Spectrum Availability for Multi-channel MAC Protocol with Dynamic Control Channel in Opportunistic Spectrum Access

†Thant Zin Oo, ‡Choong Seon Hong
Department of Computer Engineering, Kyung Hee University, Yongin, 446-701 Korea
{†tzoo, ‡cshong }@khu.ac.kr

Abstract

Opportunistic spectrum access (OSA) was proposed to improve spectrum efficiency. We consider multiple channels for opportunistic spectrum access in which spectrum handoff can be performed to mitigate interruptions by the licensed primary users (PUs) to unlicensed secondary users (SUs). We develop a renewal process framework to model the licensed primary user signal activity of M operating channels. Based on the renewal framework, we design a multi-channel MAC protocol by assigning one of M operating channels as the common control channel (CCC). We then use cumulative process to show that spectrum availability for our proposed MAC protocol can be achieved. We perform extensive simulations to evaluate our proposal.

1. Introduction

The ubiquitous wireless traffic has been growing exponentially. Radio spectrum can be seen as a scarce resource which is expected to become more crowded in the near future. However, some of the radio spectrum assigned for some licensed primary users (PUs) is underutilized [1], for example, TV white spaces [2]. Opportunistic spectrum access (OSA) aims to increase spectrum utilization by allowing the unlicensed secondary users (SUs) to access idle spectrum on the condition that their transmission must not interfere with that of PUs [3] [4]. In [5], the authors discussed about sensing techniques and MAC protocols for the OSA networks. The main difference for OSA networks is that, the service channel is not always available and subjected to interruptions by higher priority PU traffic. A SU device must stop their transmission as soon as they detect a PU signal or a collision on the current operating channel. The SU network can recover by switching to another idle channel and continue the data communication.

2. System Model

We consider a scenario where a total of M licensed channels can be accessed by the SUs. We assume that for each channel, the PU signal activity can be modeled as an independent and identically distributed (*i.i.d.*) ON/OFF renewal process. An ON state will represent the time duration the PU signal is present on a channel. An OFF state will represent the time the PU signal is absent on a channel and this channel can, therefore, be used by the SUs. Note that the average ON-periods and OFF-periods depend on the channel usage pattern of the PUs.

From the point of view of SUs, the channel is alternating between ON (busy) and OFF (idle) states. We refer a spectrum access cycle for SUs as a renewal cycle in which a busy period is followed by an idle period. For channel-m, let the random variables T_X and T_Y represents the time durations of busy and idle states, respectively as depicted in Fig(1). Then, the renewal cycle duration, referred to as inter-arrival time, $T_Z = T_X + T_Y$, is also a random variable. Let $f_Z(t)$, $f_X(t)$ and $f_Y(t)$ denote the probability density functions (PDF) of inter-arrival time, busy time and idle time, respectively. The probability denoted by β_m, that channel- m is busy at any arbitrary time instance, can be derived as follows:

$$\beta_m = \frac{\overline{T_X}}{\overline{T_X}+\overline{T_Y}} = \frac{\overline{T_X}}{\overline{T_Z}} = \frac{\int_0^\infty t.f_X(t)\,dt}{\int_0^\infty t.f_Z(t)\,dt} \tag{1}$$

where $\overline{T_X}$, $\overline{T_Y}$, and $\overline{T_Z}$ are mean sojourn times of busy, idle and inter-arrival, respectively. Furthermore, let $U_m(t)$ and $V_m(t)$ be the backward and forward recurrence times respectively. Forward recurrence time is the age and backward recurrence time is the excess or residual life of the current renewal cycle. Intuitively, for OSA system, if the age of the current renewal cycle is given, the excess of the cycle can be estimated from previously observed statistics. However, $U_m(t)$ and $V_m(t)$ are limiting distributions and t must be sufficiently large enough for the renewal process to be an equilibrium renewal process.

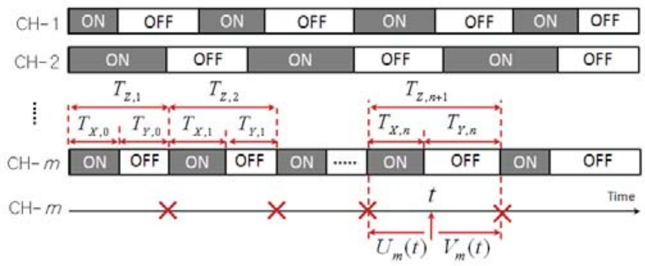

Fig.(1) ON-OFF channel model based on observation by SU network

3. Availability of Spectrum

We are interested in the number of channels available at any given time, especially for the CCC so that there is no disruption in the SU system network. As it is the nature of the OSA systems, CCC will be interrupted from time to time and has to switch to another channel to continue operations. Let N_C be the number of available channels, then the limiting probability that at least one channel is available for CCC can be expressed as:

$$\Pr\{N_C \geq 1\} = 1 - \prod_{m=1}^{M} \beta_m, \quad \beta_m \in (0,1) \tag{2}$$

where M is the total number of the channels. As can be observed from (2), as the number of channels, M, increases, $\Pr\{N_C \geq 1\}$ also increases and as M approaches infinity, $\Pr\{N_C \geq 1\}$ approaches to 1.

However, N_C is a random variable and dynamically changing with time. Since each channel- m is an alternating renewal process, $N_C(t)$ is a cumulative process and can be defined as [6];

$$N_C(t) = \begin{cases} \sum_{m=1}^{N(t)} W_m, & (N(t) = 1,2,\ldots,M) \\ 0, & (N(t) = 0) \end{cases} \tag{3}$$

where W_m is the reward or price depending on each individual alternating renewal processes. For our purposes, W_m is the number of channel and its value is either one, for a departure of a PU signal on a channel, or negative one, for the arrival of a PU signal on a channel. We created M independent alternating renewal processes and perform superposition to obtain the cumulative process, $N_C(t)$. We then calculate the PMF and CDF for each $\Pr\{N_C(t) = n\}$, $n \in \{0,1,\ldots,M\}$.

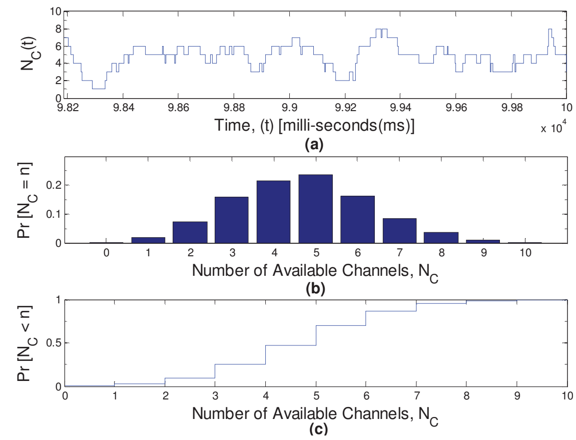

Fig.(2) (a) Number of available channels Vs time $N_C(t)$, (b) PMF of $N_C(t)$, and (c) CDF of $N_C(t)$ for the case $M = 10$

Fig.(2b) and Fig.(2c) displays the probability mass function (PMF) and CDF of number of available channels at any time $N_C(t)$, respectively. From Fig.(2b), we can see that the PMF is approximately normal, which agrees with the Central Limit Theorem. As the results in Fig.(2c) depicts, the probability of number of channels available for CCC, $\Pr\{N_C > 0\}$ almost equals one, which agrees with (17). However, we are more interested in $\Pr\{N_C > 1\}$, since our protocol design requires one channel for CCC and at least another channel for data communication. From Fig.(2c), for our simulation scenario of number of channels $M = 10$; $\Pr\{N_C < 2\} < 0.1$.

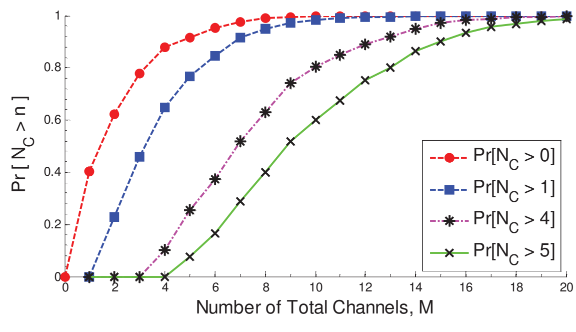

Fig.(3) Probability of spectrum availability $\Pr\{N_C > n\}$ Vs. total number of channels, M.

Furthermore, we want to study the effect of total number of channels, M, on the probability of spectrum availability. Fig.(3) depicts the probability of spectrum availability $\Pr\{N_C > n\}$ versus the total number of channels, M. The red (circle) line represents the availability of CCC for our proposal and the blue (square) line represents the availability of at least two channels. From Fig.(3), we can clearly see that, we need at least $M = 10$ channels for our proposal to achieve over 90% spectrum availability.

4. Recovery Time for Secondary Network

We are interested how long does the SU network takes to resume data communication after an interruption to the CCC by the PU signal. This recovery process is termed spectrum handoff and discussed in detailed in [7][8][9]. We will only focus on the recovery time in this paper.

If the SU devices have already agreed a backup channel to switch to in case of interruption by PU signal, the total recovery time, T_R, can be calculated as:

$$T_R = T_{CS} + T_{Sense} + \widehat{T_X} + T_{RxTx}, \qquad (4)$$

where T_{CS} is the channel switching time, T_{Sense} is the compulsory sensing time to check PU signal is present or absent and T_{RxTx} is the transceiver turn-around time. $\widehat{T_X}$ is the waiting time for PU signal activity and given by:

$$\widehat{T_X} = \begin{cases} \arg\min_{m \in \{1,\dots,M\}} \left\{ \overline{T_X} - U_m(t) \right\}, N_C(t) = 0 \\ 0 \qquad\qquad\qquad\qquad , otherwise \end{cases} \qquad (5)$$

and the average waiting can be given by:

$$E\left[\widehat{T_X}\right] = E\left[\widehat{T_X} \mid N_C = 0\right].\Pr\{N_C = 0\} + E\left[\widehat{T_X} \mid N_C > 0\right].\Pr\{N_C > 0\} \qquad (6)$$

where the second term of (6) equals to zero following (5). The first term of (6) depends on $\Pr\{N_C = 0\}$ and it approaches to zero when total number of channels, M, is increased. Therefore, for a sufficiently large M, the waiting time, $\widehat{T_X}$, is negligible.

If the SU devices have no agreed backup channel, each SU must switch to one channel after another until the network coordinator beacon can be detected. On each channel-m, a SU device must take a minimum time of $(T_{CS} + T_{Sense})$ to detect the beacon. Therefore, (4) is transformed into:

$$T_R = N_H.(T_{CS} + T_{Sense}) + \widehat{T_X} + T_{RxTx} \qquad (7)$$

where N_H is the number of channels the SU devices have to switch to meet with the coordinator. The value of N_H is dependent upon the current number of available channels $N_C(t)$ and its average value can be computed by:

$$\overline{N_H} = \overline{N_C} = \sum_{n=0}^{M} n.\Pr\{N_C = n\} \qquad (8)$$

The situation described in (7) is rare and most likely found in a new SU device joining an existing network. As long as the SU network has a backup channel and M is sufficiently large, $T_R = T_{CS} + T_{Sense} + T_{RxTx}$.

5. Conclusions

In this paper, we have shown that dynamic control channel can be adopted for opportunistic spectrum access. Moreover, our simulation results shown that we need a minimum of total operating channels, $M = 10$ to achieve over 90% spectrum availability for CCC. In addition, we discussed about the recovery time from PU signal interruption. We concluded that if total number of operating channels, M, is sufficiently large, the recovery time for PU activity is a constant. However, monitoring a large number of channels increase complexity and processing time.

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