Opportunistic Spectrum Access in Cognitive Radio Network

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1. Introduction

Cognitive radio (Mitola III, 2000) also known as opportunistic spectrum access (OSA) has emerged as a promising solution to increase the spectrum efficiency Haykin (2005). In OSA, the SU finds spectrum holes (white space) by sensing the radio frequency spectrum. The presence of spectrum holes in the PU channels are highlighted in Fig. 1. These spectrum holes are used by the SU for its transmission. This scheme is often referred to as opportunistic spectrum access (OSA). No concurrent transmission of the PU and the SU is allowed. The SU must vacate the channel as soon as the PU reappears, which leads to the forced termination of the SU connection. Since the SU has no control over the resource availability, the transmission of the SU is blocked when the channel is occupied by the PU. The forced termination and blocking of a SU connection is shown in Fig. 2. The forced termination probability and blocking probability are the key parameters which determine the throughput of the SU, and thus its viable existence. The forced termination depends on the traffic behaviour of the PUs and the SUs (e.g. arrival rates, service time etc.). In the case of multiple SU groups with different traffic statistics, the forced termination and blocking probabilities lead to unfairness among the SU groups. The QoS provisioning task becomes difficult.

2. Related work and contributions

In the existing literature, several authors Weiss & Jondral (2004)-Ahmed et al. (2010) have studied the forced termination and blocking probabilities for one and two groups of SUs. In these papers, spectrum pooling Weiss & Jondral (2004) is used as a base system model. Spectrum pooling refers to an OSA paradigm which enables the PU network to rent out its idle spectrum bands to the SU group. It is assumed that the SU group will be able to perform wideband sensing and during their transmissions will introduce spectral nulls in the frequency bands where they find the PU active. It is suggested that in order to accommodate simultaneous SU connections, a wideband PU channel can be divided into multiple narrowband subchannels for SU access. The Continuous Time Markov Chain (CTMC) Mehdi (1991) is extensively used in modelling spectrum sharing scenarios based on interweave access. To simplify mathematical analysis it is commonly assumed that the traffic behaviour of the PU and the SU groups obey a Markov (memoryless) property i.e. the arrival rates follow a Poisson distribution and the service rates follow an exponential distribution. In

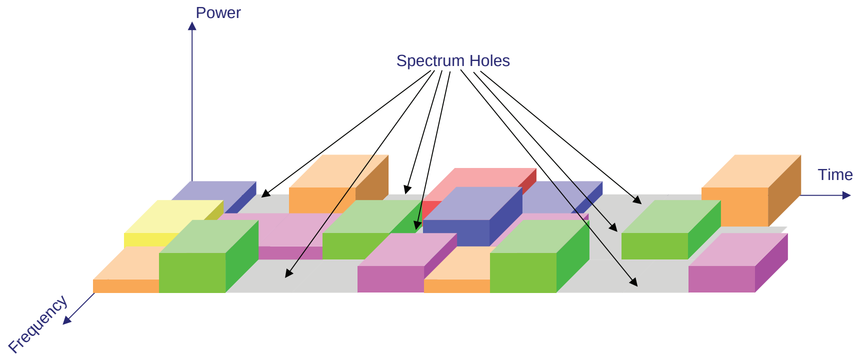

Fig. 1. Conceptual view of spectrum holes for interweave approach

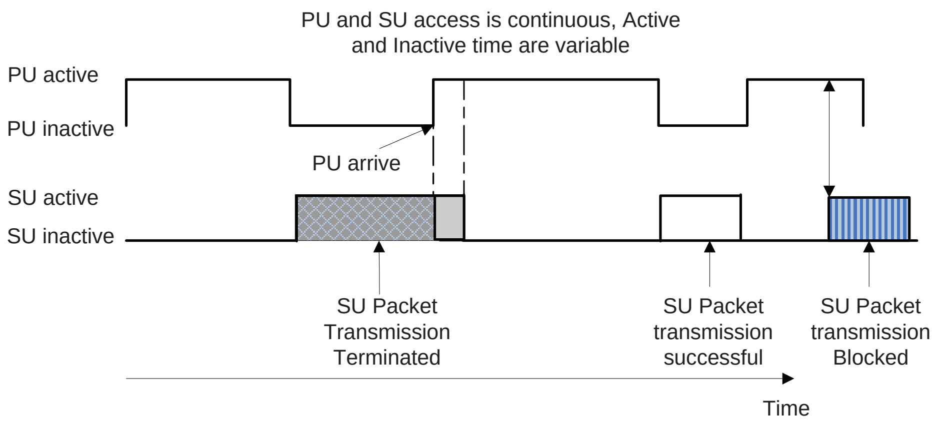

Fig. 2. Illustration of forced termination and blocking

addition, the SU connections are coordinated through a central entity (centralised secondary network) which ensures no collision between the SU connections i.e, no concurrent SU connections on the same frequency band or subchannel. The SU connections have negligible access, switching delays and perfect sensing information is available to them at all times. In a CTMC model, the number of connections from the user groups are represented by states (written as $n - tuple$), such as (x_1,x_2), where x_1 and x_2 may represent the number of PU and SU connections. The transition of one state to another is based on the Markov propertyMehdi (1991) which assumes memoryless arrival and departure. Under stationarity assumptions, the rate of transition from and to a state is equal. This fundamental fact is used to calculate the state probabilities under the constraint that the sum of all state probabilities is equal to 1. These state probabilities are further used to calculate the parameters of interest. The papers dealing with QoS analysis can be divided into two scenarios: without forced termination; with forced termination, described in the following.

2.1 Without forced termination

The main aim in this type of system model is to understand the blocking probability tradeoff between two users with different bandwidth requirements. In Raspopovic et al. (2005) while investigating the blocking probability tradeoff between equal priority users, the authors concluded that the blocking probability of the wideband user is lower bounded by the blocking probability of the narrowband user. The best probability tradeoff can only be achieved by changing the arrival rates of both the wideband and the narrowband user Raspopovic & Thompson (2007). This fact is used in Xing et al. (2007) where it is shown that the optimal arrival rates which achieve airtime fairness can be derived using the Homo-Egualis model. Furthermore, the blocking probability in the network can be reduced when the narrowband users pack the channels (Xing et al., 2007, Fig. 6) by employing spectrum handoff[1]. The authors in Chou et al. (2007) developed an upper bound on the throughput that can be achieved using spectrum agility with a listen before talk rule[2]. It was found that a fixed channel assignment strategy yields better results than spectrum agility under heavy load conditions. Although, the above mentioned schemes provide a fair understanding of the blocking probability and airtime behaviour in a CRN, these analyses are only applicable to users in open unlicensed networks (e.g. ISM bands in 900MHz, 2.4 GHz and 5GHz), when the SU group utilizes the unlicensed channels for coordination or backup (in case the PU channels are fully occupied Xing et al. (2007)).

2.2 With forced termination

Initial investigation carried out in Capar et al. (2002), focused on the advantages of primary assisted SU spectrum sharing; termed controlled spectrum sharing. In controlled spectrum sharing, the PU network assigns channels to its users (PUs) so as to avoid termination of SU connections. It is concluded that this approach increases bandwidth utilization without causing any significant increase in the blocking probability of the SU connections. No analytical expressions were derived for the forced termination probability and the throughput. In another controlled spectrum sharing scenario Tang et al. (2006); Tang & Chew (2010), a number of channels are allocated for SU connections by the PU network. Under saturated condition an incoming PU connection can also occupy the secondary allocated channels. Although this scheme decreases the forced termination probability, it comes with a cost of an increased SU blocking probability. To counter the effect of the forced termination the authors in Huang et al. (2008) have proposed and analyzed random access schemes employing different sensing and backoff mechanisms. However, the analysis is limited to a single channel and saturated SU traffic conditions.

To avoid this foreseeable termination, spectrum handoff techniques have also been investigated from the forced termination and blocking probability perspective. Generally, spectrum handoff techniques can be categorised as either reactive or proactive. In the reactive approach, the SU moves to another vacant channel only when the current channel is reoccupied by a PU, whereas in the proactive approach the SU avoids collision and switches

[1] Spectrum handoff allows the SU connection to move to another vacant frequency channel during its transmission.

[2] Spectrum agility refers to the ability of a user to access multiple channels. Please note that spectrum agility is a stepping stone for spectrum handoff.

to another vacant channel before a PU reappears. The channel switching is performed based on the observed statistics of the PU channels[3]. To further ensure the continuity of SU transmission, inband channel reservation (number of channels are reserved exclusively for handoff calls within the primary channels) and out-of-band channel reservation have also been suggested Zhu et al. (2007), Al-Mahdi et al. (2009).

2.2.1 Reactive spectrum handoff

In Zhu et al. (2007), authors investigated the impact of spectrum handoff and channel reservation on the forced termination and blocking probabilities. However, the paper presented an incomplete CTMC analysis. In addition the expressions are derived based on a false assumption of completion probability from each Markov state. The corrections on this work is provided in Ahmed et al. (2009); Zhang et al. (2008); Bauset et al. (2009). The work in Ahmed et al. (2009) forms part of this chapter and discussed in chapter 3. Although, the authors in Zhang et al. (2008) included the queuing of SU connections, the analysis is limited to only handoff scenario. The investigations in Zhang et al. (2008); Bauset et al. (2009) do not address the incomplete Markov analysis and throughput. The approach presented in Ahmed et al. (2009) can be scaled to address the inaccurate probability analysis in Al-Mahdi et al. (2009). It has been shown in Tzeng (2009) that an adaptive channel reservation scheme gives better performance than the fixed reservation policy. This adaption is based on traffic statistics of the PU. A relatively similar conclusion has been drawn in Bauset et al. (2010). Extending the work in Zhu et al. (2007)-Tzeng (2009), the authors in Kannappa & Saquib (2010) showed that the forced termination probability can be reduced by assigning multiple subchannels to each SU connection (reducing their transmission time). The forced termination probability expression derived in this paper is the termination probability seen by an incoming SU (an incoming SU call may be blocked) rather than the termination probability on the channel. The throughput in Bauset et al. (2009)-Kannappa & Saquib (2010) is defined as the average completion rate of SU connections which does not include the average duration of completed SU connections. In order to address this problem, the duration of completed SU connections is calculated in Heo (2008), however, the analytical results derived are not very accurate. A more compact and accurate expression of throughput is derived in Ahmed et al. (2009). The authors in Xue et al. (2009) consider a PU network which has three different user classes. The users are admitted into the network based on a Guarded Threshold channel reservation Policy Ramjee et al. (1996). One of the classes is treated as a SU group, while the remaining two have PU status. The results indicate that such a scheme is only useful when the collision probability between the SU class and the two PU classes is high.

Based on a simplified system model, the link maintenance probability and the forced termination probability of delay sensitive SU connections are discussed in Zhang (2009)-Willkomm et al. (2005). Including imperfect sensing, the probability derivations have been carried out in Tang & Mark (2009), where authors derive the collision probability rather than the forced termination probability[4]. In Wang & Anderson (2008); Willkomm et al. (2005)

[3] This chapter only considers reactive spectrum handoff techniques. Some interesting proactive spectrum handoff strategies are provided in Yuan (2010)-Yoon& Ekici (2010).

[4] Without spectrum handoff the collision probability and forced termination probability is the same. However in the case of spectrum handoff, the SU connection can collide with the PU multiple times without being terminated. In essence collision probability calculation is performed on the basis of a single PU arrival, whereas the forced termination calculation are performed on the basis of multiple PU arrivals in the SU connection’s life time Ahmed et al. (2009)Zhang et al. (2008)

it has been found that reactive spectrum handoff based on dynamic channel selection is a better strategy than the static strategy, however, it results in an increased sensing overhead. To decrease this overhead, a handoff reduction policy is proposed in Khalil et al. (2010) using connection success rate as a key metric Lin et al. (2009). Based on our findings Ahmed et al. (2009), the authors in Chung et al. (2010) proposed a channel allocation technique which yields almost similar performance to a spectrum handoff system.

From the perspective that CRN will be able to support multiple SU services, call admission control is investigated in Wang et al. (2009)-Tumuluru et al. (2011). The authors in Wang et al. (2009) derived optimal access probabilities to achieve proportional fairness among two SU groups. These results are derived based on a loose definition of throughput without considering the forced termination. A channel packing scheme which provides 10%- 15% gain over random channel access has been presented in Luo & Roy (2009). The optimal access rates are derived only for a single wideband channel and three different type of users: one wideband PU: one wideband SU group; and one narrowband SU group. Although overall forced termination probability is also shown, it is strictly numerical and does not provide any insight into the individual forced termination probabilities of the two SU groups. A fair opportunistic spectrum access scheme with emphasis on two SU groups has been presented in Ma et al. (2008). Although the effect of collision probability is included, the results are only valid when the SU groups have the same connection length. The prioritisation among SU traffic from a physical layer and network integration perspective have been studied in Wiggins et al. (2008); Gosh et al. (2009). Moreover, as identified in Tumuluru et al. (2011), these works do not include the effect of spectrum handoff. The probability aspects of prioritisation between two SU groups have been recently analyzed in Tumuluru et al. (2011). Subchannel reservation policies were investigated to achieve the QoS of the prioritised SU group. The probability derivations were very similar to those previously presented by us in Ahmed et al. (2010); Ahmed et al. (2009) and now described in this Chapter. Specifically, in this chapter

- A complete and exact CTMC analyses is presented (compared to Zhu et al. (2007); Zhang et al. (2008); Bauset et al. (2009)). The QoS parameter are obtained for spectrally agile single SU group operating in multichannel PU network. These derivations also include SU spectrum handoff and channel reservation scenarios.
- Spectrum sharing between two SU groups is investigated in terms of probability tradeoff gains and airtime fairness. It is shown that compared to non-termination scenarios Raspopovic et al. (2005)-Chou et al. (2007); Wang et al. (2009) the access rates have very little impact on airtime fairness. A channel partitioning approach is developed to achieve airtime fairness.

The remainder of the chapter is organised as follows. Section 3 presents the system model and key assumptions. Section 4 extends the discussion to include multiple PU channels and two SU groups. A single SU group is treated as a special case. The airtime fairness among the two SU groups is analyzed in Section 5. Section 6 concludes the chapter.

3. System model

In this chapter, a widely acceptable spectrum pooling model (Weiss & Jondral, 2004, Fig. (3)) is adopted, in which a vacant wideband PU channel is divided into multiple narrowband subchannels. These narrowband subchannels are used by SU groups for their opportunistic transmissions. Fig. 3 shows the system model, in which there are K available PU channels

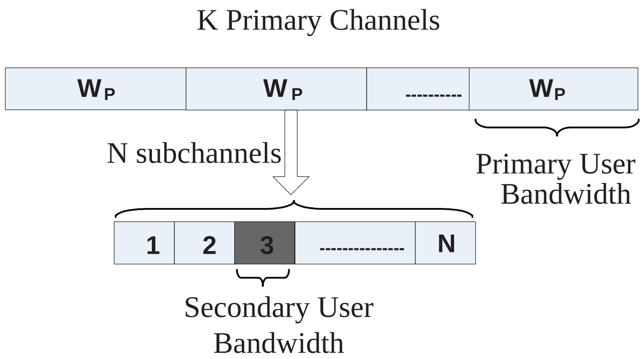

Fig. 3. Channel arrangements of PU and SU channels.

Symbol	Parameter
k	Number of PU connections
i	Number of SU connections of S^1 and S^A
j	Number of SU connections of S^B
l	Number of terminated SU connections S^1 and S^A
m	Number of terminated SU connections S^B

Table 1. List of Symbols for CTMC

$k \in \{1, 2.., K\}$. Each of the PU channels has a fixed bandwidth W_p, which is subdivided into N subchannels of bandwidth, $W_s = W_p/N$. The service duration $\frac{1}{\mu_p}$ of the PU connections are assumed to be exponentially distributed. The arrival rate λ_p of new connections from the PU group follow an independent Poisson process. It is assumed that the PU network is an M/M/m/m loss network, where channel occupancy only depends on the mean service rate of PU group Mehdi (1991). The exponentially distributed mean service duration of S^1, S^A and S^B are denoted by $\frac{1}{\mu_{se}^1}$, $\frac{1}{\mu_{se}^A}$ and $\frac{1}{\mu_{se}^B}$ respectively. Similarly, the Poisson arrival rates are λ_s^1, λ_s^A, and λ_s^B.

4. Multiple PU channels ($K \geq 1$, $N \geq 1$) and two SU groups

In this section, we first investigate the impact of spectrum sharing between two SU groups in a CRN with spectrum agility. We refer to this as the “basic system”. In a basic system, the SU connection can access one of the available PU channels, however, no spectrum handoff is allowed (Fig. 4). Each of the two SU groups has different traffic statistics. Second, we also investigate the impact of horizontal handoff and channel reservation. The single SU group is treated as a special case, by letting $\theta_{se} = \frac{\lambda_s}{\mu_{se}}$ tend to 0 for one of the SU groups. Such a spectrum sharing scenario has partially been considered in Wang et al. (2009), where the effect of forced termination was neglected. This section includes the forced termination aspect, and therefore gives a more realistic result. For mathematical convenience it is assumed that the SU header length is 0.

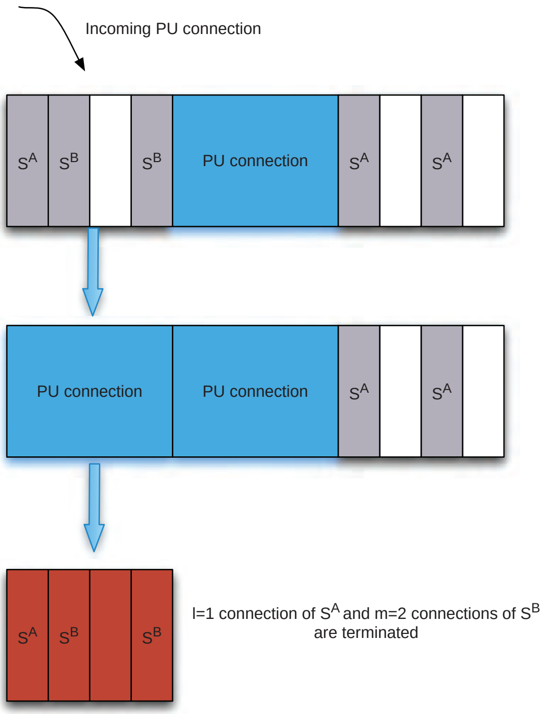

Fig. 4. Illustration of the Basic system.

4.1 Basic system

Fig. 5 shows the state transition diagram of a basic system. The states in the model are given by the number of active connections in the system, i.e., (i, j, k), whereas i, j are the number of active SU connections of S^A and S^B overlaying k active PU connections. The transition rate from state to state is given by the labels on the arrows. An example of a forced termination is the corner state $(i-l, j-m, k+1)$ from state (i, j, k) (shown as a dashed arrow in Fig. 5), where l and m represent the number of terminated active connections from S^A and S^B respectively. Following (Zhu et al., 2007, Eq. (1)), the termination of $q = l + m$ out of $x = i + j$ SU connections follows a hypergeometric distribution, and can be written as

$$P^{(i+j,k)}_{((i+j)-(l+m),k+1)} = \frac{\binom{N}{l+m}\binom{(K-k-1)N}{(i+j)-(l+m)}}{\binom{(K-k)N}{i+j}}. \tag{1}$$

Given i and j, the probability of exactly l and m can be written as

$$P^{(i,j)}_{(i-l,j-m)} = \frac{\binom{i}{l}\binom{j}{m}}{\binom{i+j}{l+m}}. \tag{2}$$

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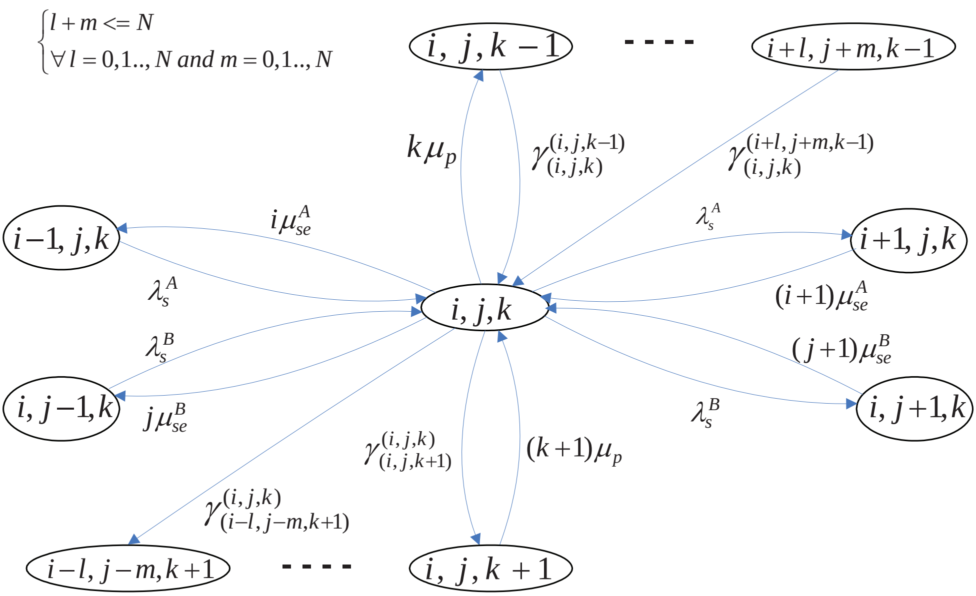

Fig. 5. CTMC for the basic system.

Combining (1) and (2) gives the probability of having exactly l and m SU connections terminated from the state (i, j, k), and can be calculated from

$$P_{(i-l,j-m,k+1)}^{(i,j,k)} = P_{(i-l,j-m)}^{(i,j)} P_{((i+j)-(l+m),k+1)}^{(i+j,k)} \tag{3}$$

The termination of l and m SU connections occurs at the arrival of each PU connection. Therefore, given the arrival rate of a PU connection λ_P, the state transition *rate* $\gamma_{(i-l,j-m,k+1)}^{(i,j,k)}$ can be written as

$$\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} = P_{(i-l,j-m,k+1)}^{(i,j,k)} \lambda_P \tag{4}$$

By substituting (1) - (3) in (4), the state transition rate from (i, j, k) to $(i-l, j-m, k+1)$ is given as

$$\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} = \frac{\dfrac{\binom{i}{l}\binom{j}{m}}{\binom{i+j}{l+m}} \binom{N}{l+m} \binom{(K-k-1)N}{i+j-l-m}}{\binom{(K-k)N}{i+j}} \lambda_P, \tag{5}$$

for $0 \le l + m \le N$. Setting j and m to zero, (5) is the same as (Zhu et al., 2007, Eq. (1)). From Fig. 5, a set of balance equations of the CTMC model for all $0 \le i, j \le KN$ and $0 \le k \le K$ can be written as

$$\lambda_s^A P_\phi(i-1,j,k) + (i+1)\mu_{se}^A P_\phi(i+1,j,k) + \lambda_s^B P_\phi(i,j-1,k) + (j+1)\mu_{se}^B P_\phi(i,j+1,k)$$
$$+(k+1)\mu_p P_\phi(i,j,k+1) + \sum_{l=0}^{N}\sum_{m=0}^{N} \gamma_{(i,j,k)}^{(i+l,j+m,k-1)} P_\phi(i+l,j+m,k-1)\delta(l+m \le N)$$
$$= \left(\lambda_s^A + i\mu_{se}^A + \lambda_s^B + j\mu_{se}^B + k\mu_P + \sum_{l=0}^{N}\sum_{m=0}^{N} \gamma_{(i-l,j-m,k+1)}^{(i,j,k)} \delta(l+m \le N)\right) P_\phi(i,j,k), \quad (6)$$

where, $P_\phi(i,j,k) = P(i,j,k)\phi(i,j,k)$, $\phi(i,j,k)$ is one for all valid states and zero for all non-valid states. Mathematically,

$$\phi(i,j,k) = \begin{cases} 1 & i+j \le (K-k)N, \\ 0 & \text{otherwise,} \end{cases} \quad (7)$$

and $P(i,j,k)$ denotes the probability that the system is in the state (i,j,k). The state probability must satisfy the following constraint

$$\sum_{i=0}^{NK}\sum_{j=0}^{NK}\sum_{k=0}^{K} P_\phi(i,j,k) = 1. \quad (8)$$

The set of equations expressed by (6) can be written as a multiplication of state transition matrix Q and state probability vector P

$$QP = 0. \quad (9)$$

Replacing the last row of Q, with the constraint in (8), the state probabilities can be solved by

$$P = Q^{-1}\epsilon, \quad (10)$$

where, $\epsilon^T = [0\ ,\ 0\ ,\ ..\ ,\ 1]$ and $(\cdot)^T$ is the transpose operator. For the basic system, the blocking of a new SU connection occurs when all PU channels are fully occupied. The state (i,j,k) is a blocking state if $i + j + Nk = NK$. The probabilities of all blocking states are summed to calculate the blocking probability which is given by

$$P_{Be}^{AB} = \sum_{i=0}^{NK}\sum_{j=0}^{NK}\sum_{k=0}^{K} \delta(i+j+Nk-NK)P_\phi(i,j,k). \quad (11)$$

From its definition and using the fact that the total termination rate (sum of forced and unforced termination rates) equals the connection rate in Fig. 5, the forced termination probability can be written as

$$\text{Forced Termination Probability} = \frac{\text{Total SU forced termination rate}}{\text{Total SU connection rate}} \quad (12)$$

For the given state (i,j,k), $\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_\phi(i,j,k)$ is the termination rate of l and m SU connections. From the state (i,j,k), the total termination rate $F(i,j,k)$ can be written as

$$F(i,j,k) = \sum_{l=0}^{NK}\sum_{m=0}^{NK} (l+m)\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_\phi(i,j,k)\delta_f, \quad (13)$$

where δ_f is given as

$$\delta_f = \begin{cases} 1 & 0 \leq l + m \leq N \\ 0 & \text{otherwise,} \end{cases} \tag{14}$$

The total connection rate is given by $(1 - P_{Be}^{AB})(\lambda_s^A + \lambda_s^B)$. Using (12) and (13) the combined forced termination probability P_{Fe}^{AB} of a SU connection can be written as

$$P_{Fe}^{AB} = \frac{\sum_{i=0}^{NK}\sum_{j=0}^{NK}\sum_{k=0}^{K}\sum_{l=0}^{N}\sum_{m=0}^{N} (l+m)\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_\phi(i,j,k)\delta_f}{(1 - P_{Be}^{AB})(\lambda_s^A + \lambda_s^B)}. \tag{15}$$

Similarly, the individual forced termination probabilities for user groups S^A and S^B can be respectively calculated as

$$P_{Fe}^{A} = \frac{\sum_{i=0}^{NK}\sum_{j=0}^{NK}\sum_{k=0}^{K}\sum_{l=0}^{N}\sum_{m=0}^{N} l\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_\phi(i,j,k)\delta_f}{(1 - P_{Be}^{AB})\lambda_s^A}, \tag{16}$$

and

$$P_{Fe}^{B} = \frac{\sum_{i=0}^{NK}\sum_{j=0}^{NK}\sum_{k=0}^{K}\sum_{l=0}^{N}\sum_{m=0}^{N} m\gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_\phi(i,j,k)\delta_f}{(1 - P_{Be}^{AB})\lambda_s^B}. \tag{17}$$

From (15),(16) and (17), it can be shown that

$$P_{Fe}^{AB} = \frac{\lambda_s^A}{\lambda_s^A + \lambda_s^B} P_{Fe}^A + \frac{\lambda_s^B}{\lambda_s^A + \lambda_s^B} P_{Fe}^B. \tag{18}$$

Note that P_{Fe}^{AB} is not the average of P_{Fe}^A and P_{Fe}^B except for the special case where $\lambda_s^A = \lambda_s^B$.

4.1.1 Special case-single SU group

In this section, the forced termination and blocking probabilities for a single SU group are treated as a special case of two SU groups. Let P_{Fe}^1 and P_{Be}^1 be the forced termination and blocking probabilities of a single SU group respectively. Setting $j = 0$, $m = 0$, $\lambda_s^B = 0$, $\mu_{se}^B = 0$ in (5) and (6), we get the same equations as in (Zhu et al., 2007, Eqs. (1-2)) i.e., $\gamma_{(i-l,0,k+1)}^{(i,0,k)} = \gamma_{(i-l,k+1)}^{(i,k)}$ and $P_\phi(i,0,k) = P_\phi(i,k)$. Under this condition, the expression in (11) for the blocking probability is identical to that of the single SU group.

Similarly, it can be shown that the forced termination probability in (15) can be simplified to

$$P_{Fe}^1 = \frac{\sum_{i=0}^{NK}\sum_{k=0}^{K}\sum_{l=1}^{N} l\gamma_{(i-l,k+1)}^{(i,k)} P_\phi(i,k)}{(1 - P_{Be}^1)\lambda_s^1}. \tag{19}$$

The term $\sum_{l=1}^{NK} l\gamma_{(i-l,k+1)}^{(i,k)} P_\phi(i,k)$ in (19) is the termination rate of the SU connections from the state (i,k). By summing over all valid states $\phi(i,0,k)$, we get the total number of terminated connections per unit time. Note that the forced termination probability P_{Fe}^1 from (Zhu et al., 2007, Eq. (4)) differs from the above, because it describes a rate rather than a probability.

4.2 Basic system with spectrum handoff and channel reservation

In this section, we extend the results derived in the previous section to system with spectrum handoff and channel reservation. As described previously, spectrum handoff allows an active SU connection to move to another vacant subchannel, rather being terminated by an incoming PU connection. This phenomena is illustrated in Fig. 6. To further ensure the continuity of existing SU connections, a small number of subchannels (marked R) are reserved exclusively for spectrum handoff purpose. These subchannels improve the forced termination probability at the expense of increased blocking probability.

In order to quantify the performance using spectrum handoff and channel reservation, the following measures are defined:

$$G_F(r) = \frac{P_{Fe}^{AB}(\text{Basic System}) - P_{Fe}^{AB}(r)}{P_{Fe}^{AB}(\text{Basic System})}, r = 0 \ldots N, \tag{20}$$

and

$$G_B(r) = \frac{P_{Be}^{AB}(r) - P_{Be}^{AB}(\text{Basic System})}{P_{Be}^{AB}(\text{Basic System})}, r = 0 \ldots N, \tag{21}$$

where, $G_F(r)$ expresses the improvement (fractional reduction) in forced termination probability of the basic system when r reserved channels are used, and $G_B(r)$ describes the degradation (fractional increase) in blocking probability with r reserved channels. Since N is the maximum number of terminations per PU connection, we only consider $r \leq N$. If $r > N$ the complexity of the CTMC increases significantly as it has to cater for multiple PU arrivals rather than a single arrival. We define a measure, *tradeoff gain* $L(r)$, which relates improvement in forced termination probability to the degradation in terms of the blocking probability as

$$L(r) = \frac{G_F(r)}{G_B(r)}. \tag{22}$$

The condition $L(r) >> 1$ indicates that the SU network has a greater improvement in forced termination probability compared to its increase in blocking probability.

Fig. 7 shows the state transitions of the CTMC with r reserved channels $0 \leq r < N$. The state diagram for $r = N$ requires slight modification. In Fig. 7(a), spectrum handoff ensures no termination when a new PU connection is made. Fig. 7(b)-(e) depicts the condition when the total number of vacant sub-channels is less than N. On the arrival of a new PU connection, we have $i + j + (k+1)N > KN$, therefore forced termination occurs. Fig. 7(b) allows new SU connections because the number of free subchannels is greater than r. Contrary to Fig. 7(b), Figs. 7(c)-(e) will allow no new SU connections since the number of free channels are less than or equal to r. Note that there is a number of states which have a single arrow to/from state (i, j, k) . These states include the cases where either forced termination occurs, or a new SU connection is blocked because there is no vacant subchannel except the reserved subchannels. The condition Figs. 7(d)-(e) also signifies that the SUs are utilising the reserved channels. The state (i, j, k) in Fig. 7(e) can also result from other states $(i + l, j - m, k - 1)$. In these transitions, forced termination occurs.

With spectrum handoff and channel reservation, the forced termination will only occur when $i + j + Nk > (K-1)N$. The arrival of a new PU connection will cause the existing SU connections to pack themselves in $(K - (k+1))N$ subchannels, i.e., the transition of

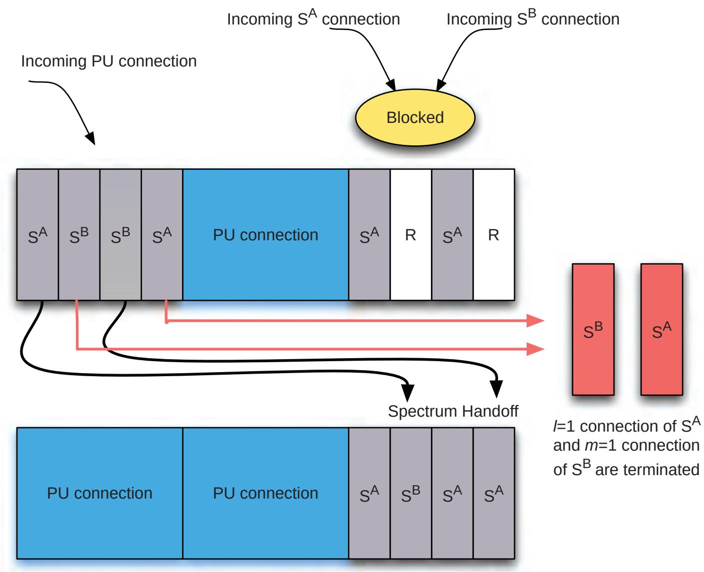

Fig. 6. Illustration of the system with spectrum handoff and channel reservation. The number of reserved channels $r = 2$.

current state (i, j, k) to state $(i - l, j - m, k + 1)$ with the *packing condition* $(i - l) + (j - m) = (K - k - 1)N$. The rate of this transition is expressed as

$$\gamma^{(i,j,k)}_{(i-l,j-m,k+1)} = \frac{\binom{i}{l}\binom{j}{m}}{\binom{i+j}{l+m}}\lambda_p. \tag{23}$$

The condition of a valid state $\phi_r(i, j, k)$ for all $i, j = \{0, \ldots, KN - r\}$ and $k = \{0, \ldots K\}$ is given as

$$\phi_r(i, j, k) = \begin{cases} 1 & i + j \leq (K - k)N \quad \text{and } \mathrm{i} + \mathrm{j} \leq \mathrm{KN} - \mathrm{r} \\ 0 & \text{otherwise.} \end{cases} \tag{24}$$

Similar to the basic system in the previous section, the set of balance equations for the CTMC are written. Together with the constraint (8), the state probabilities $P_{\phi_r}(i, j, k) = P(i, j, k)\phi_r(i, j, k)$ can be solved using (9) and (10). With spectrum handoff and channel reservation, the blocking of a new SU connection occurs when the number of vacant subchannels is less than or equal to r. Mathematically,

$$P^{AB}_{Be}(r) = \sum_{i=0}^{NK-r}\sum_{j=0}^{NK-r}\sum_{k=0}^{K}\delta(i + j + Nk \geq KN - r)P_{\phi_r}(i, j, k). \tag{25}$$

Using (12), the combined forced termination probability with r reserved subchannels can be calculated from,

$$P^{AB}_{Fe}(r) = \frac{1}{(1 - P^{AB}_{Be}(r))}\sum_{i=0}^{NK-r}\sum_{j=0}^{NK-r}\sum_{k=0}^{K}\sum_{l=0}^{N}\sum_{m=0}^{N}\frac{(l + m)}{(\lambda^A_s + \lambda^B_s)}\gamma^{(i,j,k)}_{(i-l,j-m,k+1)}P_{\phi_r}(i, j, k)\delta_{fr}. \tag{26}$$

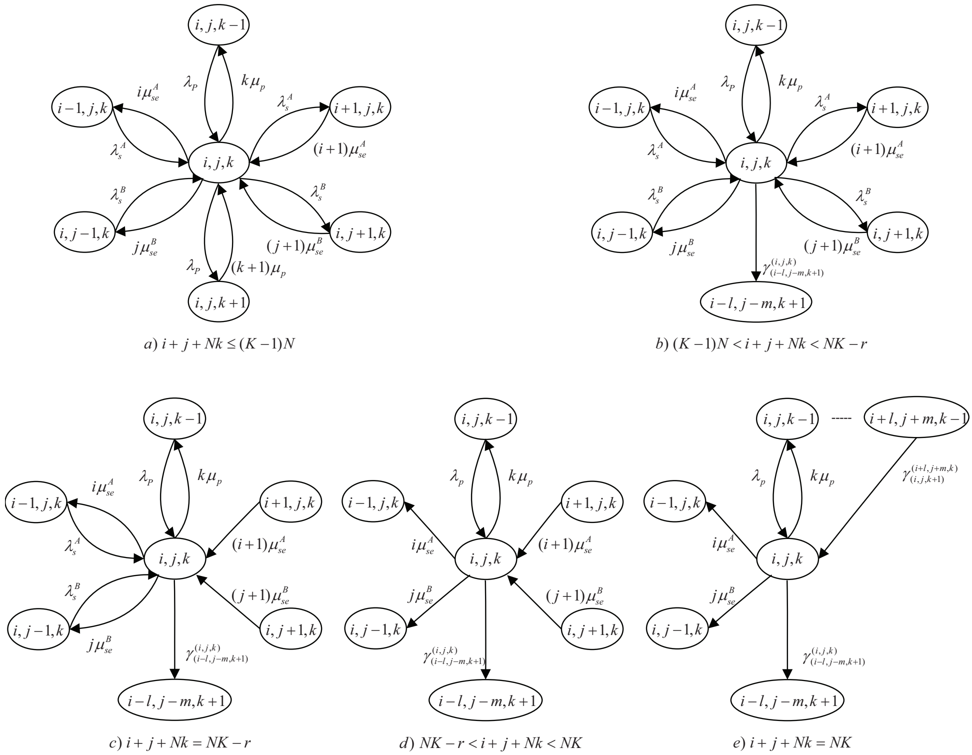

Fig. 7. A CTMC for the system with spectrum handoff and channel reservation $r < N$. The states $(i-l, j-m, k+1)$ satisfy packing condition i.e., $(i-l)+(j-m) = (K-k-1)N$ for $0 < l+m \le N$.

The individual forced termination probabilities for user groups S^A and S^B are

$$P_{Fe}^{A}(r) = \frac{1}{(1-P_{Be}^{AB}(r))} \sum_{i=0}^{NK-r} \sum_{j=0}^{NK-r} \sum_{k=0}^{K} \sum_{l=0}^{N} \sum_{m=0}^{N} \frac{l}{\lambda_s^A} \gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_{\phi_r}(i,j,k) \delta_{fr}, \tag{27}$$

and

$$P_{Fe}^{B}(r) = \frac{1}{(1-P_{Be}^{AB}(r))} \sum_{i=0}^{NK-r} \sum_{j=0}^{NK-r} \sum_{k=0}^{K} \sum_{l=0}^{N} \sum_{m=0}^{N} \frac{m}{\lambda_s^B} \gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_{\phi_r}(i,j,k) \delta_{fr}, \tag{28}$$

where, δ_{fr} is defined as

$$\delta_{fr} = \delta((i-l)+(j-m)-(K-k-1)N)\ \delta(i+j+Nk > (K-1)N)\ \delta(0 < l+m \le N). \tag{29}$$

Note that δ_{fr} consists of three conditions, i.e., the packing, termination and a valid number of dropped SU connections.

4.2.1 Special case-single SU group

In the case of a single SU group, we set the respective parameters for S^B in Figs. 7(a)-(e) to 0. Note that the resulting state transition diagrams are different from (Zhu et al., 2007, Fig. 4). The latter did not include the proper state transitions for the reserved channels, which gave over optimistic result. In Figs. 7(a)-(e) all five state transition scenarios are included which gives a complete CTMC analysis.

The state probabilities $P_{\phi_r}(i,k)$ are calculated by following the basic system's approach(). For a single SU group, the blocking probability with r reserved subchannels can be written as

$$P^1_{Be}(r) = \sum_{i=0}^{NK-r} \sum_{k=0}^{K} \delta(i + Nk \geq KN - r) P_{\phi_r}(i,k). \tag{30}$$

The above expression states that the blocking of a new SU connection can only occur when the number of vacant subchannels are less than or equal to r. For a single SU group, the forced termination probability is given by

$$P^1_{Fe}(r) = \frac{\sum\limits_{i=0}^{NK-r} \sum\limits_{k=0}^{K} \sum\limits_{l=1}^{N} \gamma^{(i,k)}_{(i-l,k+1)} P_{\phi_r}(i,k) \delta^1_f(r)}{(1 - P_B(r)^1)\lambda^1_s}, \tag{31}$$

where, $\delta^1_f(r) = \delta(i + Nk > (K-1)N)\ \delta(i - (K-k-1)N - l)$. Note that $\delta^1_f(r)$ refers to two conditions. Firstly, the forced termination occurs only when $(i + Nk) > (K-1)N$. Under this condition $\gamma^{(i,k)}_{(i-l,k+1)} = \lambda_P$. Secondly, $(i-l)$ SU connections are packed into $(K-k-1)N$ available subchannels and the remaining l connections are terminated.

4.3 Network throughput

The network throughput is defined as the products of the connection completion rate, the average service duration per connection and the data rate. For unit data rate, the theoretical throughput can be expressed as

$$\rho^{x_0}_{se} = (1 - P^{x_0}_{Be})(1 - P^{x_0}_{Fe})^2 \theta^{x_0}_{se} \tag{32}$$

where $\theta^{x_0}_{se} = (\lambda^{x_0}_s / \mu^{x_0}_{se})$ is called traffic intensity Mehdi (1991) and $x_0 \in \{1, A, B\}$ for single or two user groups (S^A and S^B), respectively.

For a fixed $\theta^{x_0}_{se}$, the throughput ρ^x_{se} reaches a maximum when the SU service rate (μ^x_{se}) approaches infinity, i.e., $\rho^{x_0*}_{se} = \lim\limits_{\mu^{x_0}_{se} \to \infty} \rho^{x_0}_{se}$. A simple proof is given as follows. When $\mu^{x_0}_{se} \to \infty$, we have $P^{x_0}_{Fe} \to 0$. The blocking probability in (32) consists of two parts i.e., $P^{x_0}_{Be} = P^{x_0}_{Be}(pri) + P^{x_0}_{Be}(sec)$, where $P_B(pri)$ is the blocking probability due to the situation in which PUs occupy all the subchannels, and $P^{x0}_{Be}(sec)$ is the blocking probability which can be computed from the probability for a given number of vacant subchannels. It is known that $P^{x_0}_{Be}(sec)$ is constant for a fixed $\theta^{x_0}_{se}$ Mehdi (1991). Therefore, the maximum achievable throughput ρ^x_{se} can be written as

$$\rho^{x_0*}_{se} = \lim_{\mu^{x_0}_{se} \to \infty} (1 - P^{x_0}_{Be})(1 - P^{x_0}_{Fe})\theta^{x_0}_{se} = (1 - P^x_{Be}(\infty))\theta^{x_0}_{se}, \tag{33}$$

where, $P^{x0}_{Be}(\infty)$ is the blocking probability when $P^{x_0}_{Fe} = 0$.

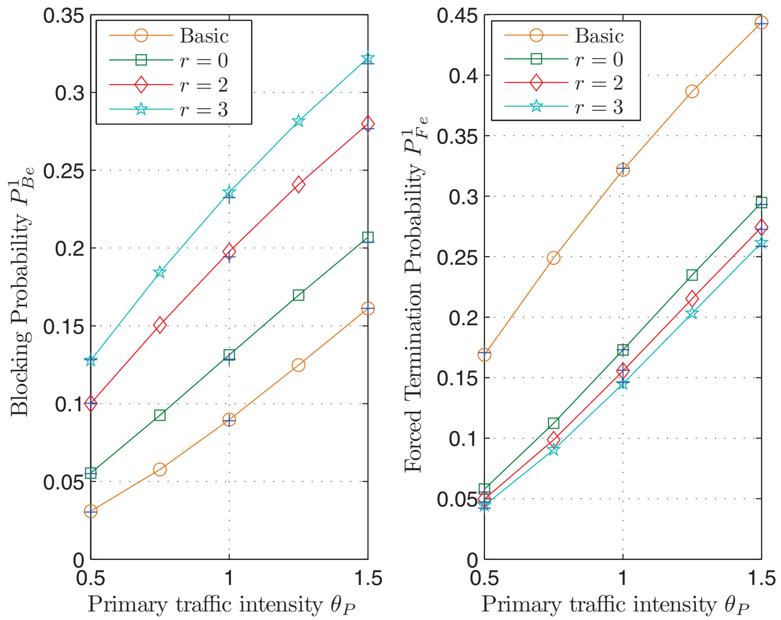

Fig. 8. Single SU group, **Left**: Blocking probability, and **Right**: Forced termination probability versus PU traffic intensity given $\theta^1_{se} = 8$ and $\hat{\mu}^1_{se} = 1$. Simulation results are shown with "+".

4.4 Numerical results

In this section we give some numerical examples of $P^{x_0}_{Fe}$, $P^{x_0}_{Be}$, and the throughput $\rho^{x_0}_{se}$ for SUs. In all of the following simulations, we set $K = 3, N = 6$ and $P^{x_0}_{Fe}$, $P^{x_0}_{Be}$, $\rho^{x_0}_{se}$ are plotted against PU (SU) traffic intensity $\theta_p(\theta^{x_0}_{se})$. In addition, service rates of the SU groups are normalised with respect to the PUs rate i.e., $\hat{\mu}^{x_0}_{se} = (\mu^{x_0}_{se}/\mu_p)$, where $x_0 \in \{1, A, B\}$. In addition, $r = 0$ indicates the spectrum handoff only condition without channel reservation.

4.4.1 Single SU group

In Fig. 8, P^1_{Fe} and P^1_{Be} are plotted against $\theta_p \in [0.5, 1.5]$, for given $\theta^1_{se} = 8$ and $\hat{\mu}^1_{se} = 1$. It can be calculated that the range of θ_p corresponds to the PU channel occupancy from 16.43% to 43.28%. Compared to systems with spectrum handoff and channel reservation, the basic system has the lowest blocking and the highest forced termination probability. Spectrum handoff results in a significant drop in P^1_{Fe} for a moderate increase in P^1_{Be}. The introduction of reserved channels are not particularly effective in this instance.

Fig. 9 shows the impact of θ^1_{se} on P^1_{Fe} and P^1_{Be}, for a given $\theta_p = 1$ and $\hat{\mu}^1_{se} = 1$. The behaviour of P^1_{Be} is similar to that in Fig. 8. For the basic system, P^1_{Fe} decreases slightly as θ^1_{se} increases. This is counter intuitive. At high θ^1_{se}, due to fixed N, the forced termination rate $\sum_{i=0}^{NK} \sum_{k=0}^{K} F(i, 0, k)$ will saturate faster than the connection rate $(1 - P^1_{Be})\lambda^1_s$, implying an increased SU occupancy.

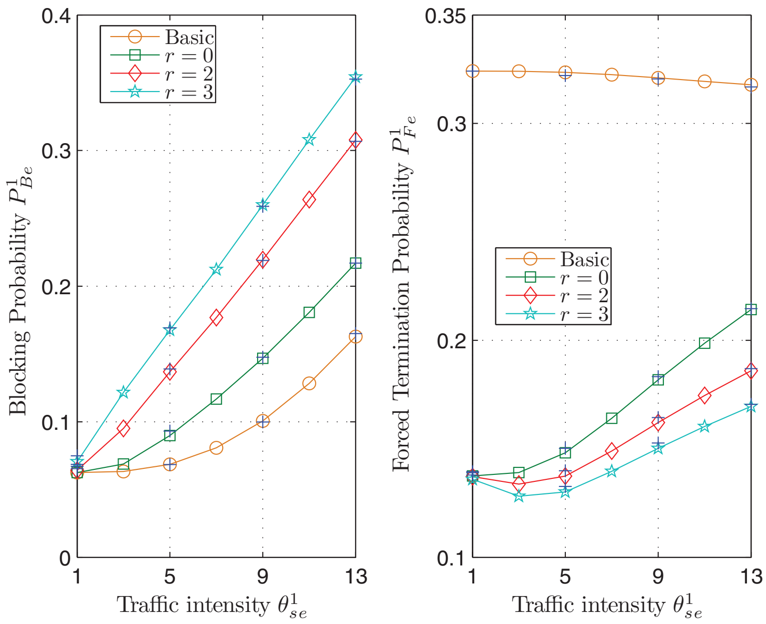

Fig. 9. Single SU group, **Left**: Blocking probability, and **Right**: Forced termination probability versus SU traffic intensity given $\theta_p = 1$ and $\hat{\mu}^1_{se} = 1$. Simulation results are shown with "+".

Note that P_F is the probability of termination per occupied channel. With spectrum handoff and channel reservation P^1_{Fe} initially decreases slightly, before increasing with θ^1_{se}. This can be explained as follows. At very low θ^1_{se} values, the existing SU connections readily find vacant subchannels. As θ^1_{se} increases the number of occupied channels increases, but there is still enough vacant subchannels to handle the arrival of a new PU connection and the probability of forced termination (for an existing connection) decreases. Eventually, at high θ^1_{se} there are fewer vacant subchannels to accomodate the displaced subchannels and forced termination probability increases.

The throughput ρ^1_{se} and the probability tradeoff gain $L(r)$ are shown in Fig. 10 for a given $\theta_p = 1$ and $\hat{\mu}^1_{se} = 1$. At low values of θ^1_{se}, the network throughput with spectrum handoff and channel reservation is higher than the basic system. However, the same cannot be said for high values of θ^1_{se}. The curves of tradeoff gain $L(r)$ show that more reserved channel give less gain in probability tradeoff. Also, for the same r, the effectiveness of the tradeoff reduces as θ^1_{se} increases.

4.4.2 Two SU groups

In Fig. 11, we compare the throughput and probability tradeoff gain $L(r)$ of two user groups with a single SU group having the same traffic intensity i.e., $\theta^1_{se} = \theta^A_{se} + \theta^B_{se}$. In this example the abscissa is the SU service rate $\mu^B_{se}(\mu^1_{se})$ and we assume that $\theta_p = 1$, $\theta^A_{se} = \theta^B_{se} = 6$, $\theta^1_{se} = 12$, $r = 0$.

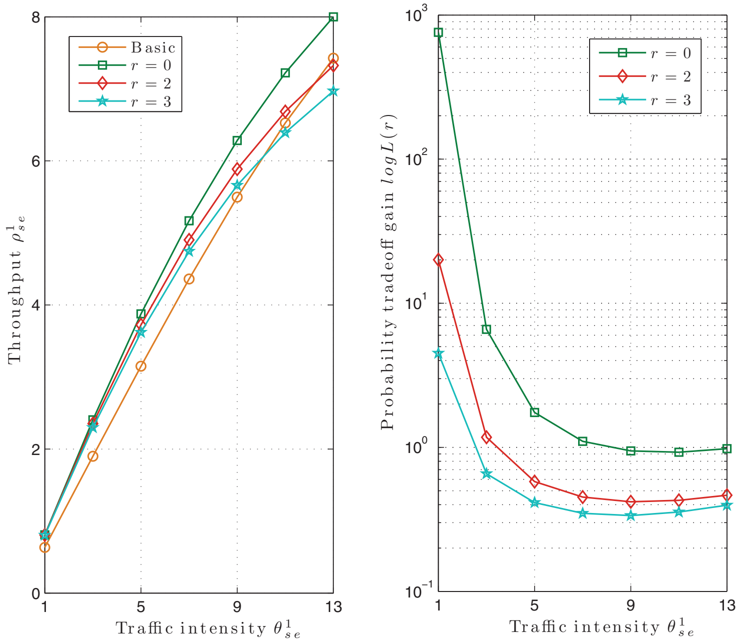

Fig. 10. Single SU group, **Left**: Aggregate throughput, and **Right**: Probability tradeoff gain versus SU traffic intensity given $\theta_P = 1$ and $\hat{\mu}^1_{se} = 1$.

The throughput $\rho^{AB}_{se} = \rho^A_{se} + \rho^B_{se}$ and ρ^1_{se} are monotonically increasing functions of both $\hat{\mu}^A_{se}$, $\hat{\mu}^B_{se}$ and μ^1_{se} respectively. When $\hat{\mu}^1_{se} = \hat{\mu}^A_{se} = \hat{\mu}^B_{se}$ the curves ρ^{AB}_{se} intersect with single user throughput ρ^1_{se}. This is expected, since at the intersection points SUs from both S^A and S^B are arriving at the same rate which is half of that of single user group S^1. The maximum achievable throughputs for both single and two user groups are identical i.e., $\rho_{max} = \rho^{AB*}_{se} = \rho^{1*}_{max}$. The aggregate throughput ρ_{AB} and ρ^1 approach maximum, when both single and two groups operate at much higher service rates than the PU arrival rate i.e., $\{\mu^1_{se}, \mu^A_{se}, \mu^B_{se}\} >> \lambda_p$.

For probability tradeoff gain $L(0)$, all the curves exhibit a U-shaped behaviour. This can be explained as follows. For relatively low service rates (long service duration), blocking probability increases at a higher rate than the rate of reduction in forced termination probability, whereas the opposite happens at high service rates (short service duration). This example demonstrates that the SU service duration relative to the PU counterpart has significant impact on the tradeoff, and the tradeoff is much more effective when the SU service rates μ^x_{se} is much larger or smaller than the PUs.

5. Airtime fairness

This section investigates the throughput fairness among two SU groups. For brevity, we limit our discussion to the spectrum handoff case only i.e., $r = 0$.

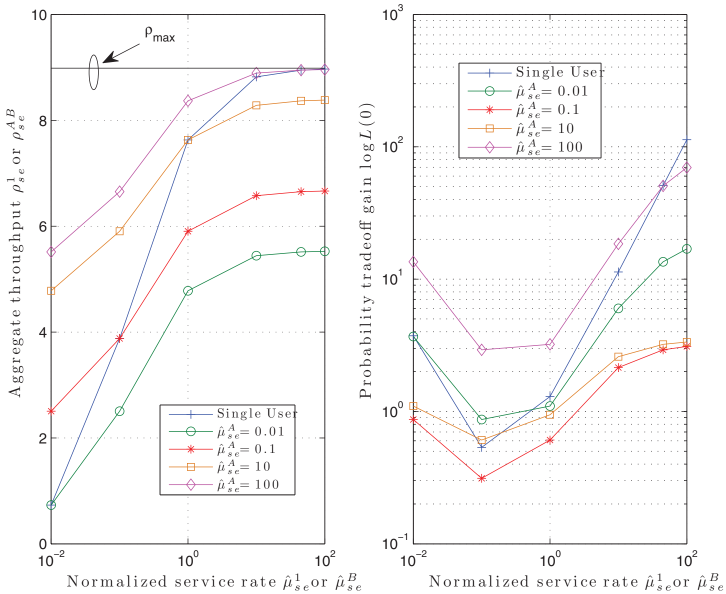

Fig. 11. Comparison of single and two SU groups, **Left**: Aggregate Throughput, and **Right**: tradeoff gain versus normalized SU service rate given $\theta_P = 1$, $\theta^1_{se} = 12$, $\theta^A_{se} = 6$, $\theta^B_{se} = 6$ and $r = 0$.

Fairness:*We define a fairness scheme in which the fractional throughput loss of both SU groups (with respect to their offered traffic θ^z_{se}) is equal, where $z \in \{A, B\}$*

$$\begin{aligned} G^A_\rho &= \frac{\theta^A_{se} - \rho^A_{se}}{\theta^A_{se}} \\ G^B_\rho &= \frac{\theta^B_{se} - \rho^B_{se}}{\theta^B_{se}} \end{aligned} \tag{34}$$

Based on the above equations, the fair metric is

$$\mathcal{F} = \frac{G^A_\rho}{G^B_\rho} \tag{35}$$

The scheme is optimally fair when $\mathcal{F}^* = 1$. In Fig. 12(a), the no constraint sharing gives an ideal fairness $\mathcal{F}^* = 1$, only for $\mu^A_{se} = \mu^B_{se}$. It applies to any values of λ^A_s and λ^B_s(Fig. 12 has $\lambda^A_s = 12$, $\lambda^B_s = 20$). When $\mu^A_{se} = \mu^B_{se}$, the two SU groups act as a single SU group due to the superposition of Poisson arrivals. Mathematically, $P^A_{Fe} = P^B_{Fe}$, and P^{AB}_{Be} is constant for both S^A and S^B. As the difference in the service rates between the SU groups increases, the fairness $\mathcal{F}$ deviates from its ideal value.

In Fig. 12(b), we investigate the fairness $\mathcal{F}$ and throughput ρ for a given $\mu^A_{se} = 0.8$ and $\mu^B_{se} = 2$. The fairness curves at low to medium values of arrival rate $\lambda^A_s(\lambda^B_s)$ show that

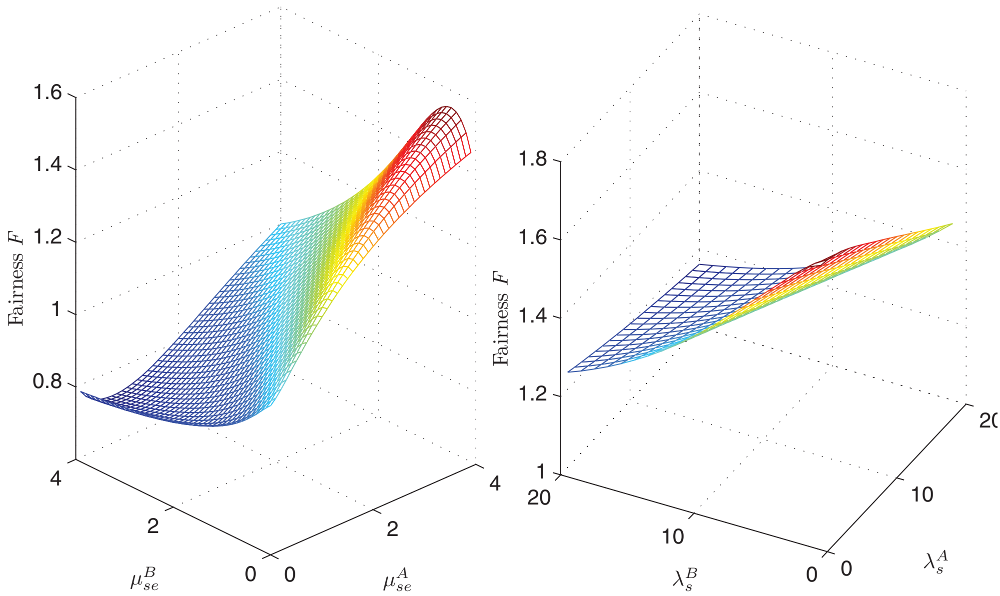

Fig. 12. **Left**: Fairness $\mathcal{F}$ versus SU service rate $\mu_{se}^A(\mu_{se}^B)$ given $\lambda_s^A = 12$, $\lambda_s^B = 20$, $\mu_p = 1$ and $\lambda_p = 1$. **Right**: Fairness $\mathcal{F}$, versus SU arrival rate $\lambda_s^A(\lambda_s^B)$ given $\mu_{se}^A = 0.8$, $\mu_{se}^B = 2$, $\mu_p = 1$ and $\lambda_p = 1$

spectrum sharing results in an unfair distribution of channel resources among the two SU groups. The percentage loss in throughput of S^A(large connection length) is significantly higher. The arrival rate has less effect on fairness.

5.1 Fairness through channel partitioning

In the previous section, the results show that dissimilar SU groups can lead to unfairness. In the following we investigate the potential of a channel partitioning policy to address unfairness. In essence, we restrict the maximum number of allowable active connections to N^A and N^B for S^A and S^B respectively, where $0 \le N^A \le NK$ and $0 \le N^B \le NK$. The variation of N^A and N^B gives rise to the following 3 conditions. The first condition $N^A = NK - N^B$ represents a channel partitioning scenario, the second condition $N^A + N^B > NK$ is a weaker channel partitioning scenario, whereas the condition $N^A = N^B = NK$ is the no constraint scenario described in the previous subsection. Here, we only consider the channel partitioning scenario because it does not require the calculation of state probabilities in which the transmission of the SU groups overlap. A channel partitioning scenario is shown in Fig. 13, in which an incoming S^B connection is allowed to access the channel, while an incoming S^A connection is blocked even though there is a vacant subchannel. In the channel partitioning scenario, the objective is to find a feasible number of channels $\{N^A, N^B\}$ such that the access scheme is optimally fair i.e., $\mathcal{F}^* \approx 1$. Due to integer values of $\{N^A, N^B\}$ the optimally fair

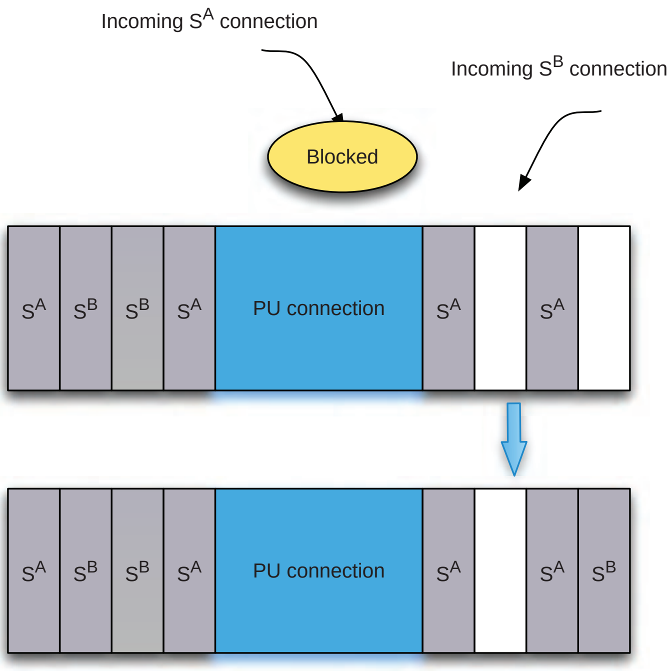

Fig. 13. Illustration of Channel partitioning scenario, $K = 3$, $N = 4$, $N^A = 4$, $N^B = 8$.

value of 1 may not always be possible. From (35) it is also obvious that the calculation of $\{N^A, N^B\}$ requires the knowledge of termination and blocking probabilities for both SU groups. In the following, we model this channel partitioning scenario as a simple extension of the CTMC in Section 3.3.3.

The maximum number of allowable connections of S^A and S^B are N^A and N^B i.e., $i = \{0, \ldots, N^A\}$, $j = \{0, \ldots, N^B\}$ and the state probabilities can be solved under the fundamental probability constraint (similar to the section 3.3). The blocking probabilities and forced termination probabilities are given as follows.

$$P^A_{Be} = \sum_{i=0}^{N^A-1} \sum_{j=0}^{N^B} \sum_{k=0}^{K} \delta(i + j + Nk - NK) P_{\phi_0}(i, j, k) + \sum_{j=0}^{N^B} \sum_{k=0}^{K} P_{\phi_0}(N^A, j, k), \tag{36}$$

$$P^B_{Be} = \sum_{i=0}^{N^A} \sum_{j=0}^{N^B-1} \sum_{k=0}^{K} \delta(i + j + Nk - NK) P_{\phi_0}(i, j, k) + \sum_{j=0}^{N^A} \sum_{k=0}^{K} P_{\phi_0}(i, N^B, k). \tag{37}$$

The combined blocking probability of SU groups P^{AB}_B seen by PU network is given as

$$P^{AB}_{Be} = \frac{\lambda^A_s}{\lambda^A_s + \lambda^B_s} P^A_{Be} + \frac{\lambda^B_s}{\lambda^A_s + \lambda^B_s} P^B_{Be}, \tag{38}$$

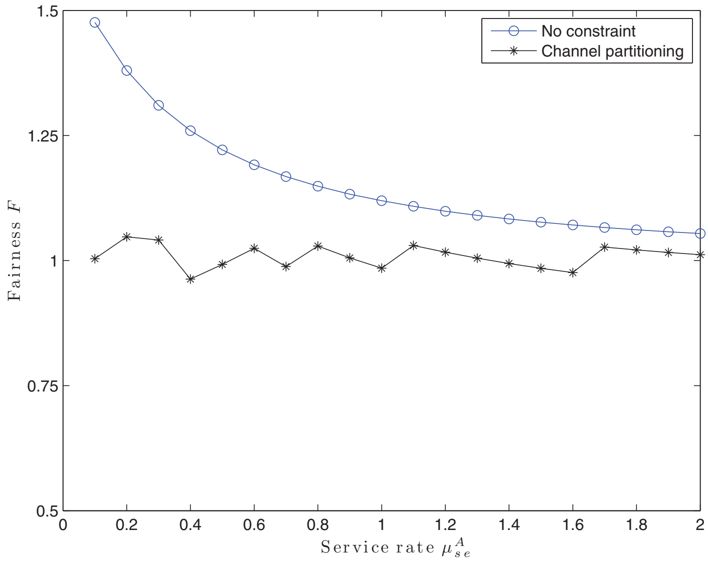

Fig. 14. Fairness F versus SU service rate μ_{se}^A given $\theta_{se}^A = 4$, $\theta_{se}^B = 7$, $\mu_{se}^B = \mu_{se}^A + 0.3$, $\mu_p = 1$ and $\lambda_p = 1$.

$$P_{Fe}^A = \frac{1}{(1 - P_{Be}^A)} \sum_{i=0}^{N^A} \sum_{j=0}^{N^B} \sum_{k=0}^{K} \sum_{l=0}^{min\{N^A,N\}} \sum_{m=0}^{min\{N^B,N\}} \frac{l}{\lambda_s^A} \gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_{\phi_0}(i,j,k) \delta_{f0}, \tag{39}$$

and

$$P_{Fe}^B = \frac{1}{(1 - P_{Be}^B)} \sum_{i=0}^{N^A} \sum_{j=0}^{N^B} \sum_{k=0}^{K} \sum_{l=0}^{min\{N^A,N\}} \sum_{m=0}^{min\{N^B,N\}} \frac{m}{\lambda_s^B} \gamma_{(i-l,j-m,k+1)}^{(i,j,k)} P_{\phi_0}(i,j,k) \delta_{f0}. \tag{40}$$

5.2 Scenario 1 $\theta_{se}^A \neq \theta_{se}^B$, $\mu_{se}^A \neq \mu_{se}^B$ and $\lambda_s^A \neq \lambda_s^B$

In Fig. 14 and Fig. 15, the fairness F and throughput ρ are plotted against μ_{se}^A respectively, for given $\mu_{se}^B = \mu_{se}^A + 0.3$, $\theta_{se}^A = 4$ and $\theta_{se}^B = 7$. In this condition, $P_{Fe}^A \neq P_{Fe}^B$, and $P_{Be}^A \neq P_{Be}^B$. The fairness curves at low to medium values of service rate μ_s^A show that the no constraint scenario results in an unfair distribution of channels among two SU groups. The percentage loss in throughput of S^A is significantly higher (due to large P_{Fe}^A). At large values of service rate μ_{se}^A the fairness improves and throughput saturates due to the lower termination probability of both SU groups. On the other hand, the channel partitioning achieves fairness at a cost of the decrease in aggregate and individual throughput i.e., by assigning more subchannels to S^A than S^B. At higher values of $\mu_{se}^A(\mu_{se}^B)$ there is almost no difference between the fairness and throughput in both strategies. The fluctuation in fairness occurs due to the integer number of subchannels.

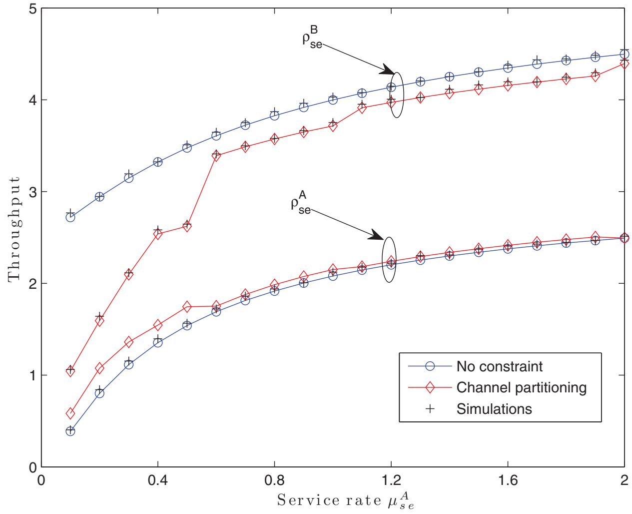

Fig. 15. Throughput ρ versus SU service rate μ_{se}^{A} given $\theta_{se}^{A} = 4$, $\theta_{se}^{B} = 7$, $\mu_{se}^{B} = \mu_{se}^{A} + 0.3$, $\mu_p = 1$ and $\lambda_p = 1$.

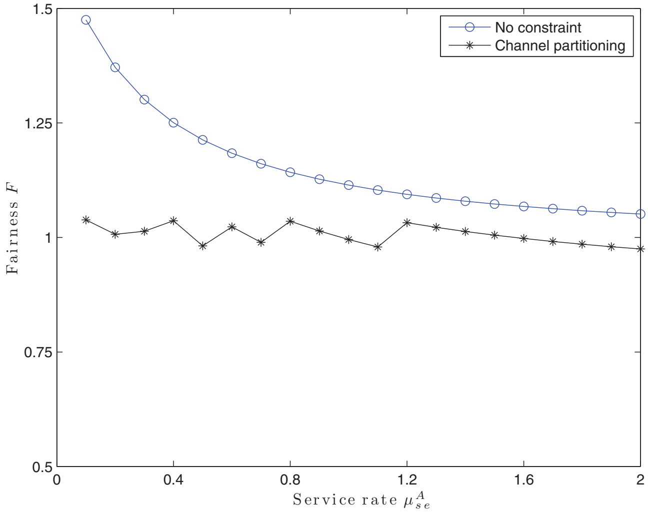

Fig. 16. Fairness F versus SU service rate μ_{se}^{A} given $\theta_{se}^{A}(\theta_{se}^{B}) = 6$, $\mu_{se}^{B} = \mu_{se}^{A} + 0.3$, $\mu_p = 1$ and $\lambda_p = 1$.

5.3 Scenario 2 $\theta_{se}^A = \theta_{se}^B$, $\mu_{se}^A \neq \mu_{se}^B$ and $\lambda_s^A \neq \lambda_s^B$

Fig. 16 shows the fairness $\mathcal{F}$ curves plotted against SU service rate μ_{se}^A, given $\mu_{se}^B = \mu_{se}^A + 0.3$, $\theta_{se}^A = 6$ and $\theta_{se}^B = 6$. The arrival rate of S^A is higher than S^B because of the offered traffic is constant for both SU groups. The curves are fairly similar to the previous figure and indicate that the smaller durations achieve better fairness.

6. Summary

In this Chapter, using a CTMC we have presented the exact solutions to determine the forced termination and blocking probabilities, and aggregate throughput of a SU group as well as two SU groups. Specifically,

- For multiple PU channels (with more than one subchannel) and two SU groups, three types of systems with were considered; without spectrum handoff (basic system): with spectrum handoff and channel reservation. For all these systems the single SU group was treated as a special case. In the former case, the results show that the blocking and forced termination probabilities increase with PU traffic intensity, as expected. However, SU traffic intensity has a different impact on the forced termination probability. The forced termination probability decreases slightly as SU traffic intensity increases for the basic system. For the systems with spectrum handoff, forced termination probability is always less than the basic system. However, there exists an optimal arrival rate that minimizes the forced termination probability. Spectrum handoff ($r = 0$) is more effective than channel reservation $r > 0$ in reducing forced termination probability for a given increase in blocking probability (tradeoff gain). The tradeoff is much more beneficial when the service rate is either very high or very low compared with the PU service rate.
- For two SU groups, we found that spectrum sharing can result in unfair channel occupancy. The problem is most prevalent when the difference between the two service rates is large. Channel partitioning (where a limit is placed on the maximum number of active connections of each S^A and S^B group) forces fairness but the throughput penalty might not be worth it.

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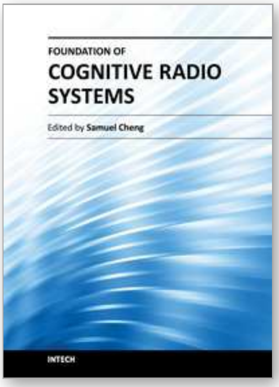

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The fast user growth in wireless communications has created significant demands for new wireless services in both the licensed and unlicensed frequency spectra. Since many spectra are not fully utilized most of the time, cognitive radio, as a form of spectrum reuse, can be an effective means to significantly boost communications resources. Since its introduction in late last century, cognitive radio has attracted wide attention from academics to industry. Despite the efforts from the research community, there are still many issues of applying it in practice. This books is an attempt to cover some of the open issues across the area and introduce some insight to many of the problems. It contains thirteen chapters written by experts across the globe covering topics including spectrum sensing fundamental, cooperative sensing, spectrum management, and interaction among users.

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