Alternating Renewal Theory-based MAC Protocol for Cognitive Radio Networks

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Abstract—We propose a MAC protocol for cognitive radio-enabled secondary networks, which opportunistically use the channels of CSMA/CA-based primary network. We have considered IEEE 802.11 WLAN as a de facto primary network in ISM band. Our study focuses on a single WLAN channel that is used by a WLAN client and server for HTTP-based web browsing application. We use the theory of alternating renewal processes to model the occupancy of channel by WLAN nodes. This model is used by a pair of secondary nodes for estimating idle time durations on the channel and opportunistically transmit frames during the estimated idle times to maximize channel throughput without significantly degrading the WLAN and web application performance.

I. INTRODUCTION

Electromagnetic spectrum is a scarce resource in wireless communication, which needs to be utilized efficiently. Recent studies, such as [1], have shown that a significant part of the spectrum, specifically the licensed spectrum, is extremely under-utilized. A number of independent programs, such as DARPA’s Next Generation Networks Program and Alcatel-Lucent’s DIMSUMNet program [2], have been initiated to explore the possibility and mechanisms of using the underutilized part of the licensed spectrum. One possibility being explored is to allow unlicensed devices (also referred to as secondary devices) to use parts of the licensed spectrum in overlay and underlay mode of operations. In overlay mode, also called as Opportunistic Spectrum Access (OSA), the secondary devices use those part of licensed spectrum that are not currently utilized in space or time by any licensed device (also referred to as primary device, primary user, licensee, or incumbent). In doing so, the secondary devices must ensure that their transmissions do not cause unacceptable interference at any licensed receiver within their interference range. The secondary devices are equipped with cognitive radios, and therefore, their network is also referred to as cognitive radio network. The OSA approach has been investigated by DARPA as a part of their next generation networking program (XG Program) [3]. In underlay mode of operation, secondary devices transmit with sufficiently low power, and share the licensed spectrum band dynamically and concurrently with the licensed devices in such a manner that there is no perceptible change in the interference environment of any primary device. For a detailed taxonomy of dynamic spectrum access networks, see [4].

In this paper, we focuses on the Medium Access Control (MAC) protocol for a secondary cognitive radio network that operates in overlay mode. We refer to this protocol as Cognitive MAC (CG-MAC) protocol. We consider an IEEE 802.11 WLAN network as a de facto primary network in the ISM and UNII bands. 802.11 protocol uses CSMA/CA-based MAC protocol, and has been considered as de facto primary network in recent studies such as [5] and [6]. In the following subsections, we briefly introduce the challenges posed by CSMA/CA-based primary networks (such as WLAN) in design of secondary network cognitive MAC protocol, specify some sensing architecture options, and provide a brief overview of the proposed CG-MAC protocol.

A. Challenges in CSMA/CA-based Primary Network Systems

The MAC protocol for any secondary cognitive radio network depends significantly on the transmission characteristics and media access protocols of the primary network. CSMA/CA-based primary network systems, such as IEEE 802.11 WLAN, pose different types of challenges to secondary networks, which primarily stem from two characteristics of such primary systems: (i) A Primary User (PU) (also referred as Primary Node (PN), or WLAN node in this paper) performs Clear Channel Assessment before transmitting a frame, and defers its transmission if the channel is sensed busy, and (ii) Unlike time-slotted primary systems, a PU in CSMA/CA network does not have any pre-defined fixed time instants at which it may initiate frame transmission. Whenever a PU in CSMA/CA-based primary network, such as 802.11 WLAN, has a frame to transmit, it senses the channel. If the channel is sensed idle for a pre-defined amount of time (DIFS), the PU transmits the frame. If the channel is sensed busy, the PU defers its access and waits for the channel to become idle for the DIFS duration. It then generates an exponential counter value and decrease the counter by one after every slot time. The node freezes the counter as soon as the channel becomes idle again. The frame is transmitted as soon as the counter value reaches zero.
The above-mentioned characteristics of CSMA/CA-based primary systems have several consequences. The consequence of the first characteristic is that if a PU has a frame to transmit on a channel, and the channel is currently being used by a Secondary User (SU) (also referred to as Secondary Node (SN) in this paper), then the PU is forced to defer its transmission till the SU relinquishes the channel! This is clearly an infringement by the SU into the privileges of the primary user. This consequence also highlights the fact that an SU should not capture the channel for an unreasonably long duration, as this may force ready-to-transmit PUs to defer their transmissions. In absence of any knowledge of when the PUs may require the channel for their transmissions, the secondary users do not have any logical criteria to decide when to stop transmission and relinquish the channel. Also, unlike time-slotted primary systems, where PUs start transmission in the beginning of the slot irrespective of whether the slot is used or not by any other SU, the CSMA/CA PUs do not even start using the channel if the channel is being used by an SU (as indicated by their Clear Channel Assessment). Therefore, ignoring this consequence in the design of MAC protocols for SNs operating in CSMA/CA-based primary networks may enable an SU to prevent a PU from using a channel if the SU transmits a large number of frames after acquiring an idle channel.

The second characteristic of CSMA/CA-based PN mentioned above leads to an uncertainty in the time instants when a PU may initiate its frame transmission. This uncertainty poses the following problem for SUs: Once an SU acquires an idle channel, it can not decide how long it can keep the channel. A trivial solution is to relinquish the channel after one frame transmission. But sensing and channel selection on per-frame basis is costly from power consumption point-of-view, and decreases the secondary network throughput. Some authors have proposed to set a fixed maximum transmission time \( T \) (for e.g. see [7]). The SU can transmit back-to-back multiple frames on an idle channel, subject to the maximum time limit of \( T \). The problem is to select an appropriate value of \( T \). If \( T \) is set to a very high value, it may force PUs to defer access to the channel. If \( T \) is set to a low value (for e.g. equal to one frame transmission time), it will increase the MAC-level overheads and waste potential transmission times on the idle channel, thereby degrading the secondary network throughput.

B. Sensing Architectures

An important aspect of sensing is sensing architecture. For sensing the channels at each secondary node, several alternatives can be considered. Each one has its own limitations. The secondary node can either use dedicated sensors for each channel that continuously sense their respective channels (this is a costly and sometimes impractical approach, but it is required if the node wants to precisely detect Primary signals using matched filters). Otherwise, the secondary node can use one sensing module that senses the channels in round robin manner. The third alternative is to assume that a central server is dedicated to sense all the channels. The secondary nodes can obtain the sensing results from the central server. The above methods are examples of asynchronous sensing, wherein each secondary node independently and asynchronously senses the channels. The other possible approach is synchronous sensing in which secondary nodes synchronize during a quiet period and suspend their transmissions to detect the presence of any primary signals. We assume asynchronous sensing but our proposed approach is not limited by any sensing architecture.

C. Overview of the Proposed Cognitive MAC

In this paper, we propose a Cognitive MAC protocol (CG-MAC) for secondary cognitive radio networks. The proposed protocol is a model-based protocol that constructs the channel occupancy models for all the channels in the primary network, and uses these models to perform medium access control. Each secondary node constructs occupancy model for every channel based on primary user channel occupancy statistics gathered for that channel. These statistics can either be gathered by the node itself by employing one or more sensing modules, or by an external central server, as mentioned in the previous subsection. Whenever a secondary node has one or more MAC layer frames to transmit, it uses the models to decide the subset of channels that it should sense and the order in which to sense these channels. Based on the sensing outcomes, the node constructs a preferable channel list. The list contains those channels that the sender node will prefer to use for communication with the receiver. The list also contain a model-based estimation of the duration for which each channel is likely to remain idle. The sender node then uses a 3-way handshake protocol with receiver node to finally decide a mutually acceptable channel that can be used for communication between them. The handshake protocol uses a fixed dedicated control channel.

The CG-MAC protocol has been designed for opportunistic use of a multichannel primary network by a secondary cognitive radio network. But, in this paper, we focus our attention on one primary WLAN channel and investigate the advantages of using model-based CG-MAC protocol in (i) enhancing the secondary network throughput by opportunistically using a primary network channel, and (ii) increasing the channel utilization. We also study whether opportunistic use of the primary channel by CG-MAC-enabled secondary nodes lead to any performance degradation of the primary network. In view of these goals, we consider only a single WLAN channel in the primary network. Since we focus only on a single channel WLAN (primary) network, we do not address the model-based efficient channel sensing and channel selection issues in this paper, and postpone those studies for a future paper. In this paper, we mainly address the issue of how a secondary node uses channel model to opportunistically access and capture an idle primary channel to (i) maximize its own throughput, and (ii) maximize overall channel throughput/utilization, without causing any significant degradation in primary WLAN performance.

This paper is organized as follows. In Section II, we specify the assumptions and the network model used in our work.
In Section III, we specify the problem definition related to cognitive MAC protocol that we address in this paper. Section IV briefly describes the major related work. In Section V, we briefly review the theory of alternating renewal processes and availability analysis of a 2-state repairable system. This theoretical framework is used in our work of modeling the channel occupancy and controlling the access to the medium. Section VI describes the notations used in the paper. In Section VII, we describe the alternating renewal theory-based channel occupancy model that we propose in this paper. This model is used in the proposed Cognitive Medium Access Protocol (CG-MAC), which is described in Section VIII. Section IX describes simulation results. We conclude the paper with conclusions and pointers to our future work in Section X.

II. NETWORK MODEL

In this section, we specify the assumptions and the network model used in our work.

A. Assumptions

In this work, we make the following assumptions:

1) There is one WLAN channel in the primary network, which is used for data communication. Control frames, if any, are transmitted on a separate channel.
2) The primary network uses CSMA/CA-based protocol. We consider IEEE 802.11 as the de facto primary system in ISM band.
3) The secondary nodes perform perfect sensing. That is, the probability of false alarm and missed detection is zero. This assumption is made to keep the analysis tractable and has also been used in many earlier works (for e.g. see [8]).
4) We assume that each secondary node has a dedicated sensing module for the data channel to obtain channel occupancy statistics. The CG-MAC approach proposed in this paper does not depend upon this assumption, as any other sensing mechanism or architecture that can accurately obtain the channel occupancy statistics can instead be used by secondary nodes.
5) We assume that each secondary node is equipped with one data transceiver that is used to transmit and receive data frames. A separate control transceiver is required to accomplish handshake between sender and receiver nodes for media access coordination. Further details of the model are given in Section IX-A.

B. Network Model

We consider a primary 802.11 WLAN network with a single data channel. The channel is used by a primary WLAN client node, and a primary WLAN server node for HTTP-based web browsing application. We consider one pair of secondary devices (a secondary sender node and a corresponding secondary receiver node) that opportunistically uses the channel. The secondary nodes construct a channel occupancy model based on the observed channel occupancy statistics and use this model to predict residual idle time for the channel. The secondary node transmits as many frames as possible during the residual idle time so that the channel utilization can be maximized, without significantly degrading the performance of the primary network. This simple model enables us to assess the performance benefits of using model-based media access control of the channel by the secondary network.

III. PROBLEM DEFINITION

In this section we define the specific problems related to Cognitive MAC protocol for secondary network that are addressed in this paper. We first define the problem from the perspective of a multichannel primary network, and then concentrate on those parts of the problem that we address for a single channel primary network in this paper.

We consider the problem of medium access control in cognitive radio-based secondary networks. Such networks opportunistically uses idle channels in multichannel primary networks, where the channels are licensed to some primary operator. (We consider IEEE 802.11 WLAN network as de facto primary network in ISM and UNII bands.) Whenever a secondary node has one or more frames to transmit to another secondary node, the sender and receiver nodes must select one (or more) mutually acceptable channels and tune to it before commencing communication. The secondary nodes follow the following three steps to select the communication channel. First, the sender node senses the network channels. Second, out of the sensed channels, it select those channels that it finds preferable for communication. (This subset of channels is called as Preferable Channel List.) For each sensed channel, the sender node applies a condition check, that we refer to as Preferable Channel Condition check (PCC). If the channel passes the check, it is included in the Preferable Channel List of the sender. The node also uses the channel models to estimate the time for which each channel is likely to remain idle, and includes these estimates (along with corresponding preferable channels) in the list. In the final step, the sender node negotiate with the receiver and select one or more mutually acceptable channels from the Preferable Channel List.

When we focus on a single channel primary network, the problem gets narrowed down to constructing and using the channel model to predict the duration for which the channel is likely to remain idle from the time of sensing. In other words, if the channel is sensed idle by a ready-to-transmit secondary node, then the secondary node should be able to use the channel occupancy model to estimate the duration for which the channel is likely to remain idle from the time of sensing. (This duration is called as residual idle time.) The sender and receiver secondary nodes should handshack with each other to decide the minimum residual idle time for which the channel can be opportunistically used, without degrading the primary WLAN performance. The issues of efficient channel sensing order and channel selection do not arise in this case as we consider only one data channel in the primary network.

We have adopted alternating renewal theory-based approach to devise a channel occupancy model. The Cognitive MAC
protocol (CG-MAC) that uses this model is described in Section VIII.

IV. RELATED WORK

Model-based approach to spectrum utilization in cognitive radio networks have recently gained a lot of attention in research community. The authors in [7] have proposed a proactive spectrum access approach where secondary nodes take input from spectrum sensing modules, and build predictive statistical models of spectrum availability on each channel. The authors have used TV broadcast network as primary network. The model is used to intelligently plan channel usage to maximize utilization and minimize disruptions to primary users. Though the goals of this work are similar to ours, the modeling approach is different. The authors have proposed a three-tier model build using the availability statistics from the three types of observation windows: Immediate (1 minute), Short-term (15 minutes), and Long-term (30 minutes). For a given tier $k$ with observation window of length $t_k$, the availability of channel $i$ is estimated by dividing the total channel free duration observed over interval $t_k$ by the number of switches made by primary users to the channel $i$ within duration $t_k$. The overall usability of the channel is computed as the weighted sum of the availability values from all the three observation windows. The authors have also used the concept of usability filter to eliminate unreliable channels with heavy and frequent appearance of primary users.

The work on proactive spectrum access reported in [7] has been extended in a “work in progress” paper [9]. In this paper, the authors have proposed: (i) proactive channel availability prediction by secondary users using the past channel observations, and (ii) intelligent channel switching using the channel availability prediction results. The authors have also used renewal theory on past channel observations to estimate future spectrum availability. Specifically, the authors estimate the probability that a channel will be idle in the next time slot. They use this prediction to switch channel and avoid collision with any primary user transmissions. The authors have considered three models: the first one in which both the idle and busy time durations are exponentially distributed, the second, in which both idle and busy time durations are fixed periodic value, and the third, in which the idle (or busy) period is fixed, and the busy (or idle) period is exponentially distributed. Our work differs from this work in the sense that we use the alternating renewal theory based channel occupancy model to predict (or estimate) the remaining (or residual) idle time on the channel and transmit back-to-back as many frames as possible in the estimated remaining idle time.

Alternating renewal theory is also used to analyze how often to sense the availability of licensed channel and in which order to sense those channel. In [10], authors have used the renewal theory to devise optimal channel sensing periods for each channel to maximize the discovery of spectrum opportunities. Unlike our work, where the mean residual idle time duration is used to transmit multiple frames on the channel, the authors in [10] use the concepts of residual busy and idle time durations to devise optimal channel sensing periods.

Coexistence of cognitive radio based devices and WLAN nodes has recently been studied in [6]. In this work, the WLAN behavior is predicted based on a continuous-time Markov chain model. The cognitive medium access is derived from the CTMC model by casting the channel access problem as a constrained Markov decision process. In a related work reported in [5], the authors construct WLAN behavior model by fitting various distributions to the busy and idle periods recorded by a spectrum analyzer. The authors conclude that Hyper-Erlang distribution show much better fit than widely used exponential distribution, but, nevertheless, an exponential distribution is still interesting because it simplifies the derivation of access schemes.

There have been several other proposals on MAC protocol for cognitive radio networks. In [11], authors formulate the problem of optimal sensing decision for a single secondary transmission pair as an optimal stopping problem. Some of the other cognitive MAC protocols reported in the literature are [12], [13], [14], [15], [16], [17], [18] and [19].

V. ALTERNATING RENEWAL PROCESSES AND AVAILABILITY ANALYSIS OF A 2-STATE REPAIRABLE SYSTEM

In this section, we briefly review the theory of alternating renewal processes and availability analysis of a 2-state repairable system. A 2-state repairable system is one that remains operational for some duration of time before failing. It remains in down state till it gets repaired. The system is then put to use again after repair. This cycle repeats till the end-of-life of the system. The system therefore exists in one of the two possible states: an up state, and a down state. Availability measures of such a system are analyzed using the theory of alternating renewal process (see [20] and [21]). The process consists of renewal cycles, each consisting of operational period followed by down period. The renewal event occurs whenever the system becomes operational (after repair). The process starts when the new system is put to use. On time line, such alternating renewal process is shown in Figure 1 (vertical arrow denotes the renewal event, time between two vertical arrows denote a renewal cycle, solid segment within one cycle denote up time, and dashed segment within a cycle denote down time). Let the continuous random variables $T_B$, $T_C$, and $T_{U+D}$ denote the up time, down time, and total cycle time respectively. We represent the duration of ith cycle by $T_C$, the up time within ith cycle as $T_B$, and the down time within ith cycle as $T_{U+D}$. Figure 1 shows three cycles: cycle (i - 1), cycle i, and cycle (i + 1).
We assume that the sequence of random variables \( \{T_{C_i} = T_{I_i} + T_{B_i} | i = 1, 2, \ldots \} \) is mutually independent. Further, we assume that both the sequence of random variables \( \{T_{I_i}\} \) and \( \{T_{B_i}\} \) are independent and identically distributed, although \( T_{I_i} \) and \( T_{B_i} \) (within a cycle) can be dependent. In this paper, we assume that \( T_{I_i} \) and \( T_{B_i} \) are independent. We use the above model of a 2-state repairable system in our work of channel occupancy modeling. Below, we describe some availability measures for 2-state repairable system, as well as some results from alternating renewal theory that we use in design of CG-MAC protocol for secondary networks.

Let \( f_{T_{I}} \) and \( f_{T_{B}} \) represent the probability distributions for system up time and down time in each cycle. Let \( f_{T_{I}} \) and \( f_{T_{B}} \) represent the corresponding densities functions. Since \( T_{I_i} \) and \( T_{B_i} \) are independent for each cycle \( i \), and the cycle time \( T_{C_i} \) is sum of \( T_{I_i} \) and \( T_{B_i} \), therefore, the underlying density \( (f_{T_{C_i}}) \) of the renewal process (i.e., cycle C) is convolution of \( f_{T_{I}} \) and \( f_{T_{B}} \). That is,

\[
f_{T_{C_i}}(x) = \int_0^x f_{T_{I}}(\tau)f_{T_{B}}(x-\tau)d\tau, \quad 0 < x < \infty \quad (1)
\]

Assuming that Laplace transform exists for the above densities, we can write [20]:

\[
\hat{f}_{T_{C_i}}(s) = \hat{f}_{T_{I}}(s)\hat{f}_{T_{B}}(s)
\]

where \( \hat{f}_{T_{C_i}}(s) \), \( \hat{f}_{T_{I}}(s) \), and \( \hat{f}_{T_{B}}(s) \) are Laplace transforms of \( f_{T_{C_i}} \), \( f_{T_{I}} \), and \( f_{T_{B}} \) respectively.

In alternating renewal theory, a "renewal" is said to occur whenever a cycle (consisting of up and down periods) starts. A metric of interest to our work is average number of renewals \( m(t) \) in the interval \((0, t)\) which is defined as the expected number of renewals that have occurred till time \( t \). The Laplace transform of \( m(t) \) is given by [20]:

\[
\hat{m}(s) = \frac{\hat{f}_{T_{I}}(s)\hat{f}_{T_{B}}(s)}{(s[1 - \hat{f}_{T_{I}}(s)\hat{f}_{T_{B}}(s)])}
\]

(3)

Taking inverse Laplace transform of \( \hat{m}(s) \), we can obtain expression for \( m(t) \).

Other availability measure of a 2-state repairable system that can be computed using alternating renewal theory and is of interest in devising the proposed Cognitive MAC protocol is Expected residual time (or, mean residual time, or, mean forward recurrence time, or, mean excess time). If we randomly incident in any cycle at time instant \( t \), then the mean residual (or excess) time at \( t \) (i.e. the time of the next renewal event from instant \( t \)) can be written in terms of \( m(t) \) as follows [22]:

\[
E[T_{R}(t)] = \mu[m(t) + 1] - t \quad (4)
\]

Here, \( T_{R}(t) \) is the excess/residual time at \( t \), \( E[T_{R}(t)] \) is the expected residual time at \( t \), and \( \mu = E[T_{C_i}] \), expected cycle time (which can be obtained from the distribution of \( T_{C_i} \)).

Two related measures of interest are mean residual up time and mean residual down time. We explain these two measures with the help of Figure 2 and Figure 3. In both the figures, \( T_{I} \) (solid segment) and \( T_{B} \) (dashed segment) denotes the up time and down time respectively within a cycle. Again, \( t \) denotes the instant at which we randomly incident in the cycle. \( T_{R}(t) \) denote the residual time of the complete cycle at instant \( t \). If the system is up at instant \( t \) (see Figure 2), then the remaining (residual) up time is shown as \( T_{RI}(t) \) and can be obtained by subtracting the down time \( (T_{B}) \) from the total cycle’s residual time \( (T_{R}(t)) \). Similarly, if the system is down at instant \( t \) (see Figure 3), then the remaining (residual) down time is shown as \( T_{RB}(t) \) and is equal to the total cycle’s residual time.

VI. Notations

In this section, we introduce the notations used in rest of the paper.

\( T_{I} \), \( T_{B} \): Random variables denoting idle and busy periods for channel \( c \).

\( T_{C} \): Random variables denoting total cycle time for channel \( c \) \( (T_{C} = T_{I} + T_{B}) \).

\( f_{T_{I}}, f_{T_{B}}, f_{T_{C}} \): Exponential density functions of random variables \( T_{I}, T_{B}, T_{C} \) respectively.

\( \hat{f}_{T_{I}}(s), \hat{f}_{T_{B}}(s), \hat{f}_{T_{C}}(s) \): Laplace transforms of Exponential density functions \( f_{T_{I}}, f_{T_{B}}, \) and \( f_{T_{C}} \) respectively.

\( \lambda_{I} \): Parameter of Exponential distribution for Idle period on channel \( c \).

\( \lambda_{B} \): Parameter of Exponential distribution for Busy period on channel \( c \).

\( S_i(c) \): A boolean variable that denotes the outcome of sensing a channel \( c \) at time instant \( t \) by a secondary node. \( S_i(c) \) can either take value BUSY or IDLE.

\( T_{R}(t) \): A random variable that denotes residual idle time for channel \( c \) at sensing instant \( t \). \( E[T_{R}(t)] \) denotes its expected value.

\( T_{RH}(t) \): A predefined threshold for residual idle time.

\( T_{RB}(t) \): A random variable that denotes residual busy time for channel \( c \) at sensing instant \( t \). \( E[T_{RB}(t)] \) denotes its expected value.
$T^c_R(t)$: A random variable denoting residual time of the renewal cycle for channel $c$ at instant $t$. $E[T^c_R(t)]$ denotes its expected value.

$T^B_c$: A random variable denoting busy time for channel $c$. $E[T^B_c]$ denotes its expected value.

$\mu^c$, $\mu^c$: Mean busy time and mean cycle time for channel $c$ respectively.

$m^c(t)$: Average number of renewals occurred up to time $t$ on channel $c$.

$T^c_{ERI}$: Effective residual idle time on channel $c$. This is computed as: $T^c_{ERI} = \min\{T^c_{RI}(t)_{send}, T^c_{RI}(t)_{recv}\}$, where $(T^c_{RI}(t))_{send}$ is the residual idle time for channel $c$ in senders’ SRTS frame, and $(T^c_{RI}(t))_{recv}$ is the residual idle time on channel $c$ at time instant $t$ as estimated by the receiver using channel occupancy model.

SRTS: Secondary RTS frame
SCTS: Secondary CTS frame
CONF: Confirmation frame

VII. ALTERNATING RENEWAL THEORY BASED CHANNEL OCCUPANCY MODEL

In this section, we use the theory of alternating renewal process, described in the previous section, to model occupancy of each channel by primary users.

A. Channel Occupancy Modeling

We treat a licensed channel as a 2-state repairable system. From this point of view, a multichannel primary network can be considered to have multiple systems (channels) which are used concurrently. We consider a channel to be available or idle (from SU’s perspective) when it is not used by any primary user. This corresponds to the up state of the system during which it remains available for use. Similarly, we consider a channel to be busy or occupied (from SU’s perspective) when it is used by any primary user. This corresponds to the down state of the system during which it is under repair and is not available for use. Note that the channel occupancy modeling is performed by secondary user. Idle state of the channel corresponds to the up state of the system, and the busy state of the channel corresponds to the down state of the system.

Each secondary node should construct the occupancy model for all the channels in the primary network. To do this, it should gather the primary user occupancy statistics (idle and busy durations) for each channel. A channel’s occupancy is modeled as an alternating renewal process in which a cycle consists of idle duration followed by busy duration. Renewal of a cycle is said to occur when the channel becomes idle (i.e., the primary user stops transmitting on the channel). With sufficient data, each secondary node fits an appropriate distribution to idle and busy periods. Phase type distributions, such as Hyper Erlang distribution (HErD), have been shown to provide good fit to the values of non-negative continuous random variables [23], but are non-trivial to track analytically. For analytical tractability, in this paper, we fit Exponential distributions (with different parameters) to the collected traces of idle and busy periods of each channel. Exponential distributions have shown to provide acceptable fit and are used in several recent works such as [6]. Therefore, for a channel $c$, the random variables $T^I_c$ and $T^B_c$ are distributed exponentially as $EXP(\lambda^I_c)$ and $EXP(\lambda^B_c)$, where $\lambda^I_c$ and $\lambda^B_c$ are parameters of exponential distributions for $T^I_c$ and $T^B_c$. The distribution of the cycle time $T^c_{CI}$ (which is equal to $T^I_c + T^B_c$) is therefore 2-Erlang. Since $\lambda^I_c \neq \lambda^B_c$, the random variable $T^c_{CI}$ is 2-stage Hypoexponentially distributed.

In the following subsection, we derive the channel availability measures for a given channel using Exponential distributions for idle and busy periods. These measures are based on the availability measures of 2-state repairable system described in Section V.

B. Computation of Channel Availability Measures

In this section, we compute the channel availability measure based on the availability theory of 2-state repairable system described in section V.

1) Exponential density function of $T^I_c$ and its Laplace transform is computed as follows:

$$f^I_{T^I_c}(t) = \lambda^I_c e^{-\lambda^I_c t}, \quad (t \geq 0)$$

$$\hat{f}^I_{T^I_c}(s) = \frac{\lambda^I_c}{s + \lambda^I_c}$$

2) Exponential density function of $T^B_c$ and its Laplace transform is computed as follows:

$$f^B_{T^B_c}(t) = \lambda^B_c e^{-\lambda^B_c t}, \quad (t \geq 0)$$

$$\hat{f}^B_{T^B_c}(s) = \frac{\lambda^B_c}{s + \lambda^B_c}$$

3) Using (1) and (2), we obtain the expressions for the underlying Hypoexponential density ($f^E_{T^c_c}$) of the renewal process (i.e., cycle $C$) for channel $c$ and its Laplace transform as follows:

$$f^E_{T^c_c}(t) = \int_0^t \lambda^I_c e^{-\lambda^I_c \tau} \lambda^B_c e^{-\lambda^B_c (t-\tau)} d\tau$$

$$= \frac{\lambda^I_c \lambda^B_c}{\lambda^B_c - \lambda^I_c} e^{\lambda^I_c t} - \frac{\lambda^I_c \lambda^B_c}{\lambda^B_c - \lambda^I_c} e^{\lambda^B_c t}$$

$$\hat{f}^E_{T^c_c}(s) = \frac{\lambda^I_c \lambda^B_c}{(\lambda^I_c + s)(\lambda^B_c + s)}$$

The mean value of 2-stage Hypoexponential random variable $T^c_c$ for channel $c$ is given as follows [20]:

$$\mu^c = E[T^c_c] = \frac{1}{\lambda^I_c} + \frac{1}{\lambda^B_c}$$

4) Using (3), Laplace transform of the average number of renewals $m(t)$ for channel $c$ is given as follows:

$$\hat{m}^E(s) = \frac{\lambda^I_c \lambda^B_c}{s[(\lambda^I_c + \lambda^B_c)(\lambda^I_c \lambda^B_c) + s^2]}$$

Inverting the above Laplace transform using partial fraction (see [20]), we get,

$$m^c(t) = \frac{\lambda^I_c \lambda^B_c t}{\lambda^I_c + \lambda^B_c} [1 - e^{-(\lambda^I_c + \lambda^B_c) t}], \quad t \geq 0$$
5) Using (4), (11), and (13), we obtain the mean residual time at time instant $t$ for channel $c$ as follows:

$$E[T_c(t)] = \frac{1}{\lambda} + \frac{1}{\lambda_B} \left[ \frac{\lambda_t \lambda_B}{\lambda_t + \lambda_B} \right] + 1 - e^{-\left(\lambda_t + \lambda_B\right) t} + 1$$

We use the above expressions for channel availability measures in the Cognitive MAC protocol proposed in Section VIII.

VIII. COGNITIVE MEDIUM ACCESS CONTROL PROTOCOL

The Medium Access Control (MAC) protocol for cognitive radio-based secondary network plays a vital role in its opportunistic access of the idle primary channels. An efficient MAC protocol maximizes the utilization of spectrum opportunities, and minimizes the sensing and other overheads related to channel access. In this section, we describe the proposed Cognitive MAC protocol (CG-MAC) for secondary networks that opportunistically uses CSMA/CA-based primary WLAN channel. The protocol uses a model-based approach to control the channel access.

We assume that each secondary node has constructed channel occupancy model based on alternating renewal process, as described in Section VII. In a single channel primary network (as assumed in this paper), whenever a secondary sender node has one or more frames to transmit at time instant $t$, its CG-MAC algorithm performs the following actions:

1) Sense the channel at instant $t$.
2) If the channel is sensed idle, then
   a) Estimate the residual idle time for the channel using the channel occupancy model, and
   b) Send a SRTS (Secondary RTS) frame to the intended secondary receiver node. The SRTS frame contains the model-based estimated residual idle time for the channel.
3) If the channel is sensed busy, estimate the residual busy time using the model and back-off for the estimated duration before sensing again up to a maximum retry limit.

On receiving the SRTS frame, the secondary receiver node’s CG-MAC protocol performs the following actions:

1) Sense the channel. If the channel is sensed busy, do not respond (the sender will time-out).
2) If the channel is sensed idle, then
   a) Estimate the effective residual idle time using the occupancy model it has constructed for the channel as follows: Effective Residual Idle Time $= \min \{\text{residual idle time send by the sender in SRTS frame, residual idle time estimated by the receiver using its model}\}$
   b) Send the Effective Residual Idle Time value to the sender in SCTS (Secondary CTS) frame.

On receiving the SCTS frame, the secondary sender node’s CG-MAC protocol performs the following actions:

1) It transmits a CONF frame with the received Effective Residual Idle Time value so that the secondary nodes within its transmission range comes to know of the duration for which the channel will remain busy. The SRTS, SCTS, and CONF frames are sent on a dedicated control channel.
2) It computes the maximum number of secondary node frames (each of 4 KBytes), which can be transmitted in

**Algorithm 1 CG-MAC algorithm at secondary sender node (for Single Channel)**

1: procedure CG-MAC($t$, $c$)
2: Compute $S_t(c)$.
3: if $S_t(c) == IDLE$ then
4: Compute $E[T_{RI}(t)] = (\mu^c[m^c(t) + 1] - t) - E[T_B]$ (4)
5: if $E[T_{RI}(t)] > T_{RI}$ then
6: Construct $SRTS(c, T_{RI}(t))$ frame.
7: Send $SRTS(c, T_{RI}(t))$ frame to the receiver.
8: else
9: Compute $\mu^c$ using the model.
10: Backoff for $\mu^c$ duration and sense the channel again.
11: end if
12: else if $S_t(c) == BUSY$ then
13: Compute $E[T_{RB}(t)] = \mu^c[m^c(t) + 1] - t$ (11)
14: Backoff for $E[T_{RB}(t)]$ duration before sensing the channel again.
15: end if
16: On receiving $SCTS(c, T_{ERI}(t))$ frame from the receiver, broadcast $CONF(c, T_{ERI}(t))$ frame.
17: Compute number of frames (say, M) that can be transmitted in $T_{ERI}(t)$ duration.
18: Compute number of frames to transmit (say, X): X = min(M, number of frames available in transmission queue)
19: Transmit X frames back-to-back.
20: end procedure

**Algorithm 2 CG-MAC algorithm at secondary receiver node (for Single Channel)**

1: procedure CG-MAC($t$, $c$)
2: Receive $SRTS(c, T_{RI}(t))$ frame from the sender.
3: Compute $S_t(c)$.
4: if $S_t(c) == IDLE$ then
5: $E[T_{RI}(t)] = (\mu^c[m^c(t) + 1] - t) - E[T_B]$ (13)
6: if $E[T_{RI}(t)] > T_{RI}$ then
7: $T_{ERI}(t) = \min \{T_{RI}(t), T_{RI}(t rake)\}$
8: Construct $SCTS(c, T_{ERI}(t))$ frame.
9: Send $SCTS(c, T_{ERI}(t))$ frame to the Sender.
10: else
11: Do nothing. \(\triangleright\) Sender will retransmit
12: end if
13: else if $S_t(c) == BUSY$ then
14: Do nothing. \(\triangleright\) Sender will retransmit
15: end if
16: Tune to the data channel and receive the frames sent back-to-back by the secondary sender node.
17: end procedure
Effective Residual Idle Time duration. Let us represent this number by $M$.

3) If the number of frames currently available for transmission in the queue are less than $M$, then transmit all the queued frames back-to-back. If the number of available frames in queue exceeds $M$, the transmit $M$ frames back to back.

In the following subsection, we specify the CG-MAC algorithm for sender and receiver secondary nodes operating in a single channel primary network system.

A. The Cognitive MAC Protocol (CG-MAC)

The CG-MAC protocol at the secondary sender node operating in a single channel primary network is described as Algorithm 1. The arguments $t$ to the CG-MAC procedure at the sender represents the time instant when a secondary node need to transmit one or more frames, and argument $c$ represents the primary channel. The corresponding protocol for secondary receiver node is described as Algorithm 2. The arguments $t$ to the CG-MAC procedure at the receiver represents the time instant when receiver receives SRTS frame from the sender. Argument $c$ represents the primary channel.

IX. Simulation Results

In this section, we present the simulation experiments and the results.

A. Simulation Model

The simulation model consist of two 802.11 wireless LAN nodes (a WLAN HTTP client node, and a WLAN HTTP server node), and two cognitive secondary nodes (a secondary sender node, and a secondary receiver node). All the nodes use 802.11 WLAN channel number 1. The WLAN nodes are separated from each other by a distance of 150 meters, and the secondary nodes are vertically separated from each other by a distance of 100 meters. All the four nodes are within the transmission range of each other, and therefore, both the secondary nodes construct nearly identical occupancy model for the channel. Since we consider only a single WLAN channel in this work, and the channel models constructed by the secondary nodes are almost identical, therefore, we do not simulate the exchange of control frames (SRTS, SCTS, and CONF) in this work. Readers should note that the control frames are exchanged between the secondary sender and receiver nodes primarily to select an appropriate channel in a multichannel network, and to obtain minimum residual idle time at the secondary sender and receiver node. In the present simulation model, both of these points are not an issue because we have assumed only a single channel, and both secondary sender and receiver compute almost identical residual idle time (as they construct nearly similar channel occupancy models).

We use OPNET simulator [24] to simulate the model. We configure an HTTP-based web browsing application provided by the simulator to run on the WLAN nodes. The main parameters for web browsing application are given in Table I. The simulation runs for 3500 seconds. For the first 1800 seconds, a sensor module within each secondary node passively senses the WLAN channel (without transmitting any data) to gather channel occupancy data. This data includes the channel idle and busy durations (due to WLAN transmissions). For the remaining 1700 seconds (1800 seconds to 3500 seconds), the secondary node uses the Alternating Renewal Theory-based channel occupancy model to predict the residual idle durations on the channel and use the channel opportunistically along with the WLAN running web application. A packet generator module within each secondary node generates a packet every 1.0 ms. These packets are opportunistically transmitted over WLAN channel by the radio transmitter module of the secondary node. If the transmitter module is busy transmitting a packet, the other packets generated by the generator module are queued up in a transmission queue, and subsequently transmitted when the transmitter module becomes free. Generating the packets at the constant rate of 1.0 ms ensures that secondary sender node always has one or more packet to transmit. This enables us to study the maximum secondary network throughput that can be achieved by the opportunistic transmissions, as well as their impact on primary system (WLAN) performance. Table II lists the main simulation parameters.

At this point, some observations on the nature of the occupancy data gathered by the secondary nodes is in order. The occupancy data consist of sequences of very small durations (of the order of milliseconds) of idle and busy periods. These sequences are separated by relatively large idle
duration values. A synthetic example of such data sequence is: 23.0(I), 0.0002654(B), 0.0004365(I), 0.0003040(B), 53.0(I), 0.0002148(B), 0.0003329(I), 0.0003947(B), 45.0(I). The unit of duration values is seconds. The letter (B or I) beside each duration value indicates whether the value denotes busy duration (B) or idle duration (I). The intermittent large idle durations are shown as italicized values, whereas the sequence of small idle and busy periods is underlined. Very small idle periods in each sequence is due to the WLAN protocol specific inter frame spacing durations (SIFS, DIFS, and EIFS) and backoff periods, encountered during the transmission of web pages from a single session. The busy duration values are observed due to the transmissions of WLAN frames (corresponding to web pages). The intermittent large idle durations (observed after every sequence of very small idle and busy periods) corresponds to the interval between invocation of two consecutive HTTP sessions. Since very small idle durations are practically not usable for opportunistic transmission on the channel by the secondary nodes, we aggregate each sequence of very small idle and busy period values as a single busy period. Consequently, we obtain a revised occupancy data file that consist of a sequence of busy periods (obtained by aggregation of small idle and busy periods), separated by relatively large idle periods. Continuing with the example sequence mentioned above, the revised occupancy data sequence is obtained by aggregating the (underlined) small idle and busy durations, separated by relatively large idle duration (italicized). The revised occupancy data sequence is: 23.0(I), 0.0010059(B), 0.00010059(B), 53.0(I), 0.0009424(B), 45.0(I). This revised occupancy data is used to construct the channel occupancy model.

With the above simulation model, four different scenarios are simulated. The scenarios are explained below.

1) Scn-1 (Only WLAN): In this scenario, the secondary nodes are disabled and they do not transmit any traffic during the complete simulation. Only WLAN nodes running web browsing application are operational.

2) Scn-2 (WLAN + SN_{1,F}): In this scenario, the secondary nodes do not construct any channel occupancy model. Instead, whenever the secondary sender node has one or more frames to transmit, it senses the channel. If the channel is found idle, it transmits one frame, and goes back to sense the channel again if it has another frame to transmit. If the channel is sensed busy, the node backs-off exponentially (in units of transmission slot time duration). This scenario models a conservative approach of transmitting only one frame whenever the channel is sensed idle. In order to compare this scenario with other scenarios, the secondary network remain dormant for first 1800 seconds of simulation (i.e. it neither senses the channel to gather channel occupancy data nor construct occupancy model), and becomes operational during 1800 seconds to 3500 seconds (end of simulation) of the simulation to use the channel opportunistically.

3) Scn-3 (WLAN + SN_{ART}): In this scenario, the secondary nodes observe the channel for first 1800 seconds, and construct the channel occupancy model based on the revised occupancy data that they gather. The secondary nodes fit exponential distributions to the busy and idle periods, and construct Alternating Renewal Theory-based channel occupancy model. Whenever the secondary sender node has one or more frames to transmit, and it senses the channel idle for a predefined channel observation duration, it uses the channel occupancy model to predict the residual idle time on the channel and transmit as many frames as possible in the predicted residual idle time. The reason for sensing the channel to be idle for predefined channel observation duration before initiating any transmission is as follows: When the secondary sender node senses the channel idle, it can not make out whether the channel is busy due to inter frame spacing duration (SIFS, DIFS or EIFS) or exponential backoff of WLAN nodes, or the channel is idle because the WLAN nodes have no data to transmit (this corresponds to inter-HTTP sessions durations). Since the secondary nodes do not use the inter frame spacing and backoff durations for opportunistic transmissions, the node senses the channel for the channel observation duration, which is set equal to the sum of DIFS, maximum WLAN MAC frame transmission time, SIFS, and WLAN MAC ACK transmission time. If the channel remains idle for this duration, the node can be sure that the channel is idle as the WLAN nodes currently do not have data to transmit on the channel.

4) Scn-4 (WLAN + SN_{MB}): This scenario models an extreme case. The secondary nodes do not construct any channel occupancy model. Instead, whenever the secondary sender node has one or more frames to transmit, it senses the channel. If the channel is found idle, it transmit all the frames that are currently queued up for transmission in its transmission queue. If the channel is sensed busy, the node backs-off exponentially (in units of transmission slot time duration). Again, in order to compare this scenario with other scenarios, the secondary network remain dormant for first 1800 seconds of simulation (i.e. it neither sense the channel to gather channel occupancy data nor construct occupancy model), and becomes operational during 1800 seconds to 3500 seconds (end of simulation) of the simulation to use the channel opportunistically.

B. Performance Metrics

We use the following performance metrics to assess the performance of model-based scenario (Scn-3 (WLAN + SN_{ART})) and compare it with the other three scenarios (Scn-1, Scn-2, and Scn-4):

1) Instantaneous channel throughput (packets/sec): This metric represents the average number of packets successfully received on the channel. It encompasses the packets from both primary (WLAN) and secondary networks. The metric value is computed by dividing the total number of
accepted packets to date (for both the networks) by the current simulation time.

2) **Time-averaged throughput of secondary network (packets/sec):** This metric represents the time-averaged throughput of secondary network, which is achieved as a result of opportunistic transmission by secondary nodes. It is calculated only for scenarios Scn-2, Scn-3, and Scn-4. The metric computation is based on simulation duration of 1800 seconds to 3500 seconds (end of simulation) during which the secondary network opportunistically uses the channel. In the first scenario (Scn-1), the secondary nodes are not operational throughout the simulation, and therefore, the secondary network throughput is zero.

3) **Average medium access delay (in seconds) for Wireless LAN:** This metric represents the average delay in accessing the medium by all the WLAN nodes. It shows the impact of opportunistic transmissions by secondary nodes on the medium access delay experienced by WLAN nodes. The medium access delay for WLAN nodes may get effected if, as a result of carrier sensing, the WLAN nodes are forced to defer their transmissions due to an ongoing opportunistic secondary network transmission.

4) **Average page response time of HTTP-based web browsing application running on WLAN nodes:** This metric represents the average page response time of the web browsing application. It shows the impact of opportunistic transmissions by secondary nodes on the performance of web browsing application.

### C. Results

In this section, we present the simulation results and compare the performance of Alternating Renewal Theory-based cognitive MAC protocol (used in Scn-3) with other scenarios (Scn-1, Scn-2 and Scn-4). Figure 4 shows the instantaneous channel throughput (in packets/sec) achieved in all the four scenarios. Since, for the first 1800 seconds in Scn-2, Scn-3, and Scn-4, the secondary nodes do not use the channel for opportunistic transmissions, the channel throughput for this duration in these scenarios is almost same as scenario 1 (Scn-1). From 1800 seconds onwards, the channel throughput in Scn-1 (see the bottom most curve in Figure 4) remain almost same, as the only traffic on the channel is the moderate web browsing traffic across the WLAN nodes, and there is no opportunistic usage of the channel by the secondary nodes. Scenarios 2 (Scn-2) and 3 (Scn-3) are conservative schemes in the sense that the nodes transmit one frame per sensing operation. Though this scheme has less likelihood of blocking WLAN transmissions or causing collisions, yet per frame sensing overhead is non negligible and it affects secondary network throughput. This is evident in the second curve from bottom in Figure 4. The channel throughput increases due to opportunistic transmissions by secondary nodes. The third curve from the bottom (the lighter of the two topmost curves) denote the channel throughput when the secondary nodes use ART-based model (Scn-3). In this scenario, once the node senses a channel idle, it uses the ART-based channel occupancy model to estimate the residual idle time on the channel, and transmit back-to-back an equivalent number of frames that can be transmitted in the estimated residual idle time on the channel. Therefore, for a single sensing operation, the node transmits multiple frames on the channel. On the other hand, if the model inaccurately over-predicts the residual idle time, the secondary node transmissions may force WLAN nodes to defer their transmission (if any). As shown in Figure 4, the model-based opportunistic channel access and transmissions significantly increases the channel throughput as compared to single frame opportunistic transmissions. The topmost curve in Figure 4 corresponds to scenario 4 (Scn-4) in which the secondary node, on sensing the channel idle, transmits as many frames as it has in its queue. This is very aggressive scheme, which may increase the secondary network throughput at the cost of substantial degradation in WLAN network and application performance.
In addition to the instantaneous channel throughput, we compare the time averaged throughput of only the secondary network in Scn-2, Scn-3, and Scn-4 (throughput of the secondary network in Scn-1 is zero). Since secondary network in these scenarios transmit data on the channel between 1800 seconds to 3500 second, the time-averaged throughput for secondary networks is reported for this duration. As shown in Figure 5, for ART model-based MAC (Scn-3), the secondary network throughput increases to approximately 300 packets/sec, which is considerably higher than the secondary network throughput in Scn-2 (in which single frame opportunistic transmission is performed per sensing operation). The aggressive scheme of Scn-4 understandably gives highest secondary network throughput, as the secondary node transmit as many frames as they have once they sense the channel idle.

Though the opportunistic transmissions by secondary nodes increases the channel throughput, they have some drawbacks. Particularly, in CSMA/CA based networks such as 802.11 WLAN, opportunistic transmission by secondary nodes may force a ready-to-transmit WLAN node to defer its transmission. This leads to an increase in media access delay for WLAN nodes, and adversely effects the application performance. In Figure 6 and Figure 7, we compare the average media access delay experienced by WLAN nodes in presence of opportunistic transmissions by the secondary nodes. As the scale of delay values (on Y-axis) for the Scn-1 and Scn-2 differ significantly from that of Scn-3 and Scn-4, the graphs are shown in two different figures (Figure 6 and Figure 7) for better visual appreciation of the values. The average WLAN media access delay for Scn-1 and Scn-2 is shown in Figure 6, and for Scn-3 and Scn-4 is shown in Figure 7. Figure 6 shows that in comparison to “Only WLAN” scheme (Scn-1), the average media access delay experienced by WLAN nodes in Scn-2 (the conservative scheme) does not increase much. In model-based scheme (Scn-3), as shown in Figure 7, the average media access delay experienced by WLAN nodes increases as the secondary nodes start using the channel opportunistically. This increase is significant in case of Scn-4.

The effect of opportunistic transmission on WLAN media access delay (as shown in Figure 6 and Figure 7) reflects onto the web page response time as well. This is shown in Figure 8 (for Scn-1, Scn-2, and Scn-4), and Figure 9 (for Scn-3). Again, the graphs are separated due to significant difference in scale of response times in the shown scenarios. The light dots in Figure 8 (between 0.01 and 0.02 seconds) denote the page response time for each page in Scn-1. The page response time marginally increase, specially after 1800 seconds (when secondary nodes start using the channel opportunistically), in case of Scn-2 (see light red dots above 0.02 seconds). In Scn-3 (in Figure 9), the page response time is significantly high after 1800 seconds. This is due to relatively high WLAN media access delay in Scn-3 as compared to Scn-1 and Scn-2. But in Scn-4 (in Figure 8), we note that not even a single page could be transacted between WLAN client and server due to aggressive usage of channel by secondary nodes. This is evident by the absence of any black dot after 1800 second.

X. CONCLUSION AND FUTURE WORK
The results obtained in the previous section indicate that the model-based approach to medium access has potential to deliver good performance as compared to totally conservative or extremely aggressive opportunistic media access schemes, provided the model is reasonably accurate. We feel that the relatively high media access delay (in Figure 7) and high page response time (in Figure 9) in case of ART model-based scenario (Scn-3) is an indication of the fact that fitting exponential distributions to busy and idle periods may be analytically tractable, but it seems not to be very accurate for modeling idle and busy time distributions of WLAN channel. Such conclusions are also drawn in [5] and [6], though the author in [6] have assumed exponential distribution in their simulations. In view of the possible inappropriateness in using exponential distribution in WLAN channel modeling, we are working to fit Hyper-Erlang distribution (HErD) to the channel occupancy data, and derive closed form expressions for mean
number of renewals and mean residual time (corresponding
to equations (13) and (14)) based on HErD. If such closed
form expressions can not be obtained or are non-trivial to
obtain, we plan to look at approximation algorithms to obtain
approximate expressions. In this work, we have assumed that
the idle and busy period durations within each cycle are
independent. We compute the residual idle time at instant
as the difference between the total residual time of the cycle
and the mean busy time. In future work, we plan to develop
a channel model without assuming independence of busy and
idle periods.

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