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An Unreliable Opportunistic Spectrum Sharing System with Sensitive Secondary Users

Shensheng Tang[1], Rong Yu[2], Xiaojiang Chen[3], Chenghua Tang[4] and Yi Xie[5]

[1] Missouri Western State University, St. Joseph, MO 64506, USA
[2] Guangdong University of Technology, Guangzhou 510006, China
[3] Northwest University, Xi'an 710127, China
[4] Guilin University of Electronic Technology, Guilin 541004, China
[5] Sun Yat-Sen University, Guangzhou 510275, China
[1] Corresponding author: stang@missouriwestern.edu

Abstract

The focus of this paper is on the modeling and performance analysis of an unreliable opportunistic spectrum sharing (OSS) system at the call level with sensitive secondary users. Unreliable spectrum sensing is modeled by type I and type II false alarm events and class-A and class-B misdetection events, which brings more flexibility for the purpose of performance evaluation. Spectrum sensing errors negatively impact the performance of primary users and secondary users, particularly when a call collision happens. To maximize the protection of primary users under call collisions, it is required in the system design that secondary users be sensitive to the call collisions, to protect primary users. We model the unreliable OSS system through a two-dimensional Markov process and develop the steady-state probabilities of the system as well as several performance metrics of interest.

Keywords: *Opportunistic spectrum sharing, Unreliable sensing, False alarm, Misdetection, Markov process*

1.Introduction

Opportunistic spectrum sharing (OSS) is an important technique for efficient spectrum utilization. In an OSS system, the calls generated from primary users (licensed users) constitute the primary traffic (PT) stream; the calls generated from the secondary users constitute the secondary traffic (ST) stream. Secondary users equipped with cognitive radios can sense the spectrum status and opportunistically make use of it without causing harmful interference to the primary users [1-2]. An initiating secondary user senses if a channel is idle before accessing the channel. An ongoing secondary user also needs periodic spectrum sensing and vacates its channel for a primary user if one presents on the channel, and then either switches to another idle channel or moves to a buffer. The call waiting in the buffer can reconnect back when a channel becomes available or drop out from the buffer when a predefined maximum waiting time expires.

Much research about opportunistic spectrum sharing or dynamic spectrum access has been developed in the past a few years [3-12]. In [3], a multi-channel medium access control (MAC) protocol was developed to enable the interoperation of the primary system and the secondary system. A number of technical challenges pertinent to this networking environment were addressed and the performance of MAC protocol was evaluated.

In [4], the effect of user collaboration on the performance of sensing-based secondary access wad investigated in fading channels. It showed that under independent fading or

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*Corresponding Author

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shadowing, a low-overhead collaboration scheme with a very simple detector can improve the spectrum utilization significantly. In [5], three opportunistic spectrum access schemes were proposed to analyze the secondary user performance under given primary constraints, by introducing the two metrics, namely collision probability and overlapping time. In [6], a collaborative spectrum sharing mechanism was developed for a group of frequency agile radios to estimate the maximum interference-free transmit power without causing harmful interference to the primary receivers. In [7], adaptive spectrum sharing schemes were proposed for code division multiple access (CDMA) based cognitive medium access control (MAC) in the uplink communications over the cognitive radio networks. The proposed schemes addressed the joint problems of channel sensing, data transmission, and power and rate allocations. In [8], a single spectrum sensing scheme with only one cognitive user performing sensing was proposed in both network-centric and user-centric ways for cognitive radio networks, and the proposed scheme was further generalized to a multiple spectrum sensing scenario. In [9], a relay assisted spectrum sharing (RASS) scheme was proposed based on a mixed sharing strategy in cognitive radio networks. The proposed scheme was claimed to enhance the throughput of secondary users while not causing harmful interference to the primary receiver. The optimal time allocation was derived to maximize the achievable capacity of the secondary system. In [10], a linear precoding matrix optimization algorithm, named gradient-aided mutual information optimization (GAMIO), was designed to maximize the secondary users' spectrum efficiency. A framework was also proposed to develop the energy-efficient algorithm which can work with the GAMIO algorithm. In [11], a dynamic programming and graph theory based spectrum sharing algorithm was proposed for a software-defined wireless network, which brings two new entities, physical networks and virtual networks. In [12], an unreliable opportunistic spectrum sharing system was modeled by involving different types of call collision results (CCRs) and the system performance under multiple CCRs was studied.

The work in this paper is focused on the modeling and performance analysis of an unreliable OSS system at the call level with sensitive secondary users. That is, the spectrum sensing performed by secondary users is unreliable and subject to false alarm and misdetection events, which negatively impact the performance of primary users and secondary users, particularly when a call collision happens. To maximize the protection of primary users under call collisions, it is required in the OSS system design that secondary users be sensitive to the call collisions, *i.e.*., when a call collision happens (large "noise" incurred), the secondary user will vacate its current channel for the potential primary user, and find an idle channel to continue its call if one is available or drop from the system if no idle channel is available.

The remainder of the paper is organized as follows. Section 2 describes the system model. Section 3 presents the performance analysis and performance metrics. Section 4 presents numerical results. Finally, Section 5 concludes the paper.

2. System Model

The proposed system includes PT calls and ST calls. The PT calls operate as if there are no ST calls in the system because they are licensed users. When a PT call arrives to the system, its base station (BS) will assign a channel to it if there is one available; otherwise, the PT call will be blocked. Note that a channel being used by an ST call is still seen as an idle channel by a primary user because it is assumed no information sharing between the primary system and the secondary system. Secondary users perform periodic sensing to detect the presence or absence of PT calls and maintain records of the channel occupancy status. The detection mechanism may involve collaboration with other secondary users and/or an exchange with an associated BS of the secondary system, if any.

An initiating ST call (user) senses the spectrum and accesses a channel when it finds an idle channel. When an ongoing ST call senses the presence of a PT call in its channel, it immediately leaves the channel and switches to another idle channel, if one is available, to continue the call. If at that time all the channels are busy, the ST call is placed into a buffer. The head-of-line (HOL) ST call in the buffer can reconnect to the system as soon as a channel becomes available before a predefined maximum waiting time expires. In principle, the maximum waiting time of a queued ST call should be equal to its residence time in the given service area, if the effect of impatience of queued ST calls is not considered.

In practice, unreliable sensing is inevitable. An initiating ST call may incorrectly determine that a channel is busy when in fact the channel is idle; an ongoing ST call may incorrectly determine the presence of a PT call on its channel when in fact no PT call presents at the channel. We refer to the former type of error as type-I false alarm event and the latter as type-II false alarm event. On the other hand, an initiating ST call sensing the spectrum may incorrectly determine that the channel is idle when in fact the channel is being used by a PT call. We refer to this sensing error as class-A misdetection event. An ongoing ST call on a given channel may fail to detect the presence of a PT call and remain on that channel. This is referred to as class-B misdetection event. When a misdetection event occurs, both ST and PT calls are using the same channel, causing a call collision (large "noise" incurred). In the proposed model, secondary users are assumed to be sensitive to the call collision. When a call collision occurs, the secondary user will vacate its current channel for the possible potential primary user, and find an idle channel to continue its call if one is available or drop from the system if no idle channel is available.

We denote the class-A and class-B misdetection probabilities by p_a and p_b, and the type-I and type-II false alarm probabilities by p_{f1} and p_{f2}, respectively.

3. Performance Analysis

Assume that the spectrum in the considered system is divided into N channels serving the PT and ST calls. As mentioned previously, the buffer in our model is used to store the ongoing ST calls that could not find idle channels in the presence of PT calls on their channels. The maximum number of ongoing ST calls is N. Thus, the size of the buffer is set to be N. Similar to [2], we assume that the arrivals of the PT and ST calls are Poisson processes with rates λ_1 and λ_2; and the channel occupancy times of the PT and ST calls are exponentially distributed with means $1/\mu_1$ and $1/\mu_2$, respectively. The residence time for the ST calls is assumed to be exponentially distributed with mean $1/r_2$.

Let $X_1(t)$ and $X_2(t)$ be the number of PT calls and the number of ST calls (including the ST calls being served and those waiting in the buffer) in the system at time t. The process $(X_1(t), X_2(t))$ is a two-dimensional Markov process with state space $S = \{(i, j)| \ 0 \le i, j \le N\}$. We classify the channel occupancy of the system in state (i, j) as *pre-full* if $i + j < N$, *just-full* if $i + j = N$, and *post-full* if $i + j > N$. The corresponding transition rate diagrams at state (i, j) are shown respectively in Figures 1, 2, and 3, where different sensing errors from both initiating and ongoing ST calls are incorporated in the modeling. Note that in post-full status (at least one queued ST call occurs in the buffer), initiating ST calls do not try to access any channel when they see the post-full status of the system.

In Figure 1, the state (*i*, *j*) moves to state (*i*, *j* + 1) with rate $[1-p_{f1}-\bar{\delta}(i)p_a]\lambda_2$, where $\bar{\delta}(i)\hat{=}0$ if $i = 0$ and 1 if $i \neq 0$. The state (*i*, *j*) moves to (*i* - 1, *j*) with rate $i\mu_1$ and (*i*, *j* - 1) with rate $j\mu_2$, where $i\mu_1$ and $j\mu_2$ are the transitions caused by service completion, respectively. The state (*i*, *j*) moves to (*i* + 1, *j* - 1) with rate $p_b\lambda_1$ and (*i* + 1, *j*) with rate $(1 - p_b)\lambda_1$, where $p_b\lambda_1$ is the transition caused by class-B misdetection and $(1 - p_b)\lambda_1$ is the transition caused by an arrival of PT call without any misdetection.

In Figure 2, the state (*i*, *j*) moves to state (*i*, *j* - 1) with rate $(1-p_{f2})j\mu_2+p_{f2}[(j-1)\mu_2+r_2]$, where the first term is the transition without the occurrence of a type-II false alarm and the second term is the transition caused by the occurrence of a type-II false alarm (the secondary user then leaves its channel and goes to the buffer owing to the unavailability of a channel). When $i + j = N$, no initiating ST calls can enter the system, thus, there is no transition from (*i*, *j*) to (*i*, *j* + 1).

In Figure 3, the state (*i*, *j*) moves to state (*i*, *j* - 1) with rate $[1-p_{f_2}\bar{\delta}(N-i)][(N-i)\mu_2+(j-N+i)r_2]+p_{f_2}\bar{\delta}(N-i)[(N-i-1)\mu_2+(j-N+i+1)r_2]$, where the first term is the transition without the occurrence of a type-II false alarm and the second term is the transition caused by the occurrence of a type-II false alarm. When $i + j > N$, no initiating ST calls can enter the system, thus, there is no transition from (*i*, *j* - 1) to (*i*, *j*) and from (*i*, *j*) to (*i*, *j* + 1).

Let $\pi(i, j)$ denote the steady-state probability that the system is in state (*i*, *j*). The system probability vector can be represented as $\boldsymbol{\pi} = (\boldsymbol{\pi}_0, \boldsymbol{\pi}_1, \ldots, \boldsymbol{\pi}_N)$, where $\boldsymbol{\pi}_n = (\pi(n,0), \pi(n,1), \ldots, \pi(n, N))$, $0 \leq n \leq N$. The vector $\boldsymbol{\pi}$ is the solution of equations

$$\boldsymbol{\pi}Q = \mathbf{0} \text{ and } \boldsymbol{\pi}\mathbf{e} = 1, \tag{1}$$

where **e** and **0** are column vectors of all ones and zeros, and infinitesimal generator, *Q*, of the two-dimensional Markov process is obtained as

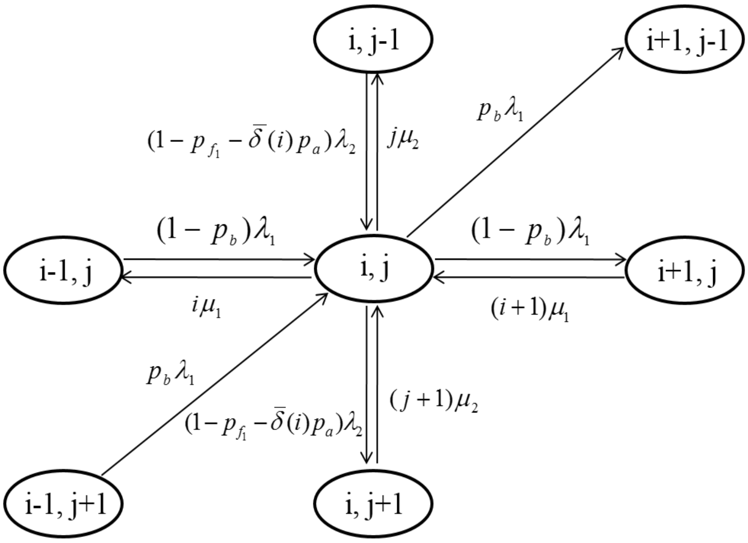

Figure 1. The State Diagram at (i, j) with Pre-full Status.

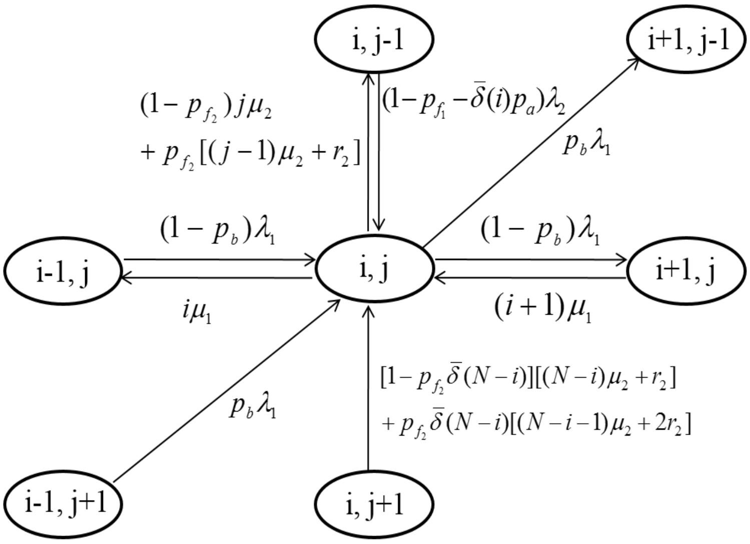

Figure 2. The State Diagram at (i, j) with Just-full Status.

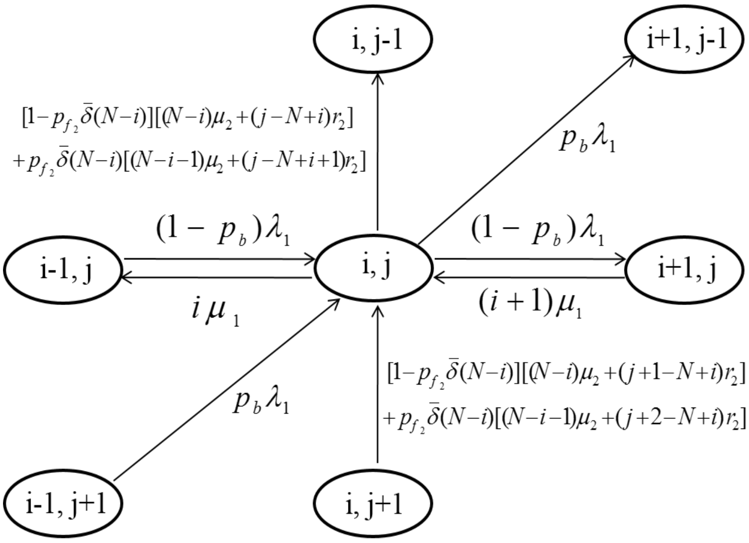

Figure 3. The State Diagram at (i, j) with Post-full Status.

$$Q = \begin{bmatrix} E_0 & B_0 & 0 & \cdots & 0 & 0 & 0 \\ D_1 & E_1 & B_1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & D_{N-1} & E_{N-1} & B_{N-1} \\ 0 & 0 & 0 & \cdots & 0 & D_N & E_N \end{bmatrix}. \tag{2}$$

In the above Q matrix, each sub-matrix has size (N+1) by (N+1) and is given by

$$B_i(j,k) = (1-p_b)\lambda_1 1_{\{0\le i<N,0\le j\le N,k=j\}} + p_b\lambda_1 1_{\{0\le i<N,1\le j\le N,k=j-1\}}, \tag{3}$$

$$D_i(j,k) = i\mu_1 1_{\{1\le i\le N,0\le j\le N,k=j\}}, \tag{4}$$

$$E_i = [A_i - \bar{\delta}(i)D_i - \bar{\delta}(N-i)B_i]1_{\{0\le i\le N\}}, \tag{5}$$

and $1_{\{\Phi\}}$ is the indicator function of set Φ defined by

$$1_{\{\Phi\}} \triangleq \begin{cases} 1, & \text{if } \Phi \text{ is true,} \\ 0, & \text{otherwise,} \end{cases}$$

and A_i is a matrix with the same size as E_i and with its element $A_i(j, k)$ given by

$$A_i(j,k) = \begin{cases} [1-p_{f1}-\bar{\delta}(i)p_a]\lambda_2, & 0\le i<N, 0\le j<N-i, k=j+1, \\ j\mu_2, & 0\le i<N, 1\le j<N-i, k=j-1, \\ \mathrm{T}_1, & 0\le i<N, j=N-i, k=j-1, \\ \mathrm{T}_2, & 1\le i\le N, N-i<j\le N, k=j-1, \\ -[A_i(j,j-1)+A_i(j,j+1)], & 0\le i\le N, 0\le j\le N, k=j, \\ 0, & \text{otherwise,} \end{cases} \tag{6}$$

with $\mathrm{T}_1 = (1\text{-}p_{f2})\, j\mu_2 + p_{f2}[(j\text{-}1)\mu_2 + r_2]$, and

$$\begin{aligned} \mathrm{T}_2 = {} & [1-p_{f2}\bar{\delta}(N-i)][(N-i)\mu_2 + (j-N+i)r_2] \\ & + p_{f2}\bar{\delta}(N-i)[(N-i-1)\mu_2 + (j-N+i+1)r_2]. \end{aligned}$$

Applying the method developed in [13], the steady state probability vector can be determined as

$$\boldsymbol{\pi}_{\mathbf{n}} = \boldsymbol{\pi}_{\mathbf{0}} \prod_{i=1}^{n} [B_{i-1}(-C_i)^{-1}], \quad 1\le n\le N, \tag{7}$$

where $\boldsymbol{\pi}_{\mathbf{0}}$ satisfies $\boldsymbol{\pi}_{\mathbf{0}}\mathrm{C}_0 = \mathbf{0}$ and

$$\boldsymbol{\pi}_{\mathbf{0}} \left[I + \sum_{n=1}^{N} \prod_{i=1}^{n} [B_{i-1}(-C_i)^{-1}] \right] \mathbf{e} = 1. \tag{8}$$

The C_i can be recursively determined by $C_N = E_N$ and

$$C_i = E_i + B_i(-C_{i+1})^{-1} D_{i+1}, \; 0\le i\le N-1. \tag{9}$$

After obtaining the steady-state probabilities, some performance metrics of interest can be easily determined, such as the PT call blocking probability, the ST call blocking probability, the total channel utilization, and the unavoidable collision probability to the primary users.

- **Blocking Probability of the PT Calls**

  The PT call blocking probability, denoted by P_1, is defined as the probability that upon an arrival of a PT call in a service area all the channels are occupied by PT calls and the arrival request has to be blocked. Thus, we have

$$P_1 = \sum_{j=0}^{N} \pi(N,j) = \boldsymbol{\pi}_{\mathbf{0}} \prod_{k=1}^{N} [B_{k-1}(-C_k)^{-1}]\mathbf{e}. \tag{10}$$

- **Blocking Probability of the ST Calls**

The ST call blocking probability, denoted by P_2, is defined as the probability when all the channels in a service area are occupied by either PT calls and/or ST calls and no channel is available for a new ST call request. Thus, we have

$$P_2 = \sum_{i=0}^{N} \sum_{j=N-i}^{N} \pi(i, j). \tag{11}$$

- **Total Channel Utilization**

The total channel utilization, denoted by η, is defined as the ratio of the mean number of occupied channels to the total number of channels. Thus, we have

$$\eta = \frac{1}{N}\left\{ \sum_{i=0}^{N} \sum_{j=0}^{N-i} (i+j)\pi(i, j) + \sum_{i=1}^{N} \sum_{j=N-i+1}^{N} N\pi(i, j) \right\}. \tag{12}$$

Unavoidable Collision Probability to the Primary Users

In the OSS system, the secondary user senses the spectrum periodically. For the initiating secondary users, when no misdetection events happen, there will be no call collision. However, for the ongoing secondary users, even though no misdetection events happen, there will still be call collision in some short time interval. For example, when the call of a primary user arrives at the system, its BS will assign a channel to it according to a certain channel assignment strategy. Since it is assumed that there is no information exchange between primary system and secondary system, the channel assigned to the primary user may be in use by a secondary user. The secondary user is responsible to detect the interference induced by the primary user, and then in a very short time interval, decide whether or not a PT call arrives and perform an appropriate action. Clearly, during this short time interval, there is a collision between the calls of primary and secondary users. Compared with a single primary system, this additional collision in the short time interval is caused completely due to the introduction of the secondary users and it is unavoidable. Therefore, the probability that is used to describe the call collision in this short time interval is referred to as the *unavoidable collision probability* to the primary users. The impact of this probability can be quickly eliminated when the secondary user performs correct spectrum detection, but it is still an important metric to evaluate the impact on the primary system due to the introduction of the secondary system. To study this performance metric quantitatively, we need to know the channel assignment strategy in the BS of the primary system. For simplicity, we consider a uniform channel assignment strategy, *i.e.*., the BS of the primary system randomly assigns a channel to an incoming PT call from its set of idle channels with equal probability.

In state (i, j), there are already i PT calls and j ST calls (either on channels or in buffer) in the system. Note that the false alarm events do not cause any call collision. We split the problem into two cases. (1) The system is in pre-full or just-full status: when a PT call arrives, its BS will randomly assign a channel from the remaining $(N - i)$ channels. Clearly, the probability that a channel occupied by an ST call is selected is $j/(N - i)$. (2) The system is in post-full status: when a PT call arrives, its BS will randomly assign a channel from the remaining $(N - i)$ channels. At this case, the probability that a channel occupied by an ST call is selected is $(N - i)/(N - i) = 1$. Thus, the collision probability, denoted by P_c, can be found as

$$P_c=\sum_{j=1}^{N}\sum_{i=0}^{N-j}\frac{j}{N-i}\pi(i,j)+\sum_{i=1}^{N}\sum_{j=N-i+1}^{N}\pi(i,j). \tag{13}$$

4. Numerical Results

We evaluate the OSS system performance under different CCRs. The system parameters as follows: $N = 16$, $\mu_1 = 10$, $\mu_2 = 10$, $r_2 = 5$, $\lambda_2 = 40$ or 60, λ_1 changes from 10 to 80. The values of other parameters are shown in individual figures. Time is represented in terms of a dimensionless time unit, which can be mapped to a specific unit of time. To show the performance benefit of the OSS system, we include the performance of the original primary system, without the secondary system, as a baseline case for comparison. We also study the performance impact of unreliable spectrum sensing by choosing different values of the false alarm and misdetection probabilities, respectively.

Figure 4 shows how the PT call blocking probability P_1 change with respect to different parameters. We observe that P_1 has almost no change in an OSS system with perfect sensing, unreliable sensing, and a single primary system. This indicates that the introduction of secondary system does not affect the performance of the primary system under perfect sensing or unreliable sensing with sensitive secondary users. In unreliable sensing, since the secondary users in the proposed model are sensitive to the call collision, once a large "noise" occurs, the secondary user actively vacates its current channel and tries to find another available channel, which avoids the negative impact on the primary users. We also observe that P_1 increases with the increase of λ_1, as expected.

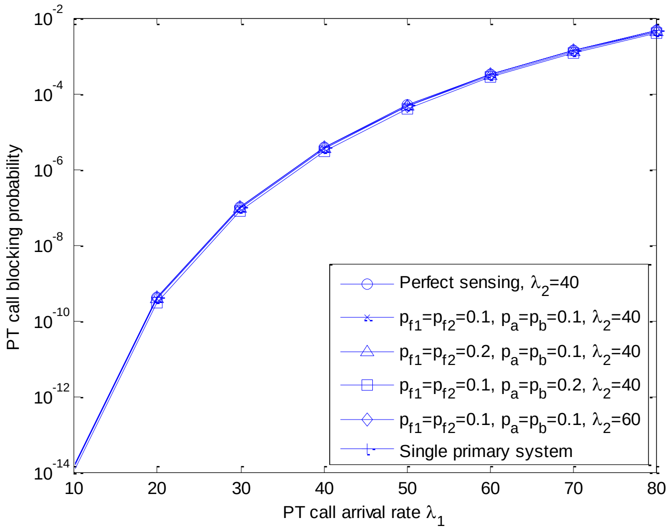

Figure 4. The PT Call Blocking Probability.

Figure 5 shows how the ST call blocking probability P_2 change with respect to different parameters. We observe that P_2 increases with increasing the call arrival rate λ_1 or λ_2, as should be expected. We also observe the impact of unreliable spectrum detection on P_2. When the false alarm probability p_f increases, P_2 will decrease. This can be explained as follows. When a false alarm event occurs, the channel remains idle, potentially to be used by other ST call requests. On the other hand, we observe that when the misdetection probability p_a (or p_b) increases, P_2 has almost no change. The minor change in the figure might be caused by the computational deviation of steady-state probabilities. This validates the benefit of using the strategy of sensitive secondary users. Normally when a misdetection happens (cf. [2]), a call collision will be caused and negatively affect the performance of the primary user. However, for a sensitive secondary user, it will actively vacate its current channel for the primary user when a misdetection happens. Note that the leaving of the sensitive ST call does not affect the calculation of P_2, since P_2 considers whether or not a new ST call can access the system. In addition, by comparing Figures 4 and 5, we observe that the ST call blocking probability is higher than that of PT calls under the same parameter settings, as should be expected.

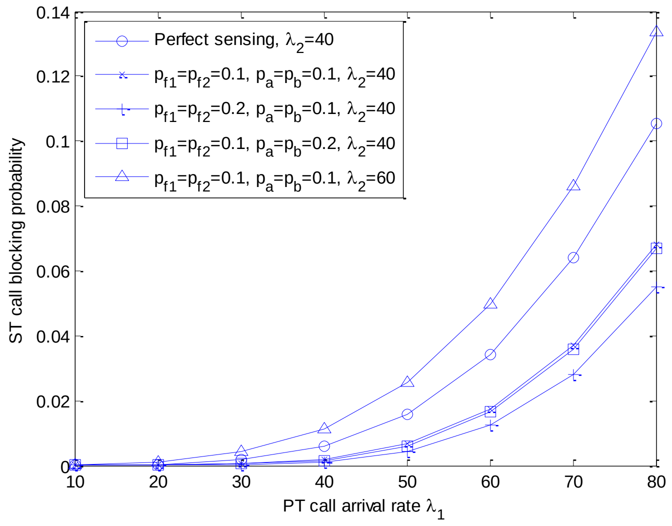

Figure 5. The ST Call Blocking Probability.

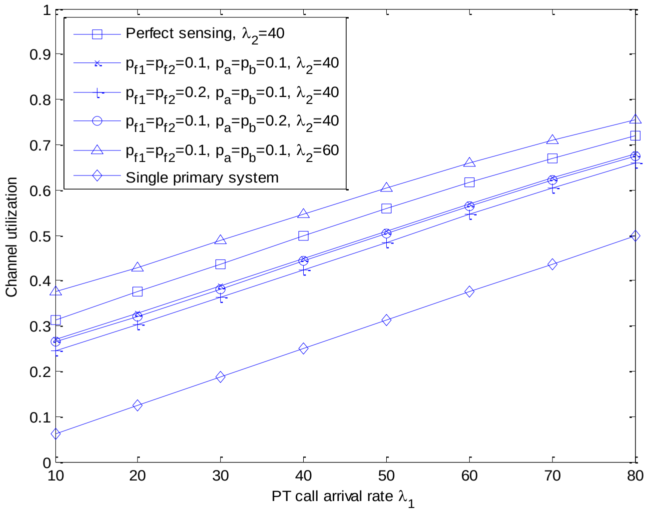

Figure 6. The Total Channel Utilization.

In Figure 6, we observe that, under the same parameter configuration, the total channel utilization of the OSS system η is the highest under perfect sensing and lowest under a single primary system. We observe that η increases with increasing λ_1 or λ_2, as should be expected. When the false alarm probability p_f increases, η will decrease. A false alarm event wastes an idle channel and lowers the channel utilization. On the other hand, when the misdetection probability p_a (or p_b) increases, η almost does not change (computational deviation of steady-state probabilities might be incurred). This again validates the advantage of using the strategy of sensitive secondary users. Normally a misdetection event causes an active channel to become an idle channel (cf. [2]). However, for a sensitive secondary user, it will actively vacate its current channel and leave it for the primary user when a misdetection happens. It is also observed that the channel utilization of the OSS system is much higher than that of the single primary system, even with unreliable spectrum sensing.

Figure 7 shows the change of the unavoidable collision probability to the primary users, P_c, with respect to different parameters. We observe that P_c increases with the increase of λ_1 or λ_2. This is because in the fixed given time period, the larger the arrival rate of primary users, the more the PT calls assigned, leading to more chance of call collision. Similarly, the larger the arrival rate of secondary users, the more chance of an assigned PT call to meet an ST call on a channel. We also observe that when the false alarm probability or misdetection probability changes, P_c almost does not change (computational deviation of steady-state probabilities might be incurred).

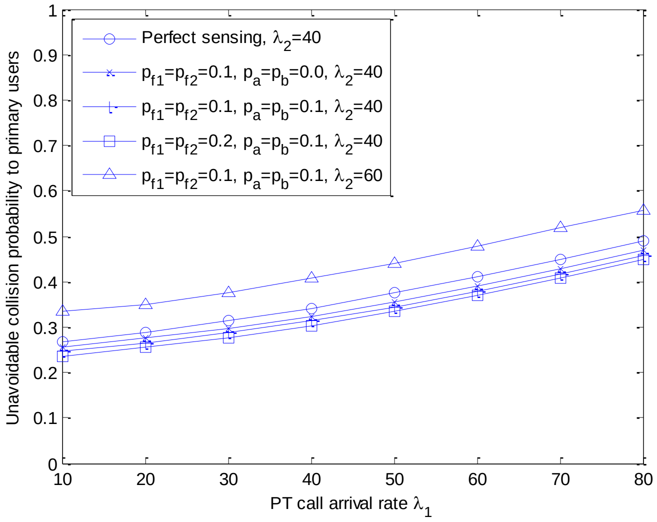

Figure 7. The Collision Probability to the PT Calls.

5. Conclusion

We analytically modeled an unreliable OSS system at the call level with sensitive secondary users through a two-dimensional Markov process. The OSS system consists of the primary users and the secondary users that opportunistically utilize the idle spectrum. Both the initiating and ongoing secondary users need spectrum sensing and perform appropriate actions. Unreliable spectrum sensing was modeled by type I and type II false alarm events and class-A and class-B misdetection events, which brings more flexibility for the purpose of performance evaluation. Spectrum sensing errors negatively impact the performance of primary users and secondary users, particularly when a call collision happens. To maximize the protection of primary users under call collisions, it is required in the OSS system design that secondary users be sensitive to the call collisions, *i.e.*., when a call collision happens (large "noise" incurred), the secondary user will vacate its current channel for the potenial primary user. We solved the steady-state probabilities of the system and derived several performance metrics of interest. Numerical results were presented for further performance analysis and comparison.

Acknowledgments

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Authors

Shensheng Tang, He is currently an associate professor of electrical engineering at Missouri Western State University (MWSU), USA. He received his Ph.D. from The University of Toledo, USA. He has eight years of industrial experience for product design and development in the field of telecommunications. His research interests include communications and networking, wireless sensor networks, cognitive radio networks, statistical signal processing, network security, and smart grids. He has produced over 80 papers in refereed journals and conference proceedings related to the above areas. He was listed several times in Marquis Who’s Who in Science and Engineering and Marquis Who’s Who in America. He was selected as the recipient of MWSU's Dr. James V. Mehl Award for Outstanding Faculty Scholar in 2012. He is a senior member of IEEE.

Rong Yu, He received his Ph.D. degree from Tsinghua University, China, in 2007. He is a full professor at Guangdong University of Technology (GDUT). His research interests mainly focus on wireless communications and networking, including cognitive radio, vehicular networks, smart grid networks, and home M2M networks. He is the co-inventor of over 30 patents, and author or co-author of over 100 international journal and conference papers. He is currently serving as the Deputy Secretary General of the Internet of Things (IoT) Industry Alliance, Guangdong, China, and Deputy Head of the IoT Engineering Center, Guangdong, China. He is a member of the Home Networking Standard Committee in China, where he leads the work on three standards.

Xiaojiang Chen, He received the Ph.D. degree in computer software and theory from Northwest University, Xi'an, China, in 2010. He is currently a Professor with the School of Information Science and Technology, Northwest University. His current research interests include localization and performance issues in wireless ad hoc, mesh, and sensor networks and named data networks.

Chenghua Tang, He received Ph.D. from the Beijing Institute of Technology, China in May 2007, and completed postdoctoral research at the Sun Yat-Sen University, China in June 2009, China. He is currently with the School of Computer Science & Engineering in Guilin University of Electronic Technology. His research interests include network information security, data fusion, and intelligent information process.

Yi Xie, He received the B.Sc., M.Sc. and Ph.D. degrees from Sun Yat-Sen University, Guangzhou, China. He was a visiting scholar at George Mason University and Deakin University during 2007 to 2008, and 2014 to 2015, respectively. He is currently an Associate Professor at the School of Information Science and Technology, Sun Yat-Sen University. His recent research interests include networking, network security, behavior modeling and algorithms. Some of his works have been published in ToN and TPDS. He has presided four research projects, including two of National Natural Science Foundation of China. He acts as a young Associate Editor of the Springer journal named "Frontiers of Computer Science".