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Analysis of Asynchronous Cognitive Radio System with Imperfect Sensing and Bursty Primary User Traffic

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Abstract This paper presents a theoretical analysis of the spectrum utilization levels in a cognitive radio system. We assume that the traffic of the primary network is bursty and asynchronous with the secondary network, which performs imperfect spectrum sensing. Collisions of the primary and the secondary packets are assumed to result in increased packet error probabilities. We present primary and secondary utilization levels under optimized secondary transmission periods for varying primary traffic characteristics and secondary sensing performance levels. The results are also validated by extensive Monte-Carlo simulations. We find that an asynchronous cognitive radio network with imperfect spectrum sensing is feasible when optimized transmission periods are used. The effects of primary traffic's burst pattern and secondary sensing performance are discussed.

Keywords Cognitive Radio · Asynchronous Opportunistic Spectrum Access · Channel Utilization

1 Introduction

Mobile Internet is experiencing a rapid growth. According to the latest Cisco Visual Networking Index [12], global mobile traffic has increased 81% in 2013 and it is expected to grow nearly eleven-fold between 2013 and 2018 to reach a monthly volume of 15 exabytes. Therefore, spectrally efficient design of wireless communication systems is of paramount importance. Recent studies show that, even when the air interface design is efficient, many bands are used sporadically in time or space, leading to inefficient overall utilization [17]. In order to improve spectral utilization, opportunistic spectrum access (OSA), also known as "cognitive radio networking," has been proposed. According to this phenomenon, whenever or wherever a band of spectrum is not used by its owners, which are called the Primary Users (PUs), Secondary Users (SUs) utilize them. When the PUs start using these bands, the SUs migrate to other unused bands.

MAC layer design has been the center of focus for a large fraction of cognitive radio (CR) literature, see [4] for a recent survey. Some of the proposed MAC strategies require synchronization of the secondary network to the slot structure of the primary network, however, this might not always be possible or desirable [3]. In this paper, we analyze such networks where the primary and secondary traffic are not synchronized.

It has been empirically shown that, WLAN traffic can be modeled by an on-off semi-Markov process [7]. Backed by this result, on-off continuous-time Markov chain (CTMC), which is an approximation to the semi-Markov process, is used to model unsynchronized traffic in the literature. In [16] and [11], joint CTMCs are used to model PU and SU traffic. Zahmati *et al.* [19] extend on [16] to consider multiple users. Delay analysis on a CTMC is performed based on queueing theory in [18]. Feng *et al.* [6] analyze SU handoff, blocking and forced termination probabilities, and utilization under various PU access models, as a function of number of SUs. The work in [13] focuses on the average SU delay as a function of PU traffic characteristics. The tradeoff between the sensing time and the SU system perfor-

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mance when the SU network employs channel bonding is investigated in [9]. In [2], Bayhan and Alagöz investigate the channel selection problem when PU traffic is modeled by CTMCs. All of the works above assume perfect channel sensing.

Among the works that assume the possibility of simultaneous transmission between the primary and secondary networks, one approach is the underlay OSA. In this approach, the SU network transmits with constraints on its radiated power such that the impact on the PU network is limited [8, 10, 14]. In this paper, we assume simultaneous transmission between happen PU and SU networks because SU sensing is imperfect and PU and SU traffic are asynchronous, and such transmission might result in collided packets. Among the works with similar approach, [1] models the PU-SU interaction with a CTMC. Blocking and dropping probabilities and SU utilization are given as functions of SU traffic arrival rate. In [15], Shah and Akan analyze the rate and delay of the SUs in a multi-user CR sensor network, where the PU and SU traffic are modeled by on-off CTMCs. In [20], spectrum sensing and transmission times of an SU network are jointly optimized for maximal SU throughput. These works do not consider the PU utilization levels. Cheng *et al.* [3] consider the PU utilization level for random access PU networks, where the carrier sensing mechanism may prevent the PU network from transmission. Unlike this work, we assume that the PU network accesses its band at will without consideration of the SU traffic.

In this work, an on-off CTMC is employed to model PU traffic that is not synchronized to the SU traffic. This work improves on the previous work on a multitude of fronts. First, both SU and PU networks' utilization levels are presented theoretically, where the PU network accesses the primary channel without consideration of the SU traffic, SU network is not synchronized to the PU network, and SU sensing is imperfect. Second, effect of simultaneous PU and SU transmission is incorporated into the analysis via an increased probability of packet error in a fashion that accounts for the asynchronous nature of the PU and SU transmission. Third, optimal transmission durations for maximal total utilization are presented for varying PU traffic characteristics and SU sensing performance levels, and the resulting utilization levels are reported, which are verified via extensive Monte-Carlo simulations. We find that an asynchronous cognitive radio network with imperfect spectrum sensing is feasible when optimized transmission periods are used. The effects of primary traffic's burst pattern and secondary sensing performance on the achieved utilization levels are also discussed.

The remainder of the paper is organized as follows. Section 2 presents the PU and SU network models. In Section 3, the theoretical analysis of PU and SU utilization levels is performed. Section 4 presents the utilization levels for optimal SU transmission periods under various system parameters and discusses the results.

2 System Model

We consider a single wireless communication channel owned by a PU network who can transmit at will regardless of any ongoing SU traffic. The SU network, on the other hand, may transmit over the channel only when it senses that PU traffic is absent. The transmissions of both networks are assumed to have finite packet error probabilities. Since SU sensing is imperfect and due to the asynchronous nature of the PU and SU traffic, simultaneous transmissions may occur, which we call as collisions. When there is a collision, the packet error probabilities for both networks increase. The details of the packet error models are given in Section 2.3. We define the channel utilization as the ratio of the time that the channel is used by the PU or SU networks for successful transmissions. The coordination of resource allocation between the users of the PU and SU networks is assumed to be performed by the relevant MAC functionalities [4], and is out of scope of this paper. Under this assumption, we will refer to the PU and SU networks as single entities and we will call them as PU and SU respectively, in the remainder of the paper.

2.1 PU Network Model

PU traffic is assumed to occupy the channel according to a two-state (on-off) continuous-time Markov Chain X_t, where $X_t = 0$ and $X_t = 1$ denote that the channel is not used (idle) and in use (busy) by the PU at time t, respectively. Composite PU traffic arrives at and leaves the channel at a rate λ and μ per unit time, respectively. Steady-state probabilities of idle and busy states are

$$\mathbb{P}\left(X_t = 0\right) = \frac{\mu}{\lambda+\mu}, \quad \mathbb{P}\left(X_t = 1\right) = \frac{\lambda}{\lambda+\mu} = U_{P_o}, \quad (1)$$

where, the probability of busy state is equal to the mean fraction of the time that the channel is occupied by PU traffic. We will call this as the "PU occupancy" and denote it by U_{P_o} in the remainder of the paper.

2.2 SU Network Model

Majority of the CR MAC layer literature assume a silent period for channel sensing [4]. Following a similar approach, we assume a time-slotted model for the SU network. At the beginning of each slot, SU senses the channel for the presence of PU for a sensing period of duration T_s. At the end of sensing, if the channel is found to be idle, the SU accesses it for a transmission period of T_t, assuming infinitely backlogged composite SU traffic. Without any loss of generality, we assume that $T_s = 1$ unit and all other time related quantities, such as the rates λ and μ, are defined relatively.

We assume imperfect sensing for SU, where, if the SU decides the channel to be idle at the end of the sensing period when there is an ongoing PU transmission, this is called a *missed detection*. According to this definition if the SU decides the channel to be idle, albeit any PU transmission present during the sensing period that has ended before the start of the transmission period, this is assumed to be a correct decision. On the other hand, collisions might occur even when a missed detection does not happen, due to the asynchronous nature of PU and SU traffic. This happens if PU transmission starts at a later time during the transmission period. We assume that at the end of the sensing period, if the SU decides the channel to be busy, but there is no ongoing PU transmission, this is called a *false alarm*.

2.3 Packet Error Model

We assume both PU and SU transmissions have finite packet error probabilities, which increase in the event of simultaneous transmission. The packet error rate (PER) in general depends on a multitude of factors such as transmission power, channel model (path loss, shadowing and fading), distance between the transmitter and the receiver, the modulation and coding scheme (MCS), *etc.* On the other hand, many modern telecommunication systems are designed to operate under a target PER [5], by adapting the transmission parameters (such as transmit power or MCS) dynamically in response to changing conditions. Thus, in the absence of any collision, the PU and SU are assumed to achieve a target PER of p_e^{PU} and p_e^{SU}, respectively, on average.

When PU and SU transmit simultaneously, we assume the average PER of the PU increases to $p_{\mathrm{int}}^{\mathrm{PU}}$, which is greater than p_e^{PU}. We assume that the SU network transmits one packet per SU slot. On the other hand, the PU traffic is assumed to be consisting of infinitely small packets conforming to the continuous-time traffic model. Therefore when there is a collision, the entirety of collided PU packets overlap with the SU transmission. On the other hand collided SU packets might partially overlap with the PU transmission. Therefore, the average PER for collided SU packets should be a function of PU channel occupancy.

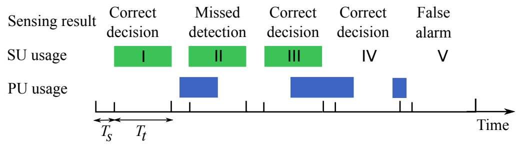


Fig. 1 Channel access example.

To model this, we define *effective* SU signal and noise energies $S_{\mathrm{eff}}^{\mathrm{SU}}$, and $N_{\mathrm{eff}}^{\mathrm{SU}}$, and *effective* interference power I_P due to simultaneous PU transmission. Actual signal, noise and interference levels might be different and varying over time due to changing conditions. However, we assume a target PER is achieved by dynamically adapting the MCS scheme and transmit power. Thus, these variables are defined to effectively achieve the target and reference PER levels according to our model. Consider p_t^{SU} to be the average PER of SU resulting from an average interference duration of t. We assume p_1^{SU} is known as a reference. Assuming packet error happens when the effective SINR, which is assumed to be Gaussian, drops below a threshold,

$$p_e^{\mathrm{SU}} = 2Q\left(\sqrt{\frac{S_{\mathrm{eff}}^{\mathrm{SU}}}{N_{\mathrm{eff}}^{\mathrm{SU}}}}\right),\ p_1^{\mathrm{SU}} = 2Q\left(\sqrt{\frac{S_{\mathrm{eff}}^{\mathrm{SU}}}{N_{\mathrm{eff}}^{\mathrm{SU}} + I_P}}\right), \quad (2)$$

where $Q(z) = \mathbb{P}(Z > z)$ when Z is a unit Gaussian random variable.

Given p_e^{SU} and p_1^{SU} values, the corresponding ratios $S_{\mathrm{eff}}^{\mathrm{SU}}/N_{\mathrm{eff}}^{\mathrm{SU}}$ and $S_{\mathrm{eff}}^{\mathrm{SU}}/I_P$ can be found using (2). Then for an average PU occupancy $\lambda/(\lambda+\mu)$ and SU transmission duration T_t, the average error rate for the SU packets when there is a collision is assumed to be

$$p_{\mathrm{int}}^{\mathrm{SU}} := p_{\frac{\lambda}{\lambda+\mu}T_t}^{\mathrm{SU}} = 2Q\left(\sqrt{\frac{S_{\mathrm{eff}}^{\mathrm{SU}}}{N_{\mathrm{eff}}^{\mathrm{SU}} + I_P\frac{\lambda}{\lambda+\mu}T_t}}\right). \quad (3)$$

The channel access model is illustrated with an example in Figure 1. In the first slot, SU correctly determines the channel to be idle and transmits a packet, which is successful with probability $1 - p_e^{\mathrm{SU}}$. In the second slot, SU performs a *missed detection*, attempts to transmit, PU and SU's transmissions collide. Both users' packets are lost with probabilities $p_{\mathrm{int}}^{\mathrm{PU}}$ and $p_{\mathrm{int}}^{\mathrm{SU}}$. In the third slot, the SU performs a correct decision on the idle state of the channel, however, the PU starts transmission during the SU transmission period T_t. In this case the transmissions of PU and SU collide again and their packets are lost with probabilities $p_{\mathrm{int}}^{\mathrm{PU}}$ and $p_{\mathrm{int}}^{\mathrm{SU}}$. In the fourth slot, SU correctly finds that the channel is busy and does not transmit. In the fifth slot, a false alarm is performed; SU decides that the channel is busy when it is not at the beginning of transmission period V.

3 Analysis

3.1 Probability of Collision

According to the PU and SU channel access models discussed above, collision of PU and SU traffic occurs under two distinct scenarios:

(i) The channel is busy at the end of the sensing period, the SU does not detect this (*i.e.*, a missed detection occurs), and SU attempts transmission (*e.g.*, slot II in Figure 1).
(ii) The channel is idle at the end of sensing period, the SU correctly detects this and attempts transmission, but the PU starts transmission during the transmission period (*e.g.*, slot III in Figure 1).

These events are mutually exclusive. Assuming that the PU CTMC is in steady-state, the probability of collision, p_c, may be written as

$$p_c = \frac{\lambda}{\lambda+\mu} p_{\mathrm{MD}} + \frac{\mu}{\mu+\lambda}(1-p_{\mathrm{FA}})(1-e^{-\lambda T_t}), \tag{4}$$

where first and second terms are the probabilities of cases (i) and (ii), and p_{MD} and p_{FA} are probabilities of missed detection and false alarm, respectively.

3.2 SU Utilization

When a collision occurs SU transmits the packet successfully with probability $1-p_{\mathrm{int}}^{\mathrm{SU}}$. The other case of successful transmission is when the channel is idle at the end of sensing period, the SU correctly detects this and attempts transmission, and the PU does not start transmission during the transmission period (*e.g.*, slot I in Figure 1). Thus the SU channel utilization, U_S, is

$$U_S = \left[(1-p_{\mathrm{int}}^{\mathrm{SU}})p_c + \frac{\mu}{\lambda+\mu}(1-p_{\mathrm{FA}})e^{-\lambda T_t}\right]\frac{T_t}{T_t+T_s}, \tag{5}$$

where the multiplicative term at the end is to account for the loss to the silent sensing period.

3.3 PU Utilization

Let us focus on one SU slot. Call the PU utilization during SU sensing and transmission periods to be U_{P_s} and U_{P_t}, respectively. Then overall PU utilization is

$$U_P = \frac{T_s}{T_t+T_s}U_{P_s} + \frac{T_t}{T_t+T_s}U_{P_t}. \tag{6}$$

During the sensing time, the SU is silent thus $U_{P_s} = (1-p_e^{\mathrm{SU}})U_{P_o} = (1-p_e^{\mathrm{SU}})\frac{\lambda}{\lambda+\mu}$. On the other hand, we can find U_{P_t} as follows. First, define the random variable Y to be 1 if SU transmits during the transmission period and 0 otherwise. Without loss of generality, let $t=0$ and $t=T_t$ denote the start and end of the transmission period, respectively. Then U_{P_t} is

$$\begin{aligned} U_{P_t} &= (1-p_e^{\mathrm{PU}})\frac{1}{T_t}\int_0^{T_t}\mathbb{P}(X_t=1|Y=0)\,\mathbb{P}(Y=0)\,dt \\ &+ (1-p_{\mathrm{int}}^{\mathrm{PU}})\frac{1}{T_t}\int_0^{T_t}\mathbb{P}(X_t=1|Y=1)\,\mathbb{P}(Y=1)\,dt. \end{aligned} \tag{7}$$

Note that the integrands are functions of time. Let us focus on the first term in the first integral.

$$\begin{aligned} \mathbb{P}(X_t=1|Y=0) &= \mathbb{P}(X_t=1|X_0=0)\,\mathbb{P}(X_0=0|Y=0) \\ &+ \mathbb{P}(X_t=1|X_0=1)\,\mathbb{P}(X_0=1|Y=0). \end{aligned} \tag{8}$$

Similarly, the first term in the second integral is

$$\begin{aligned} \mathbb{P}(X_t=1|Y=1) &= \mathbb{P}(X_t=1|X_0=0)\,\mathbb{P}(X_0=0|Y=1) \\ &+ \mathbb{P}(X_t=1|X_0=1)\,\mathbb{P}(X_0=1|Y=1). \end{aligned} \tag{9}$$

The state transition probabilities for $X(t)$ are

$$\mathbb{P}(X_t=1|X_0=0) = \frac{\lambda}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu}e^{-(\lambda+\mu)t}, \tag{10}$$

$$\mathbb{P}(X_t=1|X_0=1) = \frac{\lambda}{\lambda+\mu} + \frac{\mu}{\lambda+\mu}e^{-(\lambda+\mu)t}. \tag{11}$$

We use Bayes' Rule for the remaining terms in (8) and (9)

$$\mathbb{P}(X_0=0|Y=0) = p_{\mathrm{FA}}\frac{\mu}{\lambda+\mu}\frac{1}{\mathbb{P}(Y=0)}, \tag{12}$$

$$\mathbb{P}(X_0=1|Y=0) = (1-p_{\mathrm{MD}})\frac{\lambda}{\lambda+\mu}\frac{1}{\mathbb{P}(Y=0)}, \tag{13}$$

$$\mathbb{P}(X_0=0|Y=1) = (1-p_{\mathrm{FA}})\frac{\mu}{\lambda+\mu}\frac{1}{\mathbb{P}(Y=1)}, \tag{14}$$

$$\mathbb{P}(X_0=1|Y=1) = p_{\mathrm{MD}}\frac{\lambda}{\lambda+\mu}\frac{1}{\mathbb{P}(Y=1)}. \tag{15}$$

We combine all equations in (7) to get

$$\begin{aligned} U_{P_t} &= (1-p_e^{\mathrm{PU}})\frac{\lambda}{(\lambda+\mu)^2}\left[\mu p_{\mathrm{FA}} + \lambda(1-p_{\mathrm{MD}})\right] \\ &+ (1-p_{\mathrm{int}}^{\mathrm{PU}})\frac{\lambda}{(\lambda+\mu)^2}\left[\mu(1-p_{\mathrm{FA}}) + \lambda p_{\mathrm{MD}}\right] \\ &+ (p_{\mathrm{int}}^{\mathrm{PU}} - p_e^{\mathrm{PU}})\frac{\lambda\mu}{(\lambda+\mu)^3}\frac{1}{T_t}(1-e^{-(\lambda+\mu)T_t})(1-p_{\mathrm{FA}}-p_{\mathrm{MD}}) \end{aligned} \tag{16}$$

Figure 2 shows the SU utilization levels on the top row, and corresponding *losses* in PU Utilization levels as a ratio to the PU occupancy $U_{P_o} = \frac{\lambda}{\lambda+\mu}$ on the bottom row, for varying λ and μ rates. The SU transmission duration is $T_t = 0.1$, 1 and 10 in the first, second

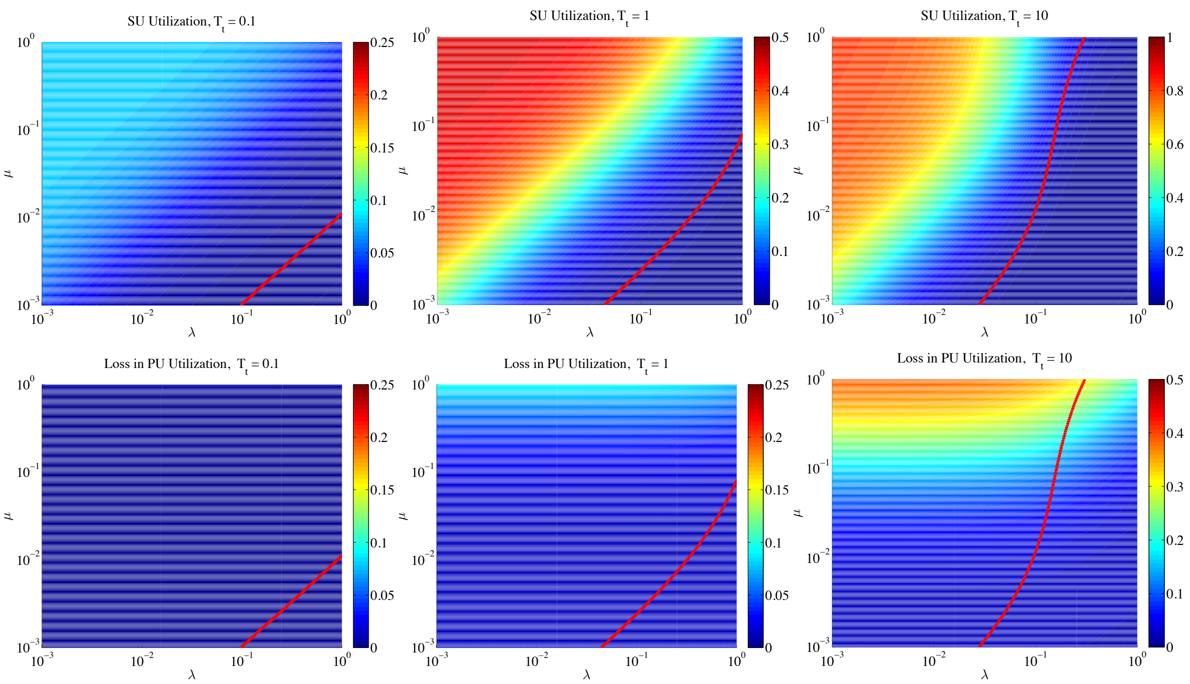


Fig. 2 SU Utilization (top row) and corresponding loss in the PU utilization (bottom row) as a ratio to the PU occupancy $U_{P_o} = \frac{\lambda}{\lambda+\mu}$ for varying SU transmission period, and rates λ and μ. Red line denotes the boundary at which the total utilization $U_P + U_S$ is equal to U_{P_o}. To the left of the line toward the arrow, sum utilization is greater than U_{P_o}.

and third columns of the figure, respectively. Here, the SU detector sensitivity levels are $p_{\text{MD}} = p_{\text{FA}} = 0.05$ and the packet error rate parameters are $p_e^{\text{PU}} = 0.01$, $p_e^{\text{SU}} = 0.05$, $p_{\text{int}}^{\text{PU}} = 0.5$ and $p_1^{\text{SU}} = 0.9$.The red solid line denotes the boundary at which the sum utilization of the PU and SU is equal to the PU occupancy U_{P_o}. In the figure, we observe the following:

(a) Toward the upper left and lower right corner of a graph, PU occupancy decreases and increases, respectively. As PU occupancy decreases, SU utilization and the impact on the PU traffic increases. On the other hand, sum utilization levels are larger than PU occupancy levels to the left of the red dotted contours.This shows that opportunistic access increases spectral utilization for lower PU occupancy, and there is a trade-off between the increased spectral utilization and impact to PU.
(b) For a given average PU occupancy, toward the upper right and lower left corner of a graph, the PU traffic becomes more and less bursty, respectively. We observe that burstier PU traffic leads to less SU utilization and higher impact on PU utilization. This is because the collision case (ii) in Section 3.1 is more likely to happen for burstier PU traffic since it is not synchronized with the SU traffic.
(c) An SU slot is composed of the silent sensing period T_s and the transmission period T_t. As T_t increases the sensing overhead becomes less. However, sensing becomes less frequent and the probability of collision due to the case (ii) in Section 3.1 becomes higher. Collisions impact the utilization levels of both PU and SU. Especially the impact is more pronounced for burstier PU traffic.

4 Transmission Period Optimization

The observations on Figure 2 clearly illustrate that there is an optimal transmission period T_t and an associated sensing frequency, for given CR system parameters. In this paper, we are interested in maximizing the total spectral utilization of an OSA system, thus we formulate the following optimization problem

$$\underset{\{T_t\}}{\text{maximize}}\ (U_P + U_S) \quad \text{subject to} \quad 0 \leq T_t. \qquad (17)$$

It can be shown that the objective function is not concave or quasi-concave. Therefore there may be multiple local optima. In such cases, finding the global optimum for a high dimensional problem may be difficult. However our problem has only one variable, T_t. Since the analytical expressions for U_P and U_S presented above are differentiable functions of T_t, local optima may exist at the boundary ($i.e.$, $T_t = 0$) or where the derivative of the sum utilization is zero and the second derivative is negative. Then the global optimum among the local optima may be selected by comparison. Although an analytical expression cannot be obtained via this approach, numerical solvers might be used. For low dimensional problems with differentiable objectives such as this one, the simple approach of using gradient based numerical methods starting from multiple points, and choosing the best result, also works.

In Figure 3, we first report the optimal transmission times as the PU occupancy U_{P_o} is swept in $[10^{-3}, 1)$. Here, the SU detector sensitivity levels are $p_{\text{MD}} = p_{\text{FA}} = 0.05$ and the packet error rate parameters are $p_e^{\text{PU}} = 0.01$, $p_e^{\text{SU}} = 0.05$, $p_{\text{int}}^{\text{PU}} = 0.5$ and $p_1^{\text{SU}} = 0.9$. Subfigures (a), (b) and (c) contain the results for $\mu = 0.1$, $\mu = 1$ and $\mu = 10$, respectively. For a given occupancy U_{P_o}, the PU traffic becomes burstier as μ increases, thus (a) and (c) represent the least and most bursty traffic cases, respectively. The figure shows that the optimal transmission period T_t decreases (or optimal sensing frequency increases) as the PU occupancy increases or as the PU traffic becomes burstier. Optimal T_t drops below 2% of sensing period, which may practically be assumed zero, when PU occupancy reaches 99%, 98%, and 90% for $\mu = 0.1$, $\mu = 1$ and $\mu = 10$, respectively. This shows that burstier PU traffic leads to smaller range of PU occupancy values where OSA increases spectral utilization.

Figure 4 presents the total and PU utilization levels for the corresponding optimal transmission times given in Figure 3, as well as the PU utilization levels in the absence of SU, which are equal to the PU occupancy values U_{P_o}. Again subfigures (a), (b) and (c) are for $\mu = 0.1$, $\mu = 1$ and $\mu = 10$, respectively. In addition to the the theoretical curves, Monte-Carlo simulation results are presented to validate our results. For each simulation, given λ, μ, p_{MD}, p_{FA}, p_e^{PU}, p_e^{SU}, $p_{\text{int}}^{\text{PU}}$ and p_1^{SU} values and corresponding T_t and $p_{\text{int}}^{\text{SU}}$ values, we used a total simulation duration of 10,000 SU slots. We generated the PU behavior according to the on-off model in Section 2.1. During each slot, the SU first performs a missed detection or false alarm with probabilities p_{MD} and p_{FA}, respectively. If the channel is decided to be empty, SU performs transmission. If a collision occurs due to a false alarm or due to PU activity starting later, packets of PU and SU are unsuccessful with probabilities $p_{\text{int}}^{\text{PU}}$ and $p_{\text{int}}^{\text{SU}}$, respectively. If there is no collision, transmission of the PU or SU are successful with probabilities $1 - p_e^{\text{PU}}$ and $1 - p_e^{\text{SU}}$, respectively. Each simulation of 10,000 SU slots is repeated 10 times for each data point, and resulting means and standard deviations are plotted as circles and error bars in Figure 4, respectively. As observed in the Figure, the means match with the theory and the standard deviations are very small, validating the theoretical results.

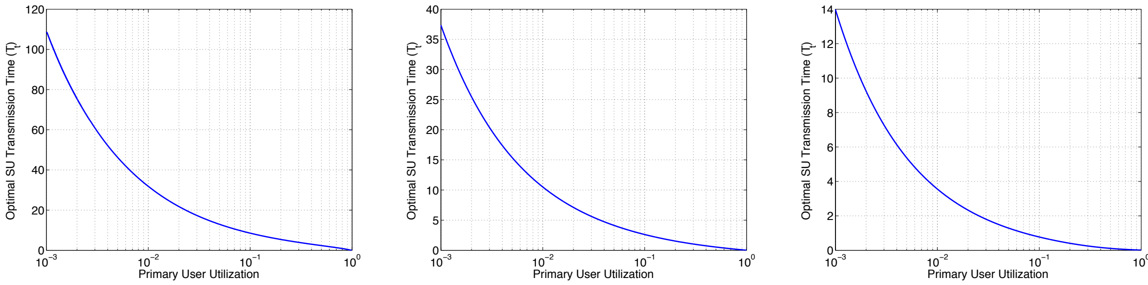
We observe from the figure that, both SU utilization and increase in the total utilization is more pronounced for lower PU occupancy. On the other hand, when the PU occupancy is less bursty, the total channel utilization is better. When PU occupancy is low, the total utilization values range from 71% to 89% when $\mu = 0.1$, whereas this range drops to 29% – 81% when $\mu = 10$. In all cases, even when $U_{P_o} \to 1$, the impact on the PU traffic is not too high when optimal transmission times are used. This may be achieved by a central base station or a cluster head of the SU network, by estimating the PU's traffic pattern over a sliding window and updating the slot duration for all SU nodes in a dynamic fashion. This demonstrates the feasibility of OSA with asynchronous SU network with imperfect sensing.

In Figure 5, optimal transmission times and corresponding sum and PU utilization levels as a function of the SU sensing performance (namely the parameters p_{MD} and p_{FA}) are given. In the figures, $\lambda = \mu = 1$ and $p_e^{\text{PU}} = 0.01$, $p_e^{\text{SU}} = 0.05$, $p_{\text{int}}^{\text{PU}} = 0.5$, $p_1^{\text{SU}} = 0.9$. When p_{MD} or p_{FA} is swept, the other sensing performance metric is kept at 0.05.

Larger p_{MD} results in more frequent collisions impacting the utilization of both PU and SU network. We observe from the figure that as p_{MD} increases, optimal transmission time decreases in order to reduce collisions due to PU traffic arriving later (case (ii) in Section 3.1). On the other hand, as p_{FA} increases, SU utilization drops due to missed spectrum opportunities, and PU utilization increases since collisions of case (ii) in Section 3.1 are also avoided when false alarms happen. As p_{FA} gets very large, optimal transmission period drops sharply in order to perform more frequent sensing, such that the number of slots without false alarm increases. All plots show that, provided that one of the sensing performance metrics, *i.e.*, p_{MD} or p_{FA} is good enough, fairly consistent PU, SU and total spectral utilization can be achieved even when the other metric is loose.

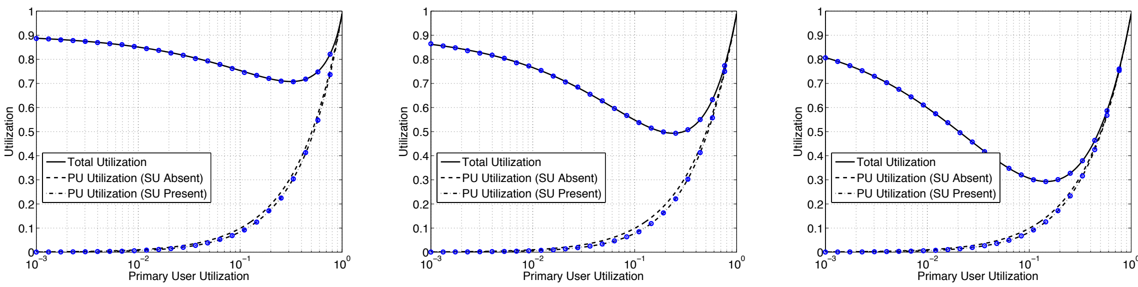
5 Conclusion

This paper presents a theoretical analysis of both of the primary and secondary networks' utilization levels in an opportunistic spectrum access (OSA) scenario where primary traffic is bursty and asynchronous with the secondary network, the secondary network performs imperfect spectrum sensing, and simultaneous primary and secondary transmission results in increased packet error rates for both networks. Theoretical analysis reveals that there is an optimal secondary user (SU) transmission period given cognitive radio system parameters. Then using the theoretical results, which are validated by extensive Monte-Carlo simulations, the pa-



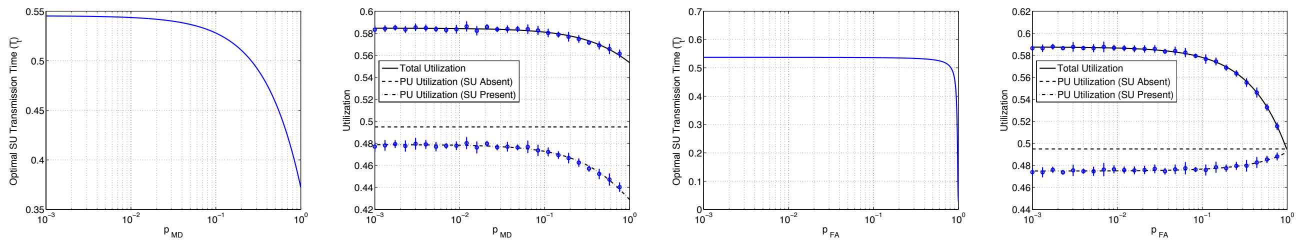
(a) (b) (c)

Fig. 3 Optimal SU transmission times as PU occupancy is swept. (a) $\mu = 0.1$, (b) $\mu = 1$, (c) $\mu = 10$.



(a) (b) (c)

Fig. 4 Utilization levels as PU occupancy is swept. (a) $\mu = 0.1$, (b) $\mu = 1$, (c) $\mu = 10$. The blue circles and the error bars represent the means and standard deviations of the Monte-Carlo simulations, respectively. Most error bars are smaller than the corresponding circles.



(a) (b) (c) (d)

Fig. 5 Optimal transmission times (a & c) and corresponding utilization levels (b & d) as a function of SU detector missed detection (a & b) and false alarm probabilities (c & d). The blue circles and the error bars represent the means and standard deviations of the Monte-Carlo simulations, respectively.

per presents utilization levels for optimized transmission periods under varying primary user (PU) traffic occupancy and burst characteristics, and SU detector performance metrics.

The results reveal that OSA increases total utilization especially when PU occupancy is lower, and when optimal transmission periods are used by the secondary network. Even for high PU occupancy, the impact of OSA to PU traffic is not too high. An SU base station or cluster head is proposed in the paper to estimate the recent PU traffic characteristics and to update SU network's slot duration in a dynamic fashion to achieve this. Under this scenario, our results show the achievable utilization levels and demonstrate that OSA is feasible for an asynchronous cognitive radio network with imperfect spectrum sensing. Moreover, our results show that less bursty PU traffic leads to higher utilization and a larger range of PU occupancy values where OSA increases utilization. Thus, just the percentage channel occupation is not a sufficient metric to assess the OSA performance, but the PU traffic behavior is also important. Finally, we showed that, given one of the SU spectrum sensing metrics, *i.e.*, p_{MD} or p_{FA} is good enough, fairly consistent PU, SU and total utilization can be achieved even when the other metric is loose.

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