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Analysis of Spectrum Handoff under General Residual Time Distributions of Spectrum Holes in Cognitive Radio Networks

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Spectrum handoff probability, spectrum handoff rate or average number of spectrum handoffs are important parameters in the evaluation of performance metrics of Cognitive Radio Networks. Due to the mobility of spectrum holes, a Cognitive Radio user needs to perform spectrum handoff successfully to complete its data transmission. This paper scrupulously investigates and analyzes the probability of spectrum handoff under diverse realistic primary and cognitive user traffic models. A theoretical analysis of spectrum handoff probability and average number of spectrum handoffs is presented here under the assumption that the residual time of spectrum holes are exponential, Erlangian and Weibull distributed. We also present impact of departure rate of cognitive users (μ) and spectrum holes (λ) on the probability of spectrum handoff and rate of spectrum handoffs. The accuracy of the derived distribution is validated by simulation results for the Weibull (k= 3) distribution function and a detailed comparison with exponential, Erlang-2 and Erlang-3, 23 distribution of residual time of spectrum holes is presented.

Keywords: cognitive radio, residual time, spectrum handoff, spectrum mobility, spectrum hole, Weibull distribution

1. INTRODUCTION

Cognitive Radio (CR) offers a promising solution for improvement of spectrum utilization. The fundamental objectives of CR systems are continuous inspection of the spectrum for the presence of licensed users and regulation of the spectrum for sharing it fairly among cognitive users (CUs) by maintaining an undisturbed relationship [1-3]. The occupied spectrum band needs to be immediately vacated when a primary user (PU) returns to its licensed band [4]. Spectrum mobility is an enabling feature for continuous data transmission of CU in an extremely dynamic scenario where the CU communication is likely to be interrupted frequently [4]. *Dynamic Spectrum Access* (DSA) offers opportunistic utilization of the unused spectrum bands through spectrum sharing [3]. However, the spectrum sharing strategy causes multiple *spectrum handoffs* for CUs in order to complete its data transmission and ensure the required QoS of the primary network [5]. The quality of transmission in CU network is likely to be degraded by service interruption caused due to multiple spectrum handoffs. Call holding time of CU, departure time

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of spectrum holes and residual time of spectrum holes play a very important role in the analysis of spectrum handoff in *CR networks* (CRNs). Therefore, for comprehensive analysis of spectrum handoff, it is necessary to have suitable distribution models for the above-mentioned parameters in determining the performance of CRNs.

Due to the memoryless property of exponential distribution, it is commonly considered for call holding time and cell residence time in the study of the traditional wireless cellular network [6, 7]. However, real traffic data analysis shows that exponential distribution is not suitable for modeling cellular network performance [8]. Fang *et al.* [9, 10] proposed handoff model and derived standardized formula for some performance metrics to study the call performance of the cellular network.

In the domain of CRN [11], authors proposed fuzzy based approaches for effective spectrum handoff decisions. Wang *et al.* [5] proposed a traffic-adaptive spectrum handoff to reduce the extended data delivery time. In [12], Zakariya *et al.* commented on [5] and modified the algorithm to reduce the processing time. In [13], Hanif *et al.* proposed a spectrum handoff decision strategy based on mobility patterns of the spectrum holes to optimizes channel utilization and minimize handoff delays. In [14], the authors implemented a hybrid spectrum handoff scheme based on PUs traffic to improve the performance of the CRNs. Liu *et al.* [15] derived the probability of spectrum handoff for the case where the call holding time of CU and residual time of spectrum holes are exponentially distributed. In [16], the authors established a standard generalized model of the *probability of spectrum handoff* under different distribution functions such as exponential and Erlangian distributions for the residual time of spectrum holes in CRN. In [17], the authors presented the impact of service time distributions of the CU on spectrum handoff performance in CRNs. However, Weibull distribution for the residual time of spectrum holes is not considered to analyze the statistical nature of the CRNs.

The parameters of wireless multimedia-services such as call service time, video streaming, data traffic access *etc.* follow heavy tail distributions [18]. The authors showed that the Weibull distribution exhibits a good approximation to multimedia-services in an Enhanced UMTS scenarios [18, 19]. Marsan *et al.* [20] analyzed the performance of a cellular network with generalized (including Weibull) call holding time distribution. The authors modeled the call performance parameters with generalized residual time distributions and also displayed that the Weibull residual time distribution may be used in the performance analysis of a wireless network [21]. Weibull distribution has an important role in the analysis of fading channel in wireless networks [22-24]. The Weibull distribution offers a good fit to the realistic fading channel measurements for indoor and outdoor environments [22]. Cheng *et al.* [23] have analyzed the performances of digital communication systems in terms of outage probability, bit error rate, and symbol error rates on Weibull fading channels. In [24], the authors analyzed the performance of macro diversity system in Weibull fading channel. Pattaramalai *et al.* [25] derived discussed the call completion probability under Weibull distributed call holding and cell residual times in a wireless cellular network. *Weibull distribution* is a useful function which is widely used in real life data analysis and reliability due to its versatility [26]. Depending on the values of the Weibull parameters (k), the Weibull distribution interpolates between exponential (k=1) and Rayleigh (k=2) distributions and hence, can be used to model a variety of real-life behavior. This has made it extremely useful among engineers and quality practitioners, who have made it the most commonly used distribution for modeling reliability of the data set [27]. The performance analysis of spectrum handoff in terms of probability and average number of spectrum handoffs with Weibull residual time distribution of spectrum holes are not reported in existing literature. The statistical nature of CRN traffic model intuitively motivates us to introduce Weibull distribution in the analysis of spectrum handoff performance.

Our main contributions to this article are accentuated as follows:

- A generalized and comprehensive analytical model for the probability of spectrum handoff with Weibull distribution function is established and compared with the results of the exponential and Erlangian distribution of spectrum holes residual time reported in the literature.
- We derive a standard generalized form of average number of spectrum handoffs of CU for different distribution models and also present a detailed comparison of results between the different distributions of residual time of spectrum holes considering CU's call duration and residual time of spectrum holes as measurement metrics.
- We also setup a CR environment to simulate the probability of spectrum handoff using Monte-Carlo method in order to validate the established analytical model.

Section 2 describes the proposed time relationship model for spectrum handoff and also presents the theoretical analysis obtained from the proposed model. Section 3 presents the simulation setup and steps for time relationship model. This section also investigates the results of performance metrics in terms of probability of spectrum handoff and average number of spectrum handoffs. Finally, Section 4 concludes the paper including future work directions.

2. SYSTEM MODEL

The time relationship model of CUs call duration with the availability of spectrum hole is shown in Fig. 1. To analysis the spectrum handoff for CUs, some basic assumptions are considered for the time relationship model.

A CRN basically consists of two types of users with different priorities: Primary User and Secondary User or CU. The PUs are also referred to as licensed users which have the higher priority over the CUs to access their licensed band. The CUs can use those licensed bands in the absence of primary user. However, when a PU arrives in that channel during CU service, the CU requires to perform spectrum handoff to maintain unbroken communication. Therefore, the CU handovers the channel to PU and switches its ongoing service to another free licensed channel. Hence, the CU may experience a number of spectrum handoffs during its complete call duration. To analyze the performance of a CU for complete service time, we consider that the interrupted CU gets at least one available channel to continue its service.

The CU is considered to be stationary that is, during service call duration it does not change its geographical area. In Fig. 1, T_i (= 0, 1, 2…) denotes the service call duration of CUs corresponding to the holding time of spectrum holes H_i. The CU call duration considered to have an exponential distribution with a mean time of $1/\mu$. The probability density function (pdf) of CU's call duration is given by

$$f(x)=\begin{cases}\mu e^{-\mu x} & \text{for } x\geq 0\\ 0 & \text{otherwise}\end{cases};\text{ where } \mu \text{ is departure rate of CUs.} \tag{1}$$

In Fig. 1, h represents the arrival time of the 1st PU (or residual departure time of spectrum holes #0) who interrupts the CU ongoing service. H_i (where i = 0, 1, 2, …) represents the holding time corresponding to the *spectrum hole* numbered as #0, #1, #2, …, H_i has the identical & independent distribution (*i.i.d*). The holding time of each spectrum hole is a continuous random variable with the probability density function (*pdf*) $f_r(x)$ and the mean value, $(1/\lambda)$.

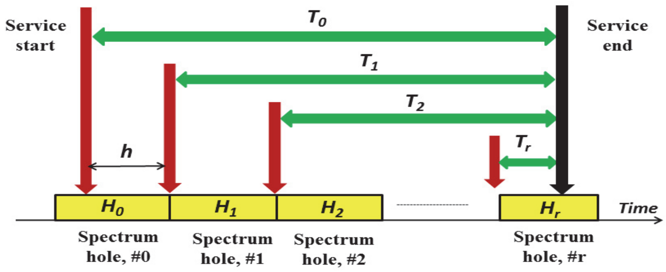

Fig. 1. Time relationship model of CUs call duration with availability of spectrum holes.

$$E[H_i] = 1/\lambda < \infty \quad \forall i[i = 0, 1, 2, \ldots];\text{ where } \lambda \text{ is departure rate of spectrum holes} \tag{2}$$

In next sub-section, we model the probability of spectrum handoff and average number of spectrum handoff with Weibull residual time distribution of spectrum holes. In our model, we use random sum approach to derive the probability of spectrum handoff and hence, the expected number of spectrum handoffs. In [9, 10], Fang *et al.*, extensively used residue theorem which uses Laplace transformation to explain the call performance analysis. However, the residue theorem approach is not applicable to the model where the Laplace transform of the distribution does not have a rational form [25]. Pattaramalai *et al.* [25] used a different approach based on the concept of random sums to analysis call completion probability in a wireless network. The random sum approach has an important advantage over the residue theorem approach in terms of its applicability to distribution functions which don't have a rational form of Laplace Transformation. This motivates us to use random sum approach as the analytical framework to model the performance analysis of spectrum handoff under the impact of various generalized distribution functions in CRN.

2.1 Derivation of Spectrum Handoff Probability

Let there are r+1 numbers of spectrum holes and a CU can transmit data successfully within rth spectrum hole (#r) as shown in Fig. 1. The probability that a CU needs only one spectrum hole to complete its ongoing data transmission is defined as zero or no spectrum handoff probability. If the service call duration, $\boldsymbol{T_0}$ is less than the $\boldsymbol{h}$, there is no handoff within that time. Hence, the probability of zero spectrum handoff is obtained as

$$P_0 = \Pr\{T_0 \le h\} = \iint_{a<b} f(a) f_r(b) da db \tag{3}$$

where $f(a)$ and $f_r(b)$ are *pdf*s of CU's call duration and residual time of spectrum holes respectively.

If a CU needs two or more than two spectrum holes to continue its ongoing data transmission, the CU has to perform spectrum handoff successfully and the probability of spectrum handoff for a new call is obtained as

$$P = \Pr\{T_0 > h\} = 1 - \Pr\{T_0 \le h\} = 1 - \iint_{a<b} f(a) f_r(b) da db. \tag{4}$$

The probability of spectrum handoff for a new call of a CU under exponential, Erlang-2 and Erlang-3, 23 distribution of residual time of spectrum holes can be calculated as,

$$\text{For exponential, } P_{\exp} = \Pr\{T_0 > h\} = 1 - \iint_{a<b} f(a) f_r(b) da db = (\lambda/(\lambda+\mu)). \tag{5}$$

$$\text{For Erlang-}m\text{, } P_{E\text{-}m} = \Pr\{T_0 > h\} = 1 - \iint_{a<b} f(a) f_r(b) da db = (m\lambda/(m\lambda+\mu))^m. \tag{6}$$

$$\begin{aligned} \text{For Erlang-}m, n\text{, } P_{E\text{-}m,n} &= \Pr\{T_0 > h\} = 1 - \iint_{a<b} f(a) f_r(b) da db \\ &= p((m\lambda/(m\lambda+\mu)))^m + (1-p)((n\lambda/(n\lambda+\mu)))^n. \end{aligned} \tag{7}$$

If T_0 is greater than h and less than $h+H_1$, the probability of 1st spectrum handoff is obtained and denoted by P_1. If we consider the total service time T_0 of CU, there will be r times spectrum handoffs (P_r) within that time and P_r can be obtained as

$$\begin{aligned} P_r &= \Pr\{h < T_0, H_1 < T_1, \ldots, H_{r-1} < T_{r-1}, H_r < T_r\} \\ &= \Pr\{h < T_0\} \cdot (\Pr\{H_1 < T_1\})^{r-1} \cdot \Pr\{H_r > T_r\} \\ &= (1 - P_0) \cdot (\Pr\{H_1 < T_1\})^{r-1} \cdot (1 - \Pr\{H_r \le T_r\}). \end{aligned} \tag{8}$$

The realistic and generalized expression of probability for 'r' time spectrum handoff (P_r) under exponential, Erlang-m and Erlang-3, 23 distribution of residual time of spectrum holes may be given by [23]

$$\text{For exponential, } P_r = \left(\lambda/(\lambda+\mu)\right)^r \left(1 - \left(\lambda/(\lambda+\mu)\right)\right) \tag{9}$$

$$\text{For Erlang-}m\text{, } P_r = \left(m\lambda/(m\lambda+\mu)\right)^{m.r} \left(1 - \left(m\lambda/(m\lambda+\mu)\right)^m\right) \tag{10}$$

For Erlang-m, n,

$$P_r = \left(p\left(\frac{m\lambda}{m\lambda+\mu}\right)^m + (1-p)\left(\frac{n\lambda}{n\lambda+\mu}\right)^n\right)^r \left(1 - \left(p\left(\frac{m\lambda}{m\lambda+\mu}\right)^m + (1-p)\left(\frac{n\lambda}{n\lambda+\mu}\right)^n\right)\right) \tag{11}$$

Here, we continue our analysis considering the residual time of spectrum holes to be Weibull distributed. The *pdf* of Weibull function is given by

$$f_r(x) = \begin{cases} (k/\beta)(x/\beta)^{k-1} e^{-(x/\beta)^k} & \text{for } x \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where k (> 0) is the shape parameter and β (> 0) is the scale parameter of the distribution. The relation between λ and β is given by

$$\beta \cdot \Gamma(1 + 1/k) = 1/\lambda; \text{ where } \Gamma(.) \text{ is the gamma function.} \tag{13}$$

Now, the probability of '0' times or no spectrum handoff (P_0) can be calculated as

$$P_0 = \Pr\{T_0 \leq h\} = \iint_{a<b} f(a) f_r(b) da db = 1 - \int_0^\infty \left(k/\beta\right)\left(b/\beta\right)^{k-1} e^{-\left(b/\beta\right)^k} e^{-\mu b} db. \tag{14}$$

The probability of spectrum handoff of a new call (at least one spectrum handoff) of a CU can be calculated as

$$P = \Pr\{T_0 > h\} = 1 - \Pr\{T_0 > h\} = \int_0^\infty \left(k/\beta\right)\left(b/\beta\right)^{k-1} e^{-\left(b/\beta\right)^k} e^{-\mu b} db. \tag{15}$$

Hence,

$$\Pr\{H_1 < T_1\} = 1 - \Pr\{H_1 \geq T_1\} = 1 - \iint_{a<b} f(a) f_r(b) da db = \int_0^\infty \left(k/\beta\right)\left(b/\beta\right)^{k-1} e^{-\left(b/\beta\right)^k} e^{-\mu b} db. \tag{16}$$

Similarly, we can calculate $Pr\{H_r \leq T_r\}$ as

$$\Pr\{H_r < T_r\} = 1 - \Pr\{H_r \geq T_r\} = \int_0^\infty \left(k/\beta\right)\left(b/\beta\right)^{k-1} e^{-\left(b/\beta\right)^k} e^{-\mu b} db. \tag{17}$$

Therefore, the generalized expression for the probability of r times spectrum handoff (r = 0, 1, 2, …) P_r may be written as

$$\begin{aligned} P_r &= \left(\int_0^\infty \left(k/\beta\right)\left(b/\beta\right)^{k-1} e^{-\left(b/\beta\right)^k} e^{-\mu b} db \right)^r \left(1 - \int_0^\infty \left(k/\beta\right)\left(b/\beta\right)^{k-1} e^{-\left(b/\beta\right)^k} e^{-\mu b} db \right) \\ &= \left(\int_0^\infty k\lambda\, \Gamma\left(1 + 1/k\right) \left(b\lambda\, \Gamma\left(1 + 1/k\right)\right)^{k-1} e^{-\left(b\lambda\, \Gamma\left(1+1/k\right)\right)^k} e^{-\mu b} db \right)^r . \\ &\quad \left(1 - \left(\int_0^\infty k\lambda\, \Gamma\left(1 + 1/k\right) \left(b\lambda\, \Gamma\left(1 + 1/k\right)\right)^{k-1} e^{-\left(b\lambda\, \Gamma\left(1+1/k\right)\right)^k} e^{-\mu b} db \right) \right). \end{aligned} \tag{18}$$

2.2 Average Number of Spectrum Handoffs for Different Distributions of Residual Time of Spectrum Holes

Average number of spectrum handoffs is an important parameter for performance analysis as it characterizes the distribution of availability of spectrum holes and also service quality of the networks. In [12, 28], authors calculated handoff rate in the cellular network under the assumption that the call holding time and cell residence time are exponentially distributed. Fang *et al.* [15] presented theoretical results for handoff rate for Erlang-m distribution of call holding time for the cellular network. In this section, we derive the standardized form of average number of spectrum handoffs for proposed time relationship model under the consideration that the residual time of spectrum holes has general (Erlang-2, Erlang-3, 23 and Weibull) distributions. As we have considered that there will be at least one spectrum hole for the interrupted CU in our analysis, hence no handoff failure occurred and there are no blocking and force terminations during one complete call of CU.

The probability of 'r' times of spectrum handoff for exponential distribution of CU's call duration and different distributions of residual time of spectrum holes can be calculated as,

$$P_r = (1 - S)S^r \tag{19}$$

where definitions of S for different distributions of residual time of spectrum holes are given in Table 1.

Table 1. Definition of *S* for different residual time distributions of spectrum holes.

Distribution Name	S
Exponential Distribution	$\lambda/(\lambda+\mu)$
Erlang-m Distribution	$(m\lambda/(m\lambda+\mu))^m$
Erlang-m, n Distribution	$p(m\lambda/(m\lambda+\mu))^m + (1-p)(n\lambda/(n\lambda+\mu))^n$
Weibull Distribution	$\int_0^\infty k\lambda\Gamma(1+1/k)(d\lambda\Gamma(1+1/k))^{k-1}e^{-(b\lambda\Gamma(1+1/k))^k}e^{-\mu b}db$

If the number of spectrum handoffs that are performed during one call duration of a CU is denoted by the random variable X in CRNs, the average number of handoffs per call is given by

$$\begin{aligned} E[X] &= \sum_{r=0}^{\infty} rP(X=r) = 0\cdot P_0 + 1\cdot P_1 + 2\cdot P_2 + 3\cdot P_3 + \ldots \\ &= (1-S)\cdot S + 2\cdot(1-S)\cdot S^2 + 3\cdot(1-S)\cdot S^3 + \ldots \\ \therefore\ & E[X]/(S(1-S)) = 1 + 2S + 3S^2 + \ldots \end{aligned} \tag{20}$$

Multiplying both side of Eq. (20) by S, we get

$$E[X]/((1-S)) = S + 2S^2 + 3S^3 + \ldots \tag{21}$$

Now subtracting Eq. (21) from Eq. (20), we get

$$E[X]/(S(1-S)) - [E[X]/((1-S))] = 1 + S + 2S^2 + S^3 + \ldots \text{ (where } S < 1). \tag{22}$$

By solving Eq. (22), we get standard form of average number of spectrum handoffs of a CU as

$$E[X] = (S/(1 - S)). \tag{23}$$

We can calculate average number of spectrum handoffs from Eq. (23) by using required expressions of 'S' from Table 1 for different distribution models of residual time of spectrum holes.

3. RESULTS AND DISCUSSION

In order to validate the analytical model, we establish a simulation environment considering the dynamics of both primary user and secondary user activity models in CRN. The Monte Carlo simulation of the time relationship model is discussed with an Algorithm in section 3.1. The typical range of values of departure rate of CU, μ is taken from 1 to 720 calls/hour and departure rate of spectrum holes, λ is taken from 40 to 320 spectrum holes /hour for a comprehensive analysis of the measuring parameter. The analysis is limited up to third handoff (P_0 to P_3) for the sake of simplified analysis.

3.1 Simulation Setup

In this section, we setup a CR environment to simulate the probability of spectrum handoff of a CU in order to validate the proposed analytical model. We assume that the simulation environment contains two types of users: primary user (PU) and cognitive or secondary user (CU). The higher priority PUs have the authorization to access their licensed bands over lower priority CU. Hence, the service of a CU may get interrupted by the arrival of PUs (or departure of spectrum holes) in the system. To investigate the probability of spectrum handoff during complete call duration of a CU, it is assumed that the interrupted CU gets at least one free channel or spectrum hole to continue its ongoing service. We generate random variables (RVs) for service time of the CU (T0) according to an exponential distribution with the mean service time $1/\mu$. Now, a series of RVs is generated with mean departure time of spectrum holes $1/\lambda$ considering exponential, Erlang, and Weibull residual time distribution of spectrum holes. Thereafter, the conditions for probabilities of spectrum handoff are checked and calculated as presented in simulation steps (Section 3.1.1). For a comprehensive analysis of the measuring parameter, the typical range of simulation parameters are taken as: (a) under impact of departure rate of spectrum holes (λ), departure rate of CU, μ =120 users/hour, and λ =40 to 320 spectrum holes/hour; (b) under impact of μ, λ =180 spectrum holes/hour, μ = 1 to 720 users/hour. We use Monte Carlo simulation method with 50000 iterations per simulation and average of those are used to plot the probability of spectrum handoff for various residual time distributions to validate the correctness of the achieved results. The simulation steps are presented as below:

3.1.1 Algorithm for simulation steps

Step 1: Declare and initialize the parameters (*i.e.* λ and μ)
Step 2: Generate random variable (t) for exponential distribution of CU's call duration (T_i) with the mean value, $1/\mu$.
Step 3: Generate a series of random variables, (H_r^j) for different distribution of residual time of spectrum holes (H_i) with the mean value, $1/\lambda$. (j = 1: Exponential, 2: Erlang-2, 3:

Erlang-3, 23, 4: Weibull).

Step 4: Compare the random variables generated from Steps 2 and 3.

If ($T_0 > H_r(1)$)
Calculate spectrum handoff probability of a new call (P)
End
If ($T_0 < H_r(1)$)
Calculate zero spectrum handoff probability (P_0).
End
If (($T_0 > H_r(1)$) && ($T_0 < (H_r(1) + H_r(2))$))
Calculate 1st spectrum handoff probability (P_1)
End
If (($T_0 > (H_r(1) + H_r(2))$) && ($T_0 < (H_r(1) + H_r(2) + H_r(3))$))
Calculate 2nd spectrum handoff probability (P_2)
End
If (($T_0 > (H_r(1) + H_r(2) + H_r(3))$)&&($T_0 < (H_r(1) + H_r(2) + H_r(3) + H_r(4))$))
Calculate 3rd spectrum handoff probability (P_3)
End

Step 5: Monte Carlo simulation with a large number of iterations is performed to obtain better results for spectrum handoff probability by repeating Steps 2-4.

3.2 Theoretical and Simulation Results for Weibull Distribution Model of Residual Time of Spectrum Holes

The theoretical and simulation results are obtained and are shown in Figs. 2 (a) and (b) under the impact of departure rate of spectrum holes (λ) and departure rate of CUs (μ), respectively. Fig. 2 (a) shows that as the departure rate of spectrum hole (λ) is increased, the mean departure time of spectrum holes ($1/\lambda$) is decreased. Hence the probability of a total number of spectrum holes experienced by the CU during a call duration becomes higher. Fig. 2 (b) depicts that P_0 increases and P_1, P_2, P_3 decreases with increasing value of μ. This is due to the fact that as the value of μ increases, the mean departure time of CU ($1/\mu$) decreases and which results in a decrement of the probability of spectrum handoff. Hence, the rate of spectrum handoff decreases with increasing value of μ.

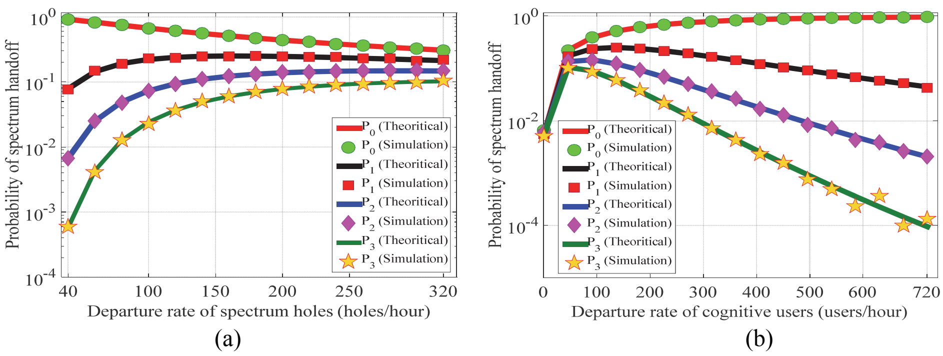

Fig. 2. Impact of departure rate of (a) spectrum holes (λ) and (b) CUs (μ) on the spectrum handoff probability for Weibull residual time distribution of spectrum holes.

3.3 Effect of Shape Parameters on Spectrum Handoff Probability for Weibull Distributed Spectrum Hole Residual Time

Under the impact of λ and μ, the Probability of spectrum handoff of a new call (P) for different shape parameters ($k = 1, 2, 3, 5, 10$) of Weibull residual time distribution is shown in Figs. 3 (a) and (b), respectively. It is seen that P attains a lower value at a higher value of k. But, as the value of k increases, the rate of improvement decreases. From Figs. 3 (a) and (b), it is observed that there is a significant difference between spectrum handoff probabilities for the case when the distribution of spectrum holes residual time is exponentially ($k = 1$) distributed and for the case when the distribution of spectrum holes residual time is Weibull ($k = 2, 3, 5, 10$) distributed. Weibull distribution becomes exponential distribution when shape parameter ($k = 1$), and it is a generalization of the Rayleigh distribution (for $k = 2$), hence we continue our analysis for Weibull distribution with shape parameter, $k = 3$ in next sections.

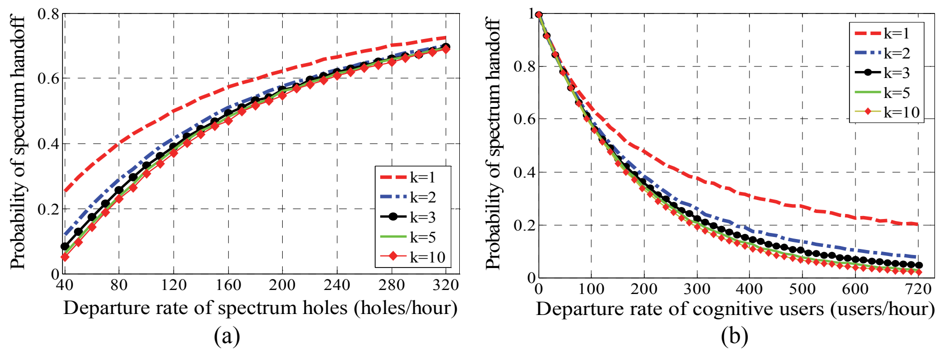

Fig. 3. Impact of λ on (a) zero spectrum handoff probability and (b) spectrum handoff probability of a new call for different shape parameter of Weibull residual time distribution of spectrum holes.

3.4 Comparison of Results under Impact of λ

In this section, comparisons of spectrum handoff probabilities between exponential, Erlang-2, Erlang-3, 23 and Weibull ($k = 3$) distribution functions of residual time of spectrum holes are discussed under the impact of λ. Fig. 4 shows the probability of at least one spectrum handoff (P) for a new call of CU with varying λ. As the value of λ increases, P also increases and the lower value of P is obtained for the case when the distribution of spectrum holes residual time is Weibull ($k = 3$) distributed.

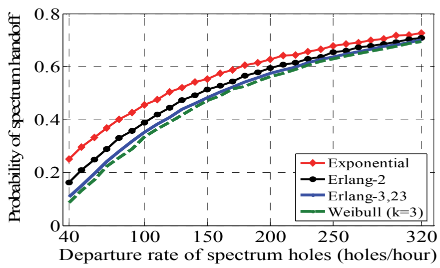

Fig. 4. Impact of λ on spectrum handoff probability of a new call.

Figs. 5 (a)-(d) show the comparison of P_0, P_1, P_2 and P_3, respectively, between general distributions of residual time of spectrum holes under impact of λ. The P_0 decreases with increasing value of λ and higher value of P_0 is obtained for Weibull ($k = 3$) distribution of residual time of spectrum holes as compared to exponential, Erlang-2 and Erlang-3, 23 distributions. The P_1 and P_2 occurred at lower values of λ (≈ 110 & 210 spectrum holes/h) for the case when spectrum holes residual time is exponentially distributed as shown in Figs. 5 (b) and (c) respectively. But, when the residual time of spectrum holes is Weibull ($k = 3$) distributed, P_1 and P_2 occurred at a higher value of λ (≈190 & 270 spectrum holes/h) as compared to other distributions mentioned here. It is also seen that the lower values of Spectrum handoff probabilities are obtained for Weibull ($k = 3$) distribution model of residual time of spectrum holes compared to exponential, Erlang-2 and Erlang-3,23 distributions as shown in Figs. 5 (b)-(d), respectively.

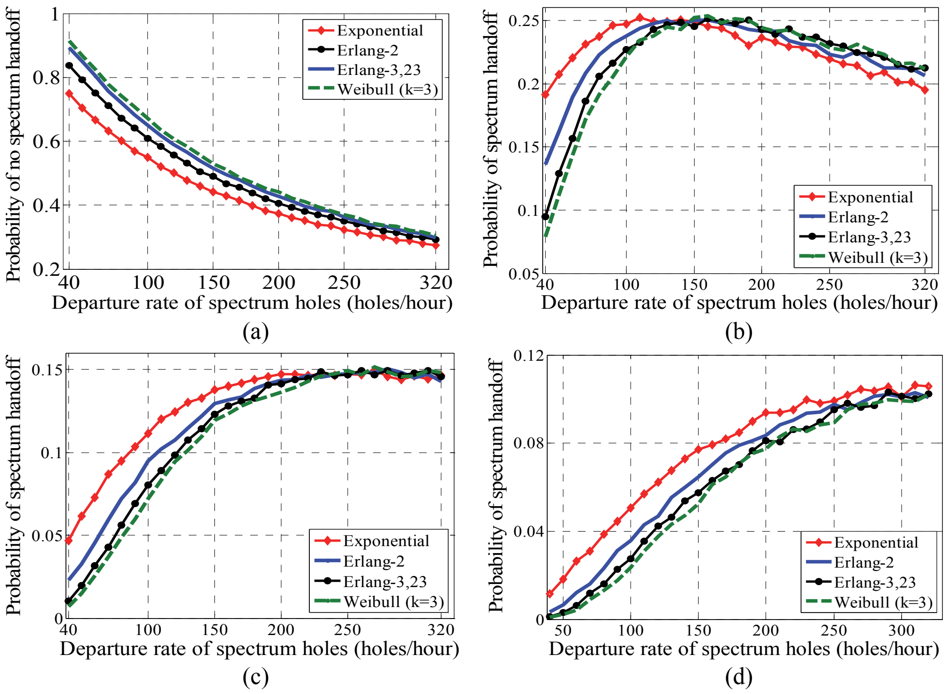

Fig. 5. Impact of λ on (a) zero, (b) 1st, (c) 2nd and (d) 3rd spectrum handoff probability for different residual time distributions of spectrum holes.

3.5 Comparison of Results under Impact of μ

The impact of μ on spectrum handoff probabilities between general distributions of spectrum holes residual time are discussed in this section. Fig. 6 shows the P for a new call of CU with varying μ. The value of P decreases with increasing value of μ (*i.e.* decreasing value of mean departure time of CU). The model with Weibull (k=3) distribution of spectrum holes residual time provides lower values of spectrum handoff probability as compared to exponential and Erlangian distributions.

Under the impact of μ, the comparison of P_0, P_1, P_2 and P_3 for diverse distributions is portrayed in Figs. 7 (a)-(d), respectively. The P_0 increases with increasing value of μ as shown in Fig. 7 (a) and higher value of P_0 is obtained for the case when the residual time of spectrum holes is Weibull (k=3) distributed. As shown in Figs. 7 (b)-(d), the P_1 occurred at a higher value of μ (≈ 151 calls/h) as compared to P_2 and P_3 which are occurred at μ ≈ 85 and 51 calls/h, respectively. Weibull (k=3) distribution model of residual time of spectrum holes offers lower values of Spectrum handoff probabilities compared to exponential, Erlang-2 and Erlang-3,23 distributions.

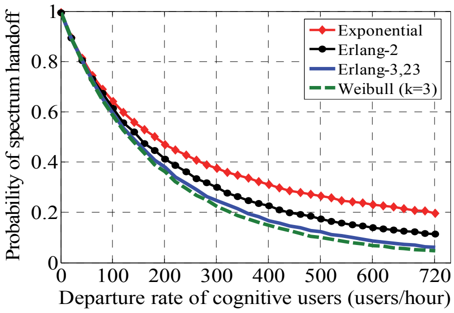

Fig. 6. Impact of μ on spectrum handoff probability of a new call.

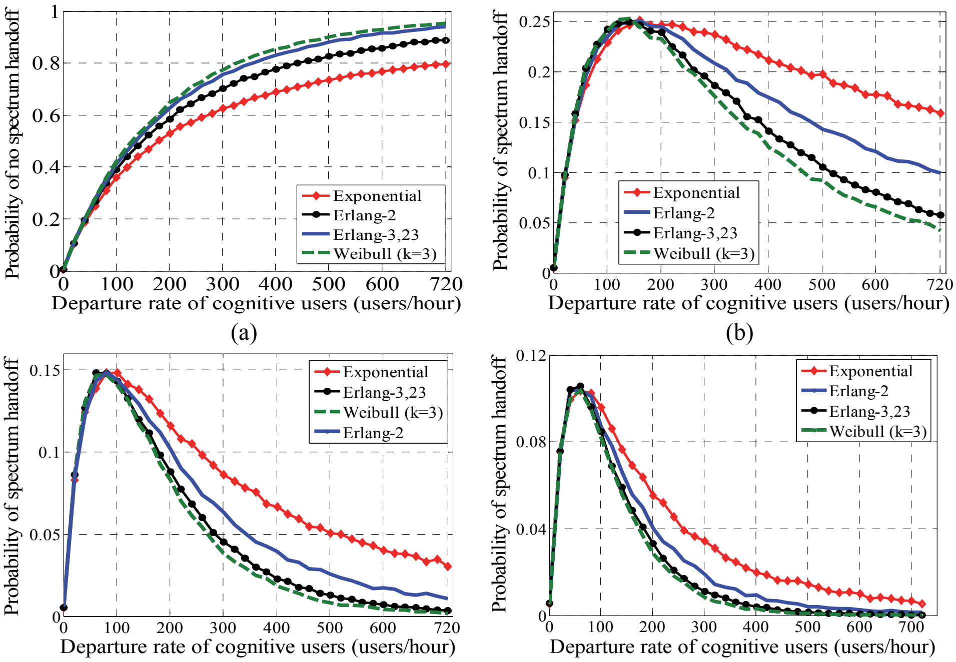

Fig. 7. Impact of μ on (a) zero, (b) 1st, (c) 2nd and (d) 3rd spectrum handoff probability for different residual time distributions of spectrum holes.

3.6 Probability of Spectrum Handoffs versus Number of Handoffs

The probability of spectrum handoff corresponding to the number of handoffs is shown in Fig. 8. The higher value of P_0 (at r=0) is obtained for Weibull (k=3) distribution as compared to others distribution functions mentioned here. From r=1, 2, 3, ... onwards, the values of spectrum handoff probability become lower for Weibull (k=3) distribution of residual time of spectrum holes. It is also observed that the number of handoffs reduced for Weibull (k=3) distribution model as compared to exponential, Erlang-2 and Erlang-3, 23 distributions of spectrum holes residual time.

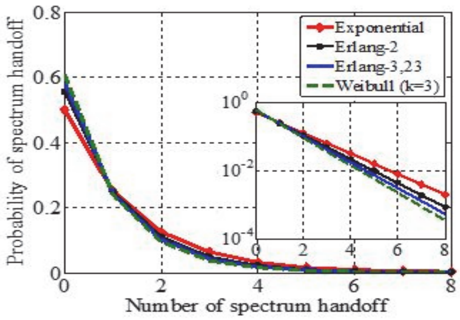

Fig. 8. Spectrum handoff probability versus number of handoffs for different residual time distributions of spectrum holes.

3.7 Average Number of Handoffs

Figs. 9 (a) and (b) show the analytical results for the average number of handoffs per call with varying μ and λ, respectively. As the value of λ increases, the number of spectrum holes during a complete call of a CU also increases.

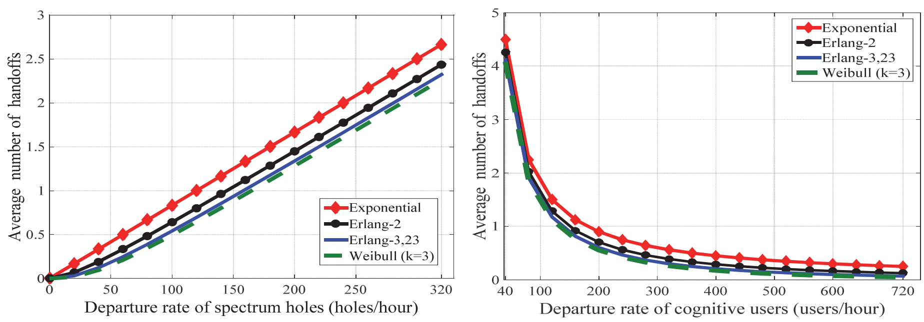

Fig. 9. Average number of handoffs with varying (a) λ and (b) μ for different residual time distributions of spectrum holes.

Hence the average number of handoff increases with the increasing value of λ as shown in Fig. 9 (a). A CU experiences a lower number of spectrum holes to complete its data transmission session for the higher value of μ. As the value of μ increases, the number of spectrum holes requires to complete the service of CU decreases. Hence, the average number of handoffs reduces with increasing values of μ as shown in Fig. 9 (b). From Figs. 9 (a) and (b), it is observed that the Weibull residual times distribution model of spectrum holes offers lesser number of spectrum handoffs in comparison to exponential and Erlang distribution models under both the impact of λ and μ, respectively.

4. CONCLUSIONS

The probability of spectrum handoff is a fundamental component for comprehensive analysis of spectrum mobility and spectrum management in a CRN. A generalized expression is established to estimate the spectrum handoff probability for the case when the residual time of spectrum holes is Weibull distributed and a comparison of theoretical results with simulation results are obtained without considerable deviation. We also have derived a standardized form of average number of spectrum handoffs for exponential, Erlang-2, Erlang-3, 23 and Weibull (k=3) distribution of residual time of spectrum holes. The impact of λ and μ on spectrum handoff probabilities, average number of handoffs are discussed and a detailed comparison of that results for different distribution models with respect to Exponential distribution is also presented. Weibull distribution function confirms better performance as compared to other distribution functions presented in this work including Erlang-3, 23. The Weibull distribution model of residual time of spectrum holes offered less number of handoffs as compared to the other distribution models mentioned here. Hence, the superiority of Weibull distribution in the analysis of spectrum handoff may be used in the domain of CRNs. Analysis of spectrum handoff probability considering user mobility is found to be an important research challenge in CRNs domain.

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