumped Markov chain model and conclude that TO follows Hyperexponential distribution. Geirhofer *et al.* [9] describe that the channel occupancy in a WLAN system can be modeled as a 2-state (ON-OFF) Semi Markov chain but approximate it by a CTMC to simplify analysis.

In [10] and [11], authors propose channel sensing and transmission strategies under the Partially-Observable Markov Decision Process (POMDP) framework, but assume that both Primary and Secondary networks are slotted. In [12], the authors consider an unslotted Primary Network with multiple channels and a slotted Secondary Network, which senses the channels at the beginning of each slot. In [13], authors propose a scheme to compute ON and OFF durations of SU. The SU need not sense the channel at all. Whenever it has frames to send, it transmits for ON duration followed by a silent period of OFF duration. Unlike RIBS, ON and OFF periods for SU in this scheme depends only on mean busy period of PU and is independent of mean idle period of PU.

Recently, Restless Multiarm Bandit formulations are used for opportunistic channel access [14], [15]. These schemes are based on exploration versus exploitation trade off and do not require an SU to know the channel idle and busy period distributions a priori. However, logarithmic bounds for regret in these schemes are shown in the literature only for Markovian and Bernoulli reward distributions. In contrast, RIBS is devised for any general continuous time distribution for idle periods and does not depend on distribution of busy periods. However, RIBS bounds the interference probability to a specified threshold η and is not designed to provide logarithmic bounds. Liang *et al.* [16] propose an adaptive channel sensing scheme to get the best estimate of the parameters of an on-off renewal channel. This scheme is complementary to RIBS and the channel parameter estimation using this scheme can be used in RIBS. In [17], the authors have proposed matrix-analytic method based algorithms for opportunistic spectrum access. This work primarily focuses on the blocking probabilities of Primary and Secondary calls, and the waiting times of an SU call that is preempted due to arrival of a Primary call. In contrast, in our work we focus on how much an SU should transmit every time it senses the channel idle while keeping the probability of interference to PU below a predefined threshold. Instead of matrix-analytic method, we use residual idle time distribution in RIBS. Many of the schemes mentioned above assume exponential distribution for idle and busy time periods for each channel, whereas some other schemes model the state of the complete system consisting of N channels as 2^N-state CTMC. In our work, the proposed channel access scheme RIBS works for any idle time distribution. If the idle time distribution does not have a closed form, then our scheme can be applied after approximating the continuous time distribution by an appropriate Phase Type distribution.

Several schemes proposed in the literature use channel idle time distribution for opportunistic transmissions under interference constraint, which is defined as a part of Interference Management (IM) policy. In [18], authors propose schemes to provide probabilistic outage guarantee to PUs in spatial domain based on power sensing information obtained at the secondary user. In contrast, RIBS enables opportunistic transmission in temporal domain and computes the duration for which SU can transmit before PU appears on the channel so that probability of interference to PU is bounded. In [3], the authors have used empirical PDF and CDF of an idle time data set (obtained using measurement of channel idle periods in simulation) to compute the number of frames that an SU should transmit on sensing a channel idle, subject to a maximum bound on probability of interference of SU frames with PU. In [19] also, the SU determines the optimal transmission duration on finding a channel idle subject to maximum interference probability threshold. Both [3] and [19] assume that start of each idle period is known, and use the channel idle time distribution in their MAC protocol design. In [4], the authors have proposed a cost and reward-based access policy to maximize the secondary network utility. The authors have considered a general PU idle time distribution but assume that the time instant of channel state transition from idle to busy is known, which would require the SU to sense the channel continuously. The RIBS scheme proposed in this paper does not require the SU to continuously sense the channel to keep track of start of each idle period, as it is based on residual idle time distribution of the channel. RIBS enables an SU to opportunistically transmit such that its probability of interference with PU is less than or equal to a predefined threshold.

3 System Model and Assumptions

We consider a hierarchical spectrum sharing paradigm in a wireless network, which consists of a set of PUs and SUs. The SUs operate in interweave mode and should access the channel only when no PU is using the channel. Thus, the SUs have to look for idle periods on the channel and opportunistically transmit their packets. The PUs are not aware of SU's transmission and can initiate their transmission whenever they require. It is SU's responsibility to detect the PU transmission and evacuate the channel. The SUs must also ensure that the probability of interference to any PU due to their transmissions is bounded below a given threshold, denoted as η. Here, probability of interference refers to the probability that SU's opportunistic transmission in an idle cycle interferes with PU. Note that this constraint is imposed from SU's perspective and similar to that used in [3] and [20]. Interference constraint that is defined from PU's perspective is also used in the literature (see [4]). In practice, a service provider would choose one of the two ways based on various factors such as application, Service Level Agreement with PU, etc.

In our work, we make the following assumptions:

1) SU knows η for the channel as well as the channel idle time distribution due to PU transmissions.
2) We consider PU transmission in a single cell scenario, i.e., co-channel and adjacent channel interference due to PU transmissions in other cells are not considered.
3) Channel occupancy distribution and parameters remain stationary (stable) for relatively larger duration than the opportunistic transmission duration of SU.
4) SU performs perfect sensing.
5) PU uses a non CSMA protocol.

The third and fourth assumptions are made to apply model-based channel access scheme and to keep the analytical formulation tractable. We assume that PU uses a non CSMA protocol because of the following reason. A CSMA-based PU senses the channel and backs off if the channel is busy due to some secondary node's transmission. This violates hierarchical model as the PU is forced to wait until SU finishes its transmission, and adversely affects PU's performance such as throughput and delay. However, RIBS can be used with other types of primary networks such as slotted primary networks (Slotted Aloha or TDMA based networks) and unslotted primary networks (such as pure Aloha based networks), without requiring any synchronization with the primary network. This is so because in RIBS, scheduled sensing time of SU need not be aligned to PU slot boundary (if PU network is slotted). If PU appears on the channel in one of its slot while SU is transmitting on the channel, the SU evacuates the channel.

4 Overview of RIBS

In RIBS, whenever an SU has one or more packets for transmission, it generates a channel sensing schedule and finds the time instant at which it will sense the channel[1]. This sensing schedule is generated such that the scheduled sensing happens at random time[2]. The SU waits upto the scheduled time and then senses the channel for a predefined sensing duration. If the channel is sensed busy, the SU backs off and senses the channel again. The backoff duration is generated using Exponential distribution. If the channel is sensed idle, then the SU transmits its frames opportunistically on the channel using RIBS channel access scheme that is described below.

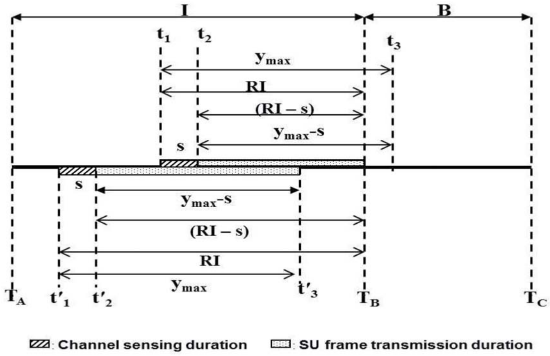

Fig. 1. SU transmission scenarios in the residual idle time of a data channel.

In RIBS, we model the channel occupancy due to PU traffic as an Alternating Renewal Process (ARP). The process alternates between idle and busy states of the channel and renews after each renewal cycle that consists of an idle period followed by a busy period. Hence, we derive and use the *channel residual idle time distribution* based on random incidence in a renewal cycle[3] (see [21, pp. 328–331]). The residual idle time distribution is derived using the known channel idle time distribution of PU traffic. Channel idle and busy time distributions can be any general distribution rather than exponential distribution that is assumed in many works in the literature. Once the residual idle time distribution is computed, the SU computes the maximum duration for which it can use the channel when it randomly senses the channel to be idle. We denote the duration of this whole *transmission operation* by y_{max}. We use the term *transmission operation* by an SU to denote the action of the SU to sense the channel for duration s and then to transmit (possibly multiple frames) for the remaining $(y_{max} - s)$ duration if the channel is idle. The method to compute y_{max} is described in Section 5. The SU transmits these frames within y_{max} duration without any further sensing of the channel, thereby reducing the sensing overhead for each transmitted frame. It waits for an acknowledgment from the receiver for each successfully received frame.

Fig. 1 shows two possible transmission scenarios in residual idle time on a single data channel, one below and one above the central line in the figure. T_A, T_B, and T_c denote respectively the start of an idle period I, end of the idle period (or, equivalently, start of the next busy period B), and end of the busy period within a renewal cycle. In the first scenario, shown below the central line, the scheduled time for the SU to sense the data channel is t'_1. The SU senses the data channel at time t'_1 for a pre-defined sensing duration s (from time t'_1 to t'_2), and since the channel is sensed idle, it transmits frames for a maximum duration of

1. The SU does not immediately sense the channel as soon as it gets a frame to transmit. Instead, it generates a sensing schedule using a scheme that is described later in this section.

2. Random sensing of the channel is required for using RIBS to opportunistically transmit on the channel. Details are given in Section 5.

3. The phrase 'random incidence in a renewal cycle' is used in [21] to denote the random time at which the renewal process is observed.

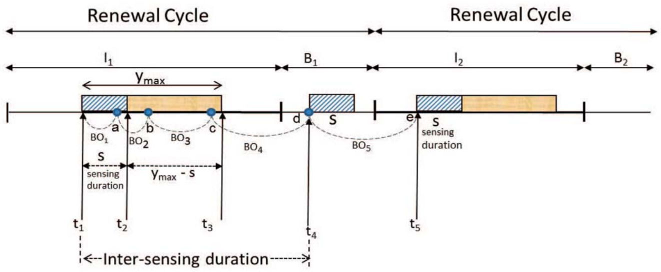

Fig. 2. Channel sensing schedule generation using exponentially distributed backoffs.

$(y_{max} - s)$ (which is equal to $t'_3 - t'_2$)[4]. The duration $(T_B - t'_1)$, represented as RI, denotes the *residual (remaining) idle time* in the cycle, starting from the incidence time t'_1 into the ARP[5]. The duration $(T_B - t'_2)$, represented as $(RI - s)$, denotes the *available residual idle time* in the cycle after the SU has sensed the channel for duration s. Since RI is more than y_{max}, (i.e., $(RI - s)$ is more than $(y_{max} - s)$), the SU successfully transmits for the entire $(y_{max} - s)$ duration. In the second scenario, shown above the central time line, since RI is less than y_{max}, the SU transmits only for $(RI - s)$ duration and collides with the next busy cycle due to PU transmission, thereby interfering with the PU. In both the above cases, if the SU has more frames to transmit, it generates a new sensing schedule for sensing the channel again.

In order to generate sensing schedule, SU generates one or more random backoffs using Exponential distribution, starting from the previous sensing time[6], until it goes past the current time. For example, in Fig. 2, the SU senses the channel for duration s (from t_1 to t_2). Since the channel is sensed idle, the SU transmits frames for $(y_{max} - s)$ duration (from instant t_2 to t_3). It then generates a random backoff value, which we denote by BO_1, using Exponential distribution with mean value $E[BO]$. BO is a random variable that denotes the backoff duration. Starting from the last sensing instant t_1, if BO_1 is large enough to surpass the current time t_3, then it computes the next incidence time as $(t_1 + BO_1)$, which also becomes its scheduled sensing time. However, as shown in the example in Fig. 2, the generated backoff value BO_1 is not large enough to surpass the current time. Therefore, the SU generates multiple backoffs, such as BO_1, BO_2, BO_3 and BO_4, starting from the previous sensing instant t_1, until it surpasses the current time t_3. Points a, b, c, and d denote the incidence times corresponding to these backoffs. t_4 is the next scheduled sensing time. As the channel is sensed busy at t_4 in Fig. 2, the SU generates another backoff value BO_5 and computes the next incidence time as $t_5 = t_4 + BO_5$ (shown as point e). The SU records t_5 as the next scheduled sensing time. The process of generating the sensing schedules is repeated in the manner described above.

There are several important points to be noted from the above description. First, as shown in Fig. 2, the SU first senses the channel at time t_1 and then senses it at time t_4. The intermediate incidence time values (a, b and c) are generated as a part of random backoffs until we exceed the current time instant t_3. Since these intermediate time values have already elapsed on the time line, SU can not perform channel sensing at these times. Second, the backoff (BO) starts from the previous incidence time rather than the end of transmission time so that inter-incidence durations are exponentially distributed. This makes it possible to use the theory of random incidence into ARP. Third, SU performs non-persistent sensing.

4. If SU does not have enough frames to consume the duration of $(y_{max} - s)$, it stops after sending all the frames.

5. The term "incidence time into the ARP" refers to the time at which SU can potentially sense the channel whose occupancy is modeled using the ARP. At some incidence times, the SU can not sense the channel, as will be explained later in this section.

6. The SU keeps record of the last time it sensed the channel. However, it *does not* keep record of the boundaries of idle and busy periods on the channel, which would have required it to sense the channel continuously.

5 Channel Access Based on RIBS

Whenever SU senses the channel to be idle, the duration for which it should transmit is determined such that the probability of its interference with PU transmission is less than or equal to a predefined threshold η. The SU uses the residual idle time distribution to compute this duration. The residual idle time distribution is obtained using the known idle time distribution for the channel. Let random variable I represent channel idle time whose Cumulative Distribution Function (CDF) is given by F_I. Suppose an SU senses the channel *at a random time instant* (such as at time t_1 in Fig. 2) and finds it to be idle. We denote the channel residual idle time in the sensed idle cycle by random variable RI. For random sensing in an idle cycle, the *residual idle time density* function f_{RI}, and the *residual idle time distribution* function F_{RI} can then be computed as follows [21, pp. 331]:

$$f_{RI}(y) = \frac{1 - F_I(y)}{E[I]} \tag{1}$$

$$F_{RI}(y) = \int_0^y f_{RI}(z)\mathrm{d}z. \tag{2}$$

$E[I]$ in (1) denotes the mean channel idle time. If SU uses the channel for duration y, then $F_{RI}(y)$ denotes the probability that the remaining idle period will end before SU transmission is over. In this case, SU transmission will interfere with PU transmission. In other words, $F_{RI}(y)$ gives the probability of interference of SU's transmission with PU if SU uses the channel for duration y on randomly sensing the channel to be idle. In RIBS, this interference probability is upper bounded by η. That is,

$$F_{RI}(y) \leq \eta. \tag{3}$$

Since, we also want to maximize the duration for which the SU transmits when it detects an idle cycle, we find the maximum value of y for which the inequality (3) holds. We denote this maximum value as y_{max}. We note several points in the above formulations. First, the above formulations are valid for the case when SU senses the channel at a *random instant* and finds it to be idle. Second, the y_{max} value, which is computed only once at the beginning by solving (3), depends on the value of residual idle time distribution parameters and η, and is independent of the channel busy time distribution and mean backoff value. In general, y_{max} is directly proportional to η and $E[RI]$ (which, in turn, is directly proportional to $E[I]$; see [22]). Larger value of η implies that PU can tolerate higher probability of interference. Therefore, as η increases, y_{max} value increases and SU transmits for longer duration during each transmission operation. Third, during each transmission operation, SU transmits the frames without further sensing the channel.

The channel access scheme for RIBS is very simple: SU remembers the last sensing time. When SU has a frame to send, it generates one or more random backoffs and adds to the previous sensing time until it goes past the current time. This future time becomes the next scheduled sensing time. At that scheduled time, the SU senses the channel for duration s and if the channel is sensed idle, the SU transmits for $(y_{max} - s)$ duration, where y_{max} is computed using (3). If the channel is sensed busy, then SU backs off again.

6 Analytical Formulation of Performance Metrics

In this section, we derive the analytical formulations for various performance metrics of SU. We use the term *raw SU frames* to refer to all the frames which are transmitted by an SU at the MAC layer during each transmission operation. This includes successfully (i.e. completely) transmitted frames as well as any partially transmitted frame which could not be transmitted completely due to appearance of PU on the channel resulting in collision with PU. We use the term *successfully transmitted SU frames* to refer to all the frames which are successfully transmitted by an SU at the MAC layer during each transmission operation. In our work, all the analytical formulations are derived using raw SU frames, and for saturated SU traffic. Analytical value of a performance metric is denoted with a notation having a widehat symbol over it. The corresponding simulation value is denoted with the same notation, but without the widehat.

6.1 Average Number of Raw Frames Transmitted Per Transmission Operation by SU ($\widehat{\varphi}$)

We once again consider two possible transmission scenarios (depicted in Fig. 1) for SU when it transmits after sensing the channel idle. In first scenario (shown below the central line in the figure), the remaining idle period duration RI is more than the transmission operation duration y_{max}. Therefore, the SU transmits for the entire $(y_{max} - s)$ duration and there is no interference to PU. In second scenario (shown above the central line in the figure), the remaining idle period duration RI is less than the transmission operation duration y_{max}, and therefore, the SU transmits only for available residual idle time duration $(RI - s)$ after sensing. In this scenario, the SU transmission interferes with PU transmission because the idle period ends (due to PU's appearance on the channel) before the SU transmission is over. Therefore, the average number of raw frames that an SU transmits during each transmission operation, can be computed as:

$$\begin{aligned}
\widehat{\varphi} &= E[(\min(RI,\, y_{max}) - s)|RI > s] \times \tfrac{R}{S} \\
&= \big\{(y_{max} - s)P(RI > y_{max}|RI > s) \\
&\quad + E[(RI - s)|RI < y_{max}]P(RI < y_{max}|RI > s)\big\} \times \frac{R}{S} \\
&= \left\{(y_{max} - s)\frac{(1 - F_{RI}(y_{max}))}{(1 - F_{RI}(s))} + \frac{1}{(1 - F_{RI}(s))}\right. \\
&\quad \left.\int\limits_{q=s}^{y_{max}} (q - s)f_{RI}(q)\mathrm{d}q\right\} \times \frac{R}{S}.
\end{aligned} \tag{4}$$

Here, s is the fixed channel sensing duration, R is data transmission rate of the wireless channel (in bits per second), and S is sum of SU data frame size and acknowledgment frame size (in bits). Therefore, R/S gives the number of SU frames transmitted per second. y_{max} is computed by solving (3). Let us use the following representations:

$$term_1 = (y_{max} - s)\frac{(1 - F_{RI}(y_{max}))}{(1 - F_{RI}(s))} \tag{5}$$

and

$$term_2 = \frac{1}{(1 - F_{RI}(s))}\int\limits_{q=s}^{y_{max}} (q - s)f_{RI}(q)\mathrm{d}q. \tag{6}$$

Note that $\frac{(1-F_{RI}(y_{max}))}{(1-F_{RI}(s))}$ is equal to the conditional probability $P(RI > y_{max}|RI > s)$ when SU transmits without interfering with PU. $term_1$ gives the average duration for which an SU transmits in the first scenario. Similarly, $term_2$ gives the average duration for which an SU transmits in the second scenario.

6.2 Average Raw SU Throughput ($\widehat{\gamma}$)

Raw SU throughput (in frames per second) is defined as the total number of raw frames transmitted by an SU per unit of time. We derive the analytical expression for average raw SU throughput as follows: Let T denote the total duration in which the average SU throughput is to be computed, and $E[BO]$ denote the mean backoff duration for exponential backoffs (please refer to Section 4). So, the backoff process is a Poisson arrival process with rate parameter $1/E[BO]$. Then, the mean number of incidences (arrivals) into the alternating renewal process (ARP) in duration T is $T \times 1/E[BO]$. Some of these incidences will be in idle cycles and some of them will be in busy cycles of the ARP. We compute the number of incidences in idle cycles using a property called Poisson Arrivals See Time Averages (PASTA) [23, pp. 293]. PASTA property states that when arrivals to a stochastic process is Poisson, the fraction of arrivals which find the stochastic process in a given state is equal to the fraction of time the process is in that state [23, pp. 77-78]. PASTA property can be used to observe any stochastic process as long as the arrivals of the observing process is Poisson. In our model, the observed stochastic process is the Alternating Renewal Process representing the idle and busy periods of the PU traffic and the observing process is the backoff incidences by SU which is Poisson. Therefore, the fraction of SU incidences which occur in idle periods of the channel is equal to the fraction of time the channel is in idle state, which is equal to $\frac{E[I]}{(E[I]+E[B])}$. Here, $E[I]$ and $E[B]$ denote the mean idle and busy periods of the channel. Using above expressions, the number of SU incidences into idle cycle, N_I, can be computed as:

$$N_I = \frac{T}{E[BO]} \times \frac{E[I]}{(E[I] + E[B])}. \tag{7}$$

However, all the incidences into idle cycles do not result in sensing of the channel by SU. As explained in the context of Fig. 2 in Section 4, an SU can not perform channel sensing at those incidence times which lie within the duration of previous transmission operation. During backoff, an SU may either incidence into the just concluded transmission operation duration one or more times (as in Fig. 2), or it may not incidence at all within this duration if the backoff value is sufficiently large to surpass the current time. In order to compute the average number of backoff incidences which occur within a transmission operation duration, we proceed as follows: Every time an SU senses the channel for a predefined duration s and finds the channel idle, it transmits, on the average, for a duration of $(term_1 + term_2)$, where $term_1$ and $term_2$ are given by equations (5) and (6) respectively. Let X be a random variable that denotes the duration of transmission operation, and let random variable Y denote the number of backoff incidences within transmission operation durations. So, $E[X] = (s + term_1 + term_2)$. The average number of backoff incidences which occur within a transmission operation duration, denoted as W_{inc}, can be computed as (see [21, pp. 262–263]):

$$\begin{aligned} W_{inc} &= E[Y] \\ &= E[E[Y|X]] \\ &= \int_{-\infty}^{\infty} E[Y|X = x] f_X(x) \mathrm{d}x. \end{aligned} \tag{8}$$

For a given transmission duration $X = x$, Y is Poisson (with parameter $\lambda = 1/E[BO]$) within that interval. Hence, $E[Y|X = x] = \lambda x$, and therefore, (8) can be computed as (see Appendix A in [24]):

$$\begin{aligned} W_{inc} &= \lambda E[X] \\ &= \frac{(s + term_1 + term_2)}{E[BO]}. \end{aligned} \tag{9}$$

We model each backoff incidence into the ARP as Bernoulli distributed with probability of success p. A *success* is reported when an incidence lies within the transmission operation duration. It can be shown that $p = \frac{W_{inc}}{1+W_{inc}}$ (see Appendix A in [24]). Hence, the probability that an SU actually senses the channel on a random backoff incidence (P^{sen}) is equal to the probability that the incidence is outside of transmission operation, which is $(1 - p)$. Thus,

$$P^{sen} = 1 - p = \frac{1}{(1 + W_{inc})}. \tag{10}$$

Using (7) and (10), the total number of idle cycle incidences within duration T on which the SU senses the channel is computed as:

$$\begin{aligned} N_I^{sen} &= N_I \times P^{sen} \\ &= \left[\frac{T}{E[BO]} \times \frac{E[I]}{(E[I] + E[B])}\right] \times P^{sen}. \end{aligned} \tag{11}$$

So, N_I^{sen} gives the number of times the SU incidences into idle cycles and senses the channel. On each sensing, the channel is sensed idle if the residual idle time is greater than the sensing duration s. Therefore, the total number of idle cycle incidences within duration T at which the SU senses the channel and finds it to be idle (and therefore, initiates a transmission operation) is given as:

$$\begin{aligned} N_{tx} &= N_I^{sen} \times P(RI > s) \\ &= \left[\frac{T}{E[BO]} \times \frac{E[I]}{(E[I] + E[B])}\right] \times P^{sen} \times (1 - F_{RI}(s)). \end{aligned} \tag{12}$$

During each such transmission operation, the average number of frames that the SU transmits is $\widehat{\varphi}$. Therefore, the total number of frames that the SU transmits in duration T is given as:

$$\begin{aligned} N_{total} &= N_{tx} \times \widehat{\varphi} \\ &= \left[\frac{T}{E[BO]} \times \frac{E[I]}{(E[I] + E[B])}\right] \times P^{sen} \times (1 - F_{RI}(s)) \times \widehat{\varphi}. \end{aligned} \tag{13}$$

For large T, the average SU throughput (in frames/sec) is given by:

$$\begin{aligned} \widehat{\gamma} &= \frac{N_{total}}{T} \\ &= \left[\frac{1}{E[BO]} \times \frac{E[I]}{(E[I] + E[B])}\right] \times P^{sen} \times (1 - F_{RI}(s)) \times \widehat{\varphi}. \end{aligned} \tag{14}$$

6.3 Average Sensing Overhead of SU ($\widehat{\delta}$)

We compute the average sensing overhead of SU as the percentage of time (with respect to one SU frame transmission time) that an SU spends in sensing the channel. This metric is measured in percentage. However, in this paper, we will simply refer to it as *sensing overhead*. It is computed as follows:

$$\widehat{\delta} = \frac{T_{sensing}}{T_{tx}} \times 100. \tag{15}$$

Here, $T_{sensing}$ and T_{tx} are the total time durations that the SU spends in sensing the channel and transmitting frames respectively during operational duration of T. The total number of incidences at which SU senses the channel, N^{sen}, is computed as:

$$N^{sen} = N_I^{sen} + N_B, \tag{16}$$

where N_B represents the number of incidences at which the SU senses the channel to be busy. N_B is computes as:

$$N_B = \frac{T}{E[BO]} \times \frac{E[B]}{(E[I] + E[B])}, \tag{17}$$

where $\frac{E[B]}{(E[I]+E[B])}$ is the fraction of SU incidences in busy cycles. Note that unlike idle cycle incidences, all the busy cycle incidences are sensed by the SU.

Substituting the expressions from (11) and (17) into (16), we get the total number of incidences at which SU senses the channel as:

$$N^{sen} = \frac{T}{E[BO]} \times \left[\frac{E[I]}{(E[I]+E[B])} \times P^{sen} + \frac{E[B]}{(E[I]+E[B])}\right]. \tag{18}$$

The total time spent by SU in sensing the channel is computed as: $T_{sensing} = N^{sen} \times s$, where s is the time required by SU to sense a channel on each sensing operation. The total time spent by SU in transmitting frames is computed as: $T_{tx} = N_{total} \times T_{sf}$, where T_{sf} is one SU frame transmission time. Substituting the above expressions for $T_{sensing}$ and T_{tx}

into (15) and using (13) and (18), we get the expression for average sensing overhead as:

$$\widehat{\delta} = \frac{\left[\frac{E[I]}{(E[I]+E[B])} \times P^{sen} + \frac{E[B]}{(E[I]+E[B])}\right] \times s}{\frac{E[I]}{(E[I]+E[B])} \times P^{sen} \times (1 - F_{RI}(s)) \times \widehat{\varphi} \times T_{sf}} \times 100. \tag{19}$$

7 Discussion on Random Channel Sensing

We have emphasized in earlier sections that in RIBS, the channel sensing schedule is generated such that the channel sensing is memoryless and random. Random sensing enables us to compute *residual idle time distribution* (F_{RI}) from a known idle time distribution (F_I) (using (2)) without knowing the start of the idle cycle. This distribution can be used to compute the maximum duration (y_{max}) for which the SU can use the channel on randomly sensing the channel idle, such that the probability of its interference with PU transmission is below a predefined threshold (η). This approach relieves the SU from continuously sensing the channel to keep track of start of each idle period on the channel. In order to enforce memoryless random sensing of the channel, the SU backs off using exponentially distributed values as described in detail in Section 4. The choice of backoff parameter of the exponential distribution is important for the performance of the system.

We need to mention that for some idle time distributions, such as Uniform distribution, y_{max} can be computed exactly (in closed form) by solving equation (3). For such distributions, the backoff parameter value can be decided analytically, and the interference probability of SU with PU will not be violated for the selected backoff parameter value. However, for some other idle time distributions (such as Erlang or Hyperexponential), y_{max} value is computed by solving equation (3) using iterative numerical methods (such as Newton Raphson method). Hence, the computed y_{max} value is only approximate. For such distributions, the backoff parameter value should be carefully selected, as the error in y_{max} value may result in violation of the interference probability constraint (η) if the selected backoff value is very small. In such cases, the BO value should be either empirically selected, or the SU should start with relatively large backoff parameter value (for example, mean idle cycle time of the channel) and gradually adapt the value during run time so that the SU throughput increases without violating the η constraint and without increasing the sensing overhead to unacceptable level.

8 Using RIBS In PU Networks With Real Application Traffic

In real world scenarios, the channel occupancy data is collected from actual PU traffic. The channel idle periods due to actual Primary applications can be low or high in terms of variability, which is captured by squared Coefficient of Variation (CoV^2) value of the data. Coefficient of Variation is defined as the ratio of standard deviation of the data to its mean value. The higher the CoV^2 value, the higher is the variability. In such scenarios, the distributions fitted to the measured data are only approximations of the ideal fit. Approximate idle time distribution does not accurately represent the variability of idle times on the channel due to PU traffic and poses new challenges in using RIBS when the idle periods are highly variable.

The main challenge in using RIBS with realistic PU applications is with those channel idle period profiles which have large CoV^2 (> 1.0) and small mean idle time $E[I]$, and where the fitted idle time distribution is approximate with respect to the actual channel idle periods. Since the fitted distribution is only approximate, the y_{max} value computed in RIBS using such distributions is also approximate. When an SU senses the channel to be idle and transmits for these approximate ($y_{max} - s$) durations, then it may violate the interference probability constraint, specially when it transmits in small idle periods. Therefore, using approximate idle time distribution in RIBS may increase the probability of interference of SU's transmission with PU, specially when channel idle periods are highly variable with low mean idle time. The analytical formulations described in Section 6 can be applied in this scenario; however the approximations lead to discrepancies in the analytical and simulation results.

There are two possible approaches to reduce the increase in interference probability when RIBS uses approximate idle time distribution for highly variable data. Both of these approaches can be used together. First, make the exponential backoff parameter large (for example, integer multiple of y_{max}, or mean cycle period $E[C]$). Statistically, this will make the SU skip small idle periods. However, this will lead to low SU throughput, but low channel sensing overhead. Second, throw out some outliers (for example, discard the top 1 to 5 percentile data and consider only 99 to 95-percentile of idle time values) and fit the appropriate distribution to this truncated data. This makes the fitted model more conservative. That is, the idle time distribution fitted to such a truncated data set gives lower y_{max} value, and therefore, the SU transmits conservatively on sensing the channel idle. However, care should be taken not to throw away too many values as it will make the fitted model to deviate even more from the ideal fit.

Fig. 3 shows the flow chart, which describes the steps to be followed by an SU to model the channel occupancy due to PU transmissions, and to use the RIBS approach for its opportunistic transmission. Note that the method proposed in the flow chart is not new. We merely have borrowed it from the literature of distribution fitting (please refer to [25] and [26] for fitting phase-type distributions) and presented here so that the readers get a comprehensive view of how to use RIBS scheme in practice. In RIBS, computation of F_{RI} (see (1) and (2)) requires closed form expression for the Cumulative Distribution Function (CDF) of the fitted idle time distribution. If the fitted distribution does not have a closed form distribution function, then such distributions must be approximated using Phase type (PH) distributions[7] and the approximated PH distribution should be used to compute F_{RI}. Another alternative is to directly fit PH distribution to the idle time data set. RIBS does not depend on the channel busy time distribution. Therefore, it is not

7. A continuous time distribution can be approximated to Phase Type distribution (for example, Exponential, or r-phase sum of exponentials, or r-phase mixture of exponentials) using tools such as EMpht [27].

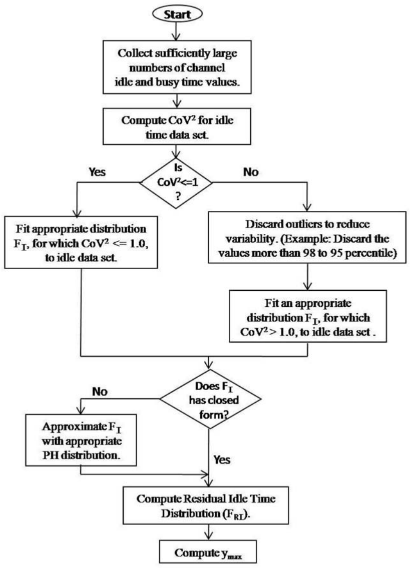

Fig. 3. Methodology to use RIBS approach for opportunistic channel access.

required to fit a distribution for the measured busy time data set. Mean value of the measured busy time data can itself be used as $E[B]$ because sample mean is an unbiased estimator of the population mean.

9 Simulation Experiments and Results

In this section, we describe the simulation experiments for synthetic PU traffic and real PU application traffic.

9.1 Case 1: Synthetic PU Traffic

9.1.1 Simulation Model

In order to validate the RIBS scheme and the analytical formulations for SU performance metrics, we simulate a single data channel network, which is opportunistically used by an SU to transmit its frames. The idle and busy periods on the channel due to PU traffic are synthetically generated using example distributions. Therefore, the exact time instants when the channel becomes idle or busy are known in simulation from the synthetically generated channel occupancy data. We simulate two different configurations to obtain the channel idle and busy time values. In **Configuration-1**, we generate the channel idle and busy time values alternately using 2-Erlang distribution with rate parameters λ_i and λ_b respectively ($\lambda_i = 1.0\,sec^{-1}$, $\lambda_b = 50.0\,sec^{-1}$). In **Configuration-2**, we generate the channel idle and busy time values alternately using Uniform distribution with parameters (a, b) and (c, d) respectively ($a, b = 0.01, 0.1\,sec$; $c, d = 0.001, 0.009\,sec$).

For each of the above configurations, the channel occupancy due to PU traffic is modeled as an Alternating Renewal Process. The SU data and acknowledgment frame sizes are 2048 bits and 128 bits respectively. The wireless channel data transmission rate is 11 Mbps. For each value of interference probability constraint η, we obtain the value of the following performance metrics using simulations: (1) Probability of interference of SU transmissions with PU (p_{intf}), (2) Average raw SU throughput (frames/sec) (γ_r), (3) Average SU goodput (frames/sec) (γ_s), (4) Average SU sensing overhead (in %) for raw frames (δ_r), (5) Average SU sensing overhead (in %) for successfully transmitted frames (δ_s). Average SU goodput is defined as the number of successfully transmitted SU frames per second. Note that these notations represent the values obtained using simulation. The corresponding analytical expressions for these performance metrics for the two example distributions (2-Erlang and Uniform) are derived using the generic formulations described in Section 6. The analytical performance metrics are denoted by placing a widehat over the corresponding symbol. Please refer to Section 7 in [24] for distribution-specific formulations and their derivations. We compare the analytical and simulation values of the performance metrics and analyze the results.

We have conducted Monte Carlo simulations (applied in a discrete event model) using OPNET simulator [28]. The performance metric values computed using simulations are obtained with 98% Confidence Interval. In some figures, the confidence interval is too narrow to be noticeable. The first simulation metric value, p_{intf}, is compared against the interference probability constraint η. We now briefly explain some important points regarding comparison of other performance metrics with their analytical counterparts.

We compare the analytical and simulation values of average SU throughput and average SU sensing overhead. The analytical values ($\widehat{\gamma}$ and $\widehat{\delta}$) are computed using raw SU frames. That is, the values of these metrics are computed by considering all the frames (successful and collided) transmitted by SU during its each transmission operation. It was hard to derive the exact analytical expressions for these metrics by considering only the successfully transmitted SU frames and discarding the partial frame. In simulation however, we compute the values using raw SU frames as well as successfully transmitted SU frames. These performance metrics, when computed in simulation using raw SU frames, are denoted as γ_r and δ_r, and when computed using successfully transmitted SU frames, are denoted as γ_s and δ_s. We compare the analytical values of the performance metrics ($\widehat{\gamma}$ and $\widehat{\delta}$) with both types of simulation values - those which are obtained using raw SU frames (γ_r and δ_r), and those which are obtained using successfully transmitted SU frames (γ_s and δ_s).

To validate the analytical formulations for different backoff parameter values, we run our simulation experiments with three different backoff parameter values: $E[C]$, y_{max} and $y_{max}/10$. $E[C]$ denotes the mean cycle time of the channel, which is equal to sum of mean idle time and mean busy time of the channel (i.e., E[C] = E[I] + E[B]). $E[C]$ is independent of η and y_{max}, and is constant for a given channel idle and busy time distribution. In our experiments, we assume the channel occupancy profile to remain unchanged, and therefore E[C] is constant in our simulation experiments. The other two backoff parameter values, namely y_{max} and $y_{max}/10$, depend on η. The relation between η and y_{max} will be often used in analysis of the results, therefore we explicitly state it: *As η increases for a given channel idle time distribution, the y_{max} value also increases. As a result, the exponential backoff parameter values that are directly proportional to y_{max} (such as y_{max} and $y_{max}/10$), also increase with increasing η*. We further note that $E[C]$ is always greater than y_{max}.

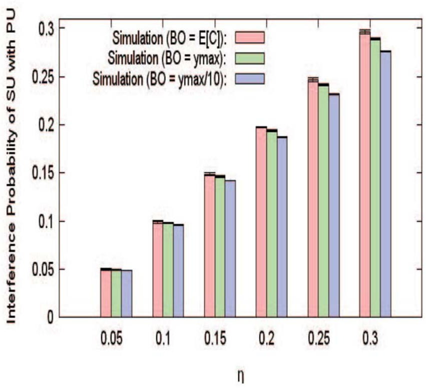

Fig. 4. Probability of interference of SU with PU (p_{intf}) for configuration 1.

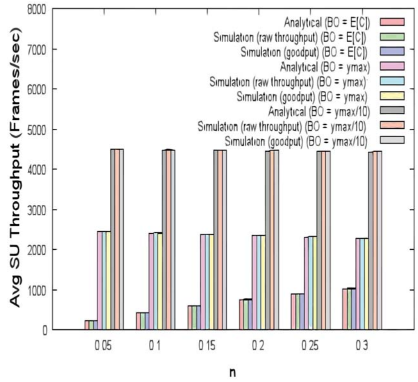

Fig. 6. Average SU throughput for configuration 1.

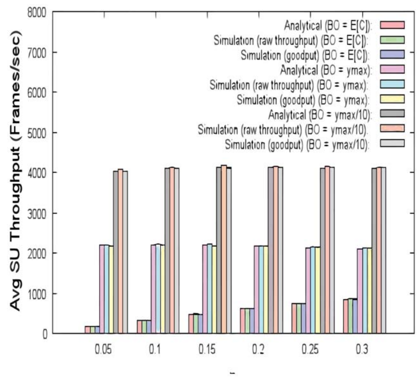

Fig. 7. Average SU throughput for configuration 2.

Therefore, $E[C]$ is largest of all the three backoff values used in our simulation experiments and $y_{max}/10$ is the smallest one. These values provide a good range of the mean exponential backoff duration.

In our experiments, we have considered η in the range of 0.05 to 0.3 (in steps of 0.05). High values of η are not of much practical interest in hierarchical networks. Higher values of η indicate that PU can accept significant interference from SU, which is usually not true in practice.

9.1.2 Results for Performance Metrics of SU

Figs. 4 and 5 show the probability of interference of SU transmission with PU for Configuration-1 and Configuration-2 respectively. We see from these figures that for each η, the probability of SU's interference with PU remains less than or equal to η for all the backoff parameter values, i.e., the interference constraint is not violated. For a given η, the interference probability for smaller backoff parameter value is marginally less than that for larger backoff parameter value. This is so because SU performs more transmission operations when the backoff parameter value is small (such as $y_{max}/10$) as compared to when the backoff parameter value is large (such as y_{max} or $E[C]$). Although number of collisions also goes up, this increase is smaller than the increase in number of transmission operations. Hence, for a given η, p_{intf} is smaller for low BO values as compared to higher BO values.

In Figs. 6 and 7, we compare the analytical value of average raw SU throughput ($\widehat{\gamma}$) with the simulation values γ_r and γ_s for different η for Configuration-1 and Configuration-2 respectively. The throughput metric depends on the backoff parameter value (see (14)). As we see from the graphs, for each η, the analytical and simulation values match reasonably well for all the backoff parameter values. We also note that for a given value of η, smaller backoffs (such as one with mean value of $y_{max}/10$) yield larger SU throughput as the SU tends to use the idle periods more frequently. For larger backoff values, the SU skips more idle periods (and therefore misses more transmission opportunities), thereby resulting in lesser average throughput. More analysis of this metric is given later.

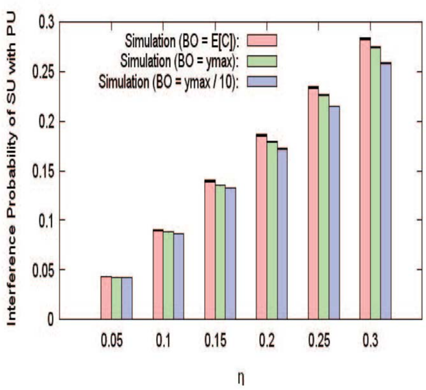

Fig. 5. Probability of interference of SU with PU (p_{intf}) for configuration 2.

Figs. 8 and 9 show the average sensing overhead for SU. This metric also depends on the parameter value of exponentially distributed backoffs (see (19))[8]. The terms *rsf*/*ssf* in the figure legends denote metric values for 'raw/successfully transmitted SU frames'. We observe good match between analytical and simulation values. We also note that for a given η, smaller backoffs result in higher sensing overheads for SU as the SU has more random incidences into the ARP which translates to more sensing instances.

We now further analyze the results shown in Figs. 6 and 8 for Configuration-1; the analysis applies to Configuration-2 as well. For any given BO parameter value, y_{max} value increases as η increases and hence, on the average, the SU transmits for longer duration in each transmission operation. That is, the average SU frames transmitted per transmission operation increases as

8. P^{sen} in (19) depends on $E[BO]$ because W_{inc} depends on $E[BO]$ (see (9) and (10)).

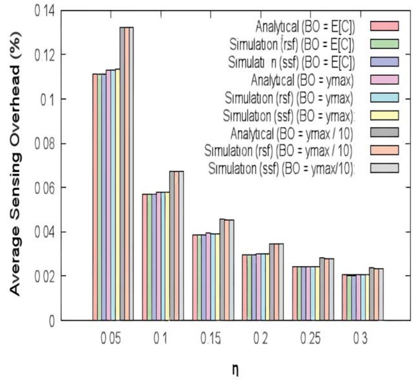

Fig. 8. Average SU sensing overhead for configuration 1.

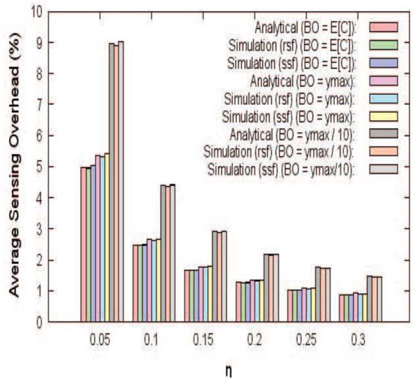

Fig. 9. Average SU sensing overhead for configuration 2.

η increases. Therefore, it is expected that for each backoff parameter value, the SU throughput (both analytical and simulation values) will also increase with the increasing η. However, in Fig. 6, we note that as η increases, the average SU throughput value increases only when the SU uses backoff parameter value of $E[C]$ and remains nearly the same when SU uses backoff parameter value proportional to y_{max} (i.e., $BO = y_{max}$ and $BO = y_{max}/10$). The reason for this is as follows: When SU uses a backoff parameter value which is directly proportional to y_{max} (such as y_{max} or $y_{max}/10$), then the backoff parameter value increases with increasing η (since the increase in η also increases y_{max}). Therefore, for larger η, the SU backs off for larger durations and hence, number of times the SU senses and transmits on the channel decreases. So, although on the average, the SU transmits more number of frames on each transmission operation as η increases, yet the number of times it performs such transmission operations on sensing the channel idle decreases. On the other hand, for smaller η, the y_{max} values are small, and therefore, the backoff parameter values are also small. Hence, the average number of frames transmitted by SU on each transmission operation is less, but the SU performs these transmission operations more frequently (because of small backoffs). As a result, the total number of successfully transmitted SU frames do not vary much when η increases, and the average SU throughput remains more or less the same for different values of η. This result indicates that by making the backoff parameter value proportional to y_{max}, we can achieve similar average SU throughput even for strict interference constraint scenarios (small η) as we achieve for relaxed interference scenarios (large η). When SU uses $BO = E[C]$, the backoff parameter is independent of η and does not increase with increasing η. However, the number of SU frames transmitted during each of these transmission operation increases with increasing η. As a result, the SU throughput value increases with increasing η for $BO = E[C]$.

As explained above, the average SU throughput remains more or less the same with increasing η when BO value is proportional to y_{max}, but the number of times the SU senses the channel decreases. Therefore, the total time spent in sensing the channel decreases but the total time spent in transmitting the frames remains nearly the same (as the average throughput remains nearly the same). As a result, for each backoff parameter value, the sensing overhead (shown in Figs. 8 and 9) decreases as η increases.

By definition, analytical values of performance metrics ($\widehat{\gamma}$ and $\widehat{\delta}$) will differ from γ_s and δ_s as the analytical values are computed using raw frames and simulation values are computed using successfully transmitted frames. However, as we see from the results, this difference is statistically negligible for both the configurations. The y_{max} value computed for these configurations is large enough to transmit multiple SU frames (y_{max} value for Configuration 1 and Configuration 2 is $100.16\,ms$ and $5.08\,ms$ respectively, and transmission time for one SU frame on the simulated data channel is $186.2\mu s$). Therefore, the fraction of partially transmitted frame, if any, is amortized by multiple successfully transmitted frames. Hence, the difference is statistically negligible.

9.1.3 Comparison of RIBS With Other Schemes

We compare RIBS scheme with three alternative channel access schemes using simulation. The first scheme, which we refer to as idle time distribution based scheme (ITBS), is broadly similar to the Contiguous SU Transmission Strategy (CSTS) proposed in [3]. In ITBS scheme, SU keeps track of elapsed idle time in current idle cycle and computes the probability of interference of its next frame with PU given the elapsed idle time. It transmits the frame if this probability is less than or equal to the predefined threshold η; otherwise it continue to senses the channel until it detects the next idle cycle. In ITBS, the SU needs to sense the channel continuously to keep track of start of each idle cycle. The second scheme is based on the theory presented in [13]. We refer to this scheme as MIL (MILCOM Scheme). We simulate MIL scheme and apply the presented theory for exponentially distributed PU activity for a single Base Station (BS) Scenario. Both ITBS and MIL schemes are compared for a single channel scenario. The third scheme is a restless multi-arm bandit scheme called Regenerative Cycle Algorithm (RCA) [14]. Since RCA is meaningful only when there are multiple arms (channels), we simulate both RCA and RIBS in a three channel scenario.

We compare these schemes with RIBS with respect to average SU goodput and sensing overhead. Values of both the metrics are obtained using simulations. We compare RIBS and ITBS schemes for Configuration-1. The results for RIBS are analyzed for each backoff parameter value. No backoff is performed in ITBS scheme as SU continuously senses the channel. For MIL and RCA simulations,

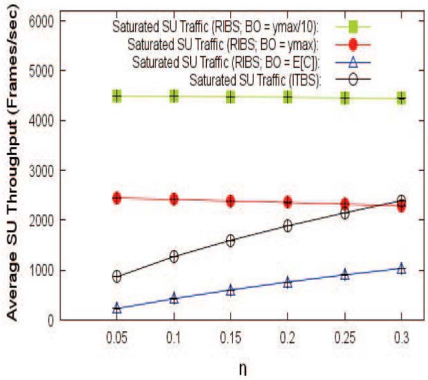

Fig. 10. Average SU throughput (RIBS vs ITBS) for configuration 1.

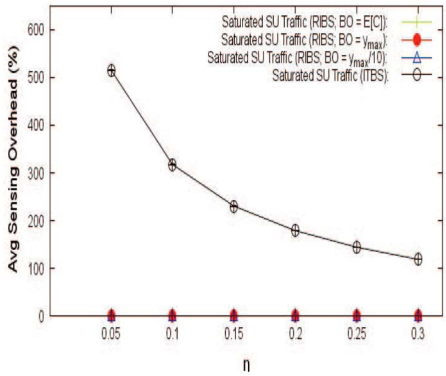

Fig. 11. Average SU sensing overhead (%) (RIBS vs ITBS) for configuration 1.

the configuration parameters are specified with the results.

Fig. 10 shows the average SU goodput for Configuration-1. We note that ITBS yields higher average network goodput as compared to RIBS for all values of η when RIBS uses $BO = E[C]$. In both the cases (i.e., when SU uses ITBS, and when it uses RIBS with BO = E[C]), the average SU goodput increases as η increases. However, due to large backoff value, the SU using RIBS senses the channel much less often, and therefore performs fewer transmission operations. This results in lower SU goodput as compared to ITBS scheme.

When SU uses RIBS with $BO = y_{max}$, the average SU goodput remains almost the same as η increases (this was also observed in Fig. 6). For low η, the SU transmits more often (as the y_{max} value is less for small η and therefore, the backoff parameter value is less) and has higher goodput as compared to ITBS which transmits conservatively for lower η. However, as η increases, the SU using ITBS starts transmitting more number of frames in each idle cycle and its goodput increases, and at $\eta = 0.28$, it surpasses RIBS. Similar is the case when SU uses RIBS with $BO = y_{max}/10$, except that in this case, backoff values are sufficiently small even for larger values of η. Therefore, when using RIBS, the SU performs enough number of transmission operations such that its average goodput exceeds the average goodput obtained using ITBS for all values of η shown in the graph.

Fig. 11 shows the sensing overhead of the SU when it uses the ITBS and RIBS (with different backoff parameter values). It is intuitive that ITBS, which performs continuous channel sensing to keep track of the start of each idle period, will have significantly higher sensing overhead, as compared to the RIBS scheme, which senses the channel only when it has frames to transmit. As the η increases, the number of frames transmitted by the SU per transmission operation also increases, and therefore, the sensing overhead per SU frame transmission time decreases. As previously mentioned in the context of Figs. 8 and 9, for each BO value in RIBS, the sensing overhead decreases as the η increases. However, these overhead values are very less as compared to ITBS, and therefore, RIBS curves for each backoff value overlap and appear as one curve (due to large scale of Y-axis).

In Table 1, we compare the RIBS and RCA schemes with 95% Confidence Interval. We run both the schemes for three channel scenarios. Channel data rates are taken to be 11 Mbps and each SU frame size is 4096 bits. For RCA, we set the transition probabilities from IDLE/BUSY state to BUSY/IDLE state for the three channels as (0.02, 0.05), (0.07, 0.03), (0.1, 0.9) respectively. These values lead to bursty channels and are used in [14]. The channel idle periods obtained using RCA simulations are used to fit idle time distribution for use in RIBS simulation. In RIBS simulation, we fit exponential distribution to the idle time values, set η threshold to 0.1 and backoff value to $y_{max}/10$. As shown in the table, RIBS gives marginally lesser average SU throughput than RCA at significantly lesser sensing overhead. In RCA, SU senses the channel at every slot and uses every idle slot for its frame transmission. However, in RIBS, the SU may skip some idle periods during backoff thereby resulting in lesser throughput. But in RIBS scheme, SU transmits one or more frames on each idle sensing, thereby resulting in lesser sensing overhead per frame transmission.

Our next simulation experiment is to compare RIBS and MIL scheme. In these simulations, channel data rate is taken to be 4 Mbps and each SU frame size is 4096 bits. PU busy durations are exponentially distributed with rate $\lambda = 5.0\,sec^{-1}$. Since the PU constraint in RIBS and MIL schemes are different (η in RIBS, and ρ and θ in MIL; please refer to [13] for definition of parameters θ and ρ.), we first simulate RIBS with $\eta = 0.1$ and compute equivalent ρ value that comes out to be 0.16. We then use $\rho = 0.16$ in simulating MIL scheme. θ value is set to 0.08. In MIL scheme, the SU transmission duration (ON period) depends on λ and ρ values and is independent of mean idle (OFF) period of PU. Fig. 12 shows the average SU goodput for different PU busy duty cycle (Busy duty cycle, DC, of a PU is the proportion of time when the PU is active) for given λ and ρ values. y_{max} duration in RIBS is more than SU's ON duration in MIL scheme for given configurations. The average SU throughput for RIBS scheme is greater than the MIL scheme for all the duty cycle values, although the difference is much

TABLE 1
Performance of RIBS vs RCA

Access Scheme	Avg SU Goodput (Frames/sec)	Avg Sensing Overhead (%)
RIBS	1825.88 +/- 0.849	19.09 +/- 0.032
RCA	1904.75 +/- 0.44425	29.85 +/- 0.0067

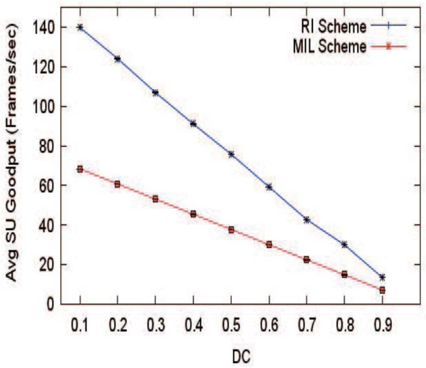

Fig. 12. Average SU throughput (RIBS vs MIL).

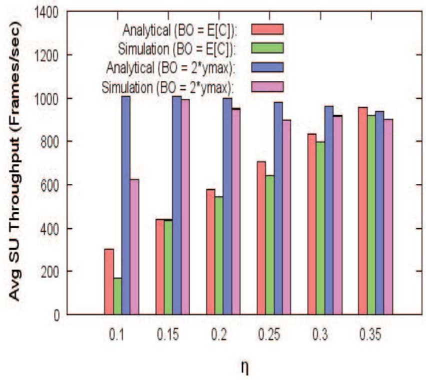

Fig. 14. Average SU throughput for 2-HED idle time distribution (VoIP + Web browsing PU applications).

smaller at heavy duty cycles. The sensing overhead in RIBS scheme becomes significantly high for large PU busy duty cycle (from approximately 4 % for duty cycle of 0.7 to 60 % for duty cycle of 0.9). We have not provided results pertaining to sensing overhead due to space limitation. However, readers can refer to Fig. 21 in [24] for details. Since MIL scheme does not sense at all, there is no sensing overhead. From these results, we can conclude that MIL scheme is preferable in high busy duty cycle scenarios whereas RIBS scheme is better in low busy duty cycle scenarios.

9.2 Case 2: Real PU Application Traffic

9.2.1 Simulation Model

We simulate a Primary network, which consist of a single 4 Mbps data channel. The channel is shared by two pairs of PUs using a simple TDMA protocol. One pair of PU nodes run Voice-over-IP application (using UDP), whereas the second pair of PU nodes run TCP/IP-based Web browsing application using HTTP 1.1 protocol. Therefore, the channel carries a mix of Voice and HTTP traffic. Details of the parameter values for primary applications are given in [24]. The measured idle time data shows high variability ($CoV^2 = 2.916$) and has low mean value ($E[I] = 5.224\,ms$). Channel idle time distribution due to primary network activity is fitted to the measured channel idle time values using the methodology specified in Fig. 3. We fit a 2-phase Hyperexponential distribution (2-HED) to the measured idle time data set using a tool called EMpht [27], which is widely used to fit phase type distributions. The details of distribution fitting are not given in the paper due to space limitation; they can be found in Section 11.2.2 of [24]. The Secondary network consists of a sender and a receiver SU node. The sender opportunistically transmits on the channel using RIBS. We simulate saturated SU traffic profile in which the SU always have enough frames to consume the available idle period. SU frame size is 1024 bits and acknowledgment frame size is 128 bits.

9.2.2 Results

Since the fitted idle time distribution for realistic PU applications is 2-phase HED, we empirically selected the backoff parameter value (please refer to last paragraph of Section 7). We checked four backoff values: y_{max}, $y_{max}/10$, $2 \times y_{max}$, and $E[C]$. BO = y_{max} and BO = $y_{max}/10$ resulted in violation of η. Therefore, we have used the other two backoff parameter values in our experiments: $E[C]$ and $(2 \times y_{max})$. The y_{max} value for the fitted 2-HED is computed for different η using Newton Raphson Method. Fig. 13 shows the simulation value of probability of SU's interference with PU transmissions. We see that for each η, the probability of SU's interference with PU is less than or equal to η.

In Figs. 14 and 15, we compare the analytical values (based on raw SU frames) of the performance metrics ($\widehat{\gamma}$ and $\widehat{\delta}$) with the simulation values computed using successfully transmitted SU frames (γ_s and δ_s). In our simulation of the network model, which is described in the beginning of Section 9.2.1, we have simulated MAC layer

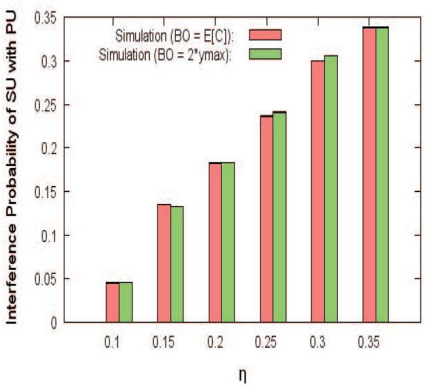

Fig. 13. Probability of interference of SU with PU for 2-HED idle time distribution (VoIP + Web browsing PU applications).

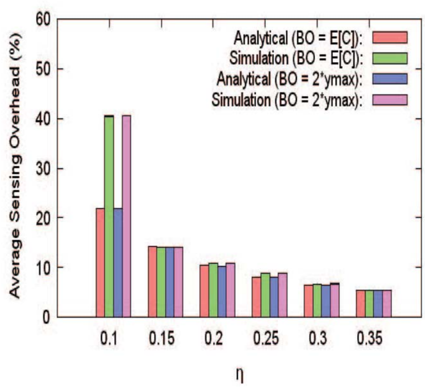

Fig. 15. Average SU sensing overhead (%) for 2-HED idle time distribution (VoIP + Web browsing PU applications).

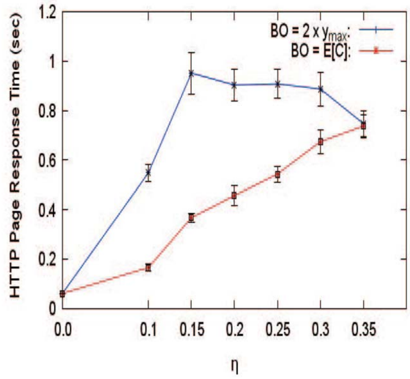

Fig. 16. Average HTTP page download response time.

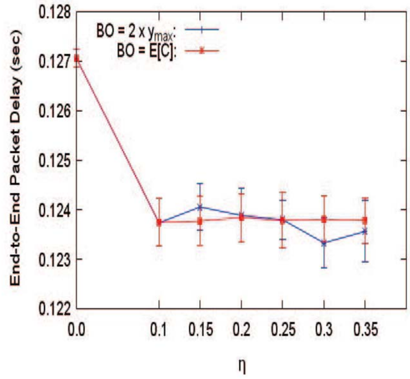

Fig. 17. Average end-to-end delay for voice packets.

operation of the network. Computing the number of raw frames transmitted by the SU in simulation would require the knowledge of exact time instant at which the SU collides with the PU at physical layer. This would require instrumenting the PHY layer code of OPNET modeler. Therefore, we have not recorded the number of raw SU frames in simulation, and do not report the corresponding simulation values (γ_r and δ_r).

Analytical values of average SU throughput and average sensing overhead are computed using average SU frames transmitted per transmission operation $\widehat{\varphi}$ (see (14), (19)). These analytical values are computed using raw frames whereas simulation values are computed using successfully transmitted frames. If the channel mean idle period is very small (such as in this case), then for low η, the computed y_{max} value is small and very few frames are transmitted per transmission operation. As a result, the fractional part of any partially transmitted frame per transmission operation is non-negligible with respect to completely transmitted frames, and the average number of raw SU frames transmitted per transmission operation is more than the average number of successfully transmitted frames. The percentage difference between these values (raw and successfully transmitted frames per transmission operation) is significantly more for small η as compared to large η. Since the average SU throughput and sensing overhead metrics depend on the average number of frames transmitted per transmission operation, their analytical value (computed using raw frames) is more than their simulation value (computed using successfully transmitted frames) (see Figs. 14 and 15). This difference, which is significant primarily at low η (such as $\eta = 0.1$), reduces with increasing η, because with increasing η, y_{max} value increases and the fraction of partially transmitted frame, if any, is amortized by multiple successfully transmitted frames. Also note that like synthetic channel occupancy case (Figs. 6 and 7), the average SU throughput increases with increasing η for $BO = E[C]$ and remains more or less the same for $BO = 2 \times y_{max}$. The average sensing overhead of SU decreases for both backoff parameter values as η increases.

We now study the performance of PU applications when SU uses RIBS for opportunistic transmissions (Figs. 16 – 18). In these figures, the value corresponding to $\eta = 0$ represents the performance metric value when only PU nodes are operational and SU nodes are silent. The other abscissa values (η = 0.10 to 0.35) correspond to the simulation scenarios in which both PU and SU nodes are operational.

First we consider the case when SU uses the exponential backoff parameter value of $2 \times y_{max}$. We see from Figs. 16 and 17 that as η increases from 0.10 to 0.25 (please refer to the curve for $BO = 2 \times y_{max}$), the average page download response time and the average voice packet end-to-end delay first increases (i.e., the application performance degrades), and then marginally decreases. The change in value is more for HTTP page download response time and very less for end-to-end delay of voice packets. This observation is counter intuitive. As the interference probability constraint is relaxed (i.e., η increases), it is expected that the PU will experience more interference from SU and primary application performance will decrease (or equivalently, the page download response time, and the voice packet end-to-end delay will increase). We trace the reason for this observation to two facts: First, the backoff parameter value ($2 \times y_{max}$) used by SU in this case is proportional to y_{max} and second, the way the TCP and UDP protocols at PU nodes react to collisions at the MAC layer. As η increases, y_{max} value increases, and therefore, the backoff value also increases. For large values of η, the backoff parameter value is also relatively large. Larger backoffs by SU results in lesser number of transmission operations by it, leading to lesser number of collisions. So, when $BO = 2 \times y_{max}$, for larger values of η, the number of collisions between SU and PU decreases with increasing η

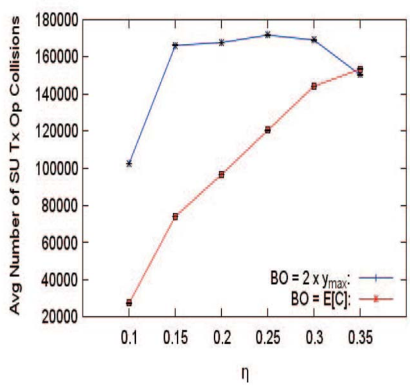

Fig. 18. Number of SU transmission operations which collide (interfere) with PU.

(see the curve for $BO = 2 \times y_{max}$ in Fig. 18 for $\eta > 0.25$). Decrease in number of collisions for higher η decreases the number of retransmissions that TCP layer of PU node needs to performs for web browsing applications. This improves the average page download response time. On the other hand, the decrease in number of collisions does not significantly affect the average end-to-end delay of voice packets in VoIP application (see the curve for $BO = 2 \times y_{max}$ in Fig. 17) as UDP neither waits for acknowledgment nor does it retransmit any lost voice frames.

We now consider another case where SU uses $E[C]$ as the exponential backoff parameter value. $E[C]$ is a constant value (for a given channel configuration), independent of η or y_{max}. For small η, the y_{max} value is small and SU transmits conservatively. However, it backs off by a duration that is exponentially distributed with parameter $E[C]$, which is larger than y_{max}. Therefore, for small η, the SU not only transmits conservatively but also transmits less often. This results in smaller number of collisions of SU with PU for low η (see the curve for $BO = E[C]$ in Fig. 18). As the η increases, the y_{max} value increases and the SU transmits more number of frames per transmission operation, but it still backs off with same backoff parameter value of $E[C]$. This results in larger number of collisions of SU with PU as η increases. Since the number of collisions increases as η increases for $BO = E[C]$, the number of retransmissions made by TCP for web browsing application also increases with η. This results in increased average HTTP page download response time (as shown by the curve for $BO = E[C]$ in Fig. 16) and performance of the web browsing application degrades as η increases. The end-to-end packet delay for VoIP application does not vary much (see the curve for $BO = E[C]$ in Fig. 17) since it uses UDP.

In Fig. 16, we note that for both the backoff parameter values, as the SU starts using the primary channel opportunistically (from $\eta = 0.1$ onwards), the HTTP page response time increases as compared to $\eta = 0$ when only PU nodes use the channel. This is expected. However, we note that in Fig. 17, the end-to-end VoIP packet delay value decreases from approximately 0.127 sec for $\eta = 0.0$ to 0.1235 sec for $\eta = 0.1$. This is due to the following reason: When SU starts using the channel opportunistically (from $\eta = 0.1$ onwards) and an SU packet collides with the HTTP packet, the SU node backs off and the HTTP node goes into congestion control mode. TCP layer at the HTTP node doubles its RTO value and decreases its congestion window size, due to which the HTTP node offers less load on the channel. As a result, the VoIP application gets more bandwidth until either the SU node tries to re-access the channel after its backoff or TCP congestion window size of HTTP node increases. Due to space limitation, we have not provided the results for comparison of RIBS and ITBS schemes in real PU application traffic case. These results are available in Section 11.2.3 of [24].

10 Conclusion and Future Work

RIBS scheme proposed in this paper enables an SU to opportunistically transmit on a primary channel, while ensuring that the probability of interference of SU with PU remains below a given threshold. It also significantly decreases the channel sensing overhead for SU as compared to the idle time distribution based approaches.

We have seen from results that the exponential backoff parameter used in RIBS not only affects SU throughput and sensing overhead but also affects primary application performance. Therefore, selection of backoff parameter value is critical. For those idle time distributions, such as uniform, for which y_{max} can be computed exactly (in closed form), the backoff parameter value can be decided analytically depending on the acceptable sensing overhead. However, for some other idle time distributions (such as Erlang or HED), the y_{max} value is only approximate as it is computed by solving the constraint inequalities using iterative numerical methods (such as Newton Raphson method). In such cases, the SU should either empirically select the backoff parameter value, or appropriately adapt the value at run time.

We describe two main areas of future work, which are related to the research work reported in this paper. First, RIBS can be modified to incorporate missed detection and false alarm during sensing. Second, opportunistic channel access schemes for SU needs to be developed for CSMA-based primary networks, such as WLAN, under Hierarchical Access Model. Current research works do not address performance degradation of PU due to deferment of channel access (caused by backoff) in such networks.

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