Voluntary Spectrum Handoff: A Novel Approach to Spectrum Management in CRNs

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***Abstract*—In this paper, a new spectrum management scheme for CRNs called *Voluntary Spectrum Handoff (VSH)* is introduced. The two mechanisms proposed under VSH estimate opportune times to initiate unforced spectrum handoff events to facilitate setup and signaling of alternative channels without having communication disruption, which occurs when a secondary user is forced out of an operating spectrum due to primary user activity. VSH has been evaluated through extensive simulations. Simulation results indicate that VSH significantly reduces the communication disruption duration due to handoffs.**

***Index Terms*—Cognitive radio networks; Handoff management; Primary user estimation.**

I. INTRODUCTION

The Cognitive Radio (CR) concept has been proposed to improve the spectrum usage efficiency by exploiting the existence of spectrum holes [1]. Devices using CRs referred to as Secondary Users (SUs), are aware of their spectrum environments and change their transmission and reception parameters to avoid interference with licensed spectrum users referred to as Primary Users (PUs). Networks consisting of nodes equipped with CRs are referred to as Cognitive Radio Networks (CRNs) [2], [3]. CRNs are networks that have cognitive and reconfigurable properties and the capability to detect unoccupied spectrum holes and change frequency for end-to-end communication [2], [4], [5].

In CRNs, spectrum mobility causes a new type of handoff referred to as *spectrum handoff* [2]. In cellular networks, mobile devices transfer an ongoing connection between base stations due to user mobility or channel degradation. However, in CRNs, the number and characteristic of available spectrum at a new location may vary with local PU behavior. Moreover, the spectrum handoffs in CRNs incur longer delays or temporary communication disruptions as SUs must search for spectrum holes and discover a new channel at every spectrum handoff. To sense and discover spectrum holes which have long life times, probabilistic and adaptive spectrum sensing algorithms have been proposed in the literature [6], [7], [8]. For opportunistic spectrum discovery, sensing-period adaptation and optimal sensing-sequencing schemes at channel switching are presented in [6]. A BTR (Busy Time Ratio)-based channel quality metric and a distributed measurement scheme are proposed in [7]. Opportunistic access schemes including frequency hopping are explored in [9]. In spectrum mobility management, spectrum sharing is also an important step to discover a commonly available channel on both transmitter and receiver SUs. To share sensing information and to setup communication links, common control channel concepts are advocated in [10], [11].

In this paper, we propose a new type of spectrum handoff referred to as *Voluntary Spectrum Handoff (VSH)* to reduce temporary communication disruption time which is caused by spectrum handoffs. VSH is not necessarily triggered by PU detection as in conventional spectrum handoff, referred to as Forced Spectrum Handoff (FSH) in this paper. Estimating remaining time until PU access, SUs voluntarily change the spectrum without conflicting with PUs. By voluntarily changing spectrum at estimated times, SUs can reduce delays caused by spectrum hole search and information sharing by overlapping these functions in time with data communication. First, we introduce a new method for PU spectrum usage estimation. We propose two spectrum selection algorithms, called Transition Probability Selection (TPS) and Reliability Based Selection (RBS), to determine the spectrum band to switch to. Our proposed algorithms can be used for arbitrary probability distributions of PU channel occupancy. VSH reverts back to FSH in case a PU accesses a spectrum currently used by an SU before a VSH occurs. Simulation results indicate that SUs have shorter communication disruption durations with VSH.

II. ARCHITECTURE

A. Preliminaries

PU channel occupancy is modeled as an ON-OFF process alternating between ON (busy) and OFF (idle) periods [6], [7]. We specifically focus on exponential and Erlang distributed ON-OFF periods. However, our methods can be applied to arbitrary ON-OFF period distributions based on sensing data using pdf estimation methods described in [12]. For spectrum information sharing and communication, our proposed work is based on a dedicated common control channel.

B. Network Model

The PUs operate on licensed bands and are “owners” of such bands. SUs can utilize unused licensed spectrum. SUs must vacate licensed spectrum as soon as PU activity starts. SUs can access one of N licensed channels at a time. A Spectrum Server (SS) is used to log SU activity, which is then used to deduce past PU activity [13], [14]. The main functionalities

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of the SS are to store spectrum usage information of SUs and to provide spectrum information to other SUs upon request. When an SU senses the spectrum locally, it observes the combined spectrum usage information of both PUs and SUs. With the SU information from SS, an SU can estimate the spectrum usage of PUs as the difference between the locally sensed combined usage and the information from SS.

III. SPECTRUM USAGE ESTIMATION

VSH is primarily based on the estimation of PU activity. When the PU traffic is more dynamic and fast varying as in cellular networks, spectrum estimation mechanisms should be more adaptive to reflect the traffic behaviors. Even when PU traffic behavior is statistically steady, PU spectrum usage may dynamically change whenever the SU moves to new locations. To cope with spectrum usage behavior changes, we define two sensing periods: *sensing window* and *history window*. Sensing window is the basic time unit over which spectrum usage is observed. An SU takes S samples of a channel's status during a sensing window T. Each sample is converted to a binary value representing primary user activity. SUs compute PU spectrum usage as the difference between the locally sampled binary values and the binary values of SU spectrum usage provided by the SS. The average obtained during a sensing window represents a short term statistics of the PU usage. For estimations to be useful for VSH, statistics must be averaged over longer periods of time. We use a history window of length K, $K \geq T$, for estimation purposes. The value of K is increased as long as the average estimated in a sensing window does not deviate more than ϵ fraction of the average obtained over the history window. If the deviation is more than ϵ, then K is decreased aggressively to capture changes that occur in the PU spectrum usage behavior.

A. Sensing Window Size Selection

Since an SU does not know the traffic behavior or rates of PUs, the spectrum sensing window size must be inferred from the spectrum sensing data. To this end, we adopt the following approach. The spectrum usage is represented as a sequence of busy (used) "1" and idle (unused) states "0" [6], [7]. In the On-Off channel model, the sojourn time of an ON period for channel n is modeled as a random variable T^n_{ON} with the probability density function $f_{T^n_{ON}}(y)$, $y > 0$. Similarly, an OFF period is modeled as T^n_{OFF} with $f_{T^n_{OFF}}(x)$, $x > 0$ [6]. The observation is based on the cycles of the spectrum states. We define a spectrum cycle C as the time from the beginning of one state to the end of another state. The average of l spectrum cycles C^n_l on channel n is computed as $C^n_l = \sum_{k=1}^{l} \frac{\sum_{t=m_{k-1}+1}^{m_{k-1}+m_k} X^n[t]}{m_k} / l$, $m = \sum_{k=1}^{l} m_k \geq 2l$, where $X^n[t]$ is the binary channel observation of channel n at t, m_k (m_0=0) is the number of samples on the k^{th} spectrum cycle, and m is the number of total samples. The sensing window size is chosen such that $var(C^n_l) \leq \alpha$, where $l \geq l_{min}$ (a pre-determined value), and α is tuning parameter. The general pdf of the PU activity durations can be estimated via pdf estimation methods of [12]. Although our methods are applicable to arbitrary distributions, we focus on two example distributions, i.e., exponential and Erlang. The spectrum sensing time T^n for channel n is determined as $T^n = l \times [E\{T^n_{ON}\} + E\{T^n_{OFF}\}]$.

B. Spectrum Usage Estimator

An SU updates the spectrum usage estimate every T seconds using the sensing data and information obtained from SS. Then, the spectrum usage estimator calculates PU spectrum usage ratio with history window data. The history window size is increased by one or decreased by D fraction according to the deviation criterion of Eq. 1. The estimated average on channel n at time t (assumed as an integer) can be expressed as follows: $\overline{X_{T^n}} = \frac{1}{T^n} \sum_{i=1}^{T^n} X^n[t - T^n + i]$, $\overline{X_{K^n}} = \frac{1}{K^n} \sum_{i=1}^{K^n} X^n[t - K^n + i]$. History window size K on channel n is computed using Equation 1:

$$K^n = \begin{cases} min(K^n + 1, K^n_{MAX}), \text{ if } \frac{|\overline{X^n_{K^n}} - \overline{X^n_{T^n}}|}{\overline{X^n_{K^n}}} \leq \epsilon \\ max(\lfloor K^n - D \times K^n \rfloor, T^n), \text{ otherwise} \end{cases} \quad (1)$$

IV. SPECTRUM HANDOFF MANAGEMENT

A. Voluntary Spectrum Handoff

Voluntary spectrum handoff is triggered by reaching the threshold probability or time of PU presence prediction. Without PU detection, an SU can predict a future PU activity and change the spectrum band which has lower probability of PU detection. The voluntary spectrum handoff time which is called *residual spectrum lifetime* can be estimated by the spectrum selection algorithms. The purpose of VSH is to reduce communication disruption time caused by the sudden PU presence. If an SU knows the time to switch to another channel, it prepares for channel switching by searching for spectrum holes and sharing spectrum information with other SUs in advance. In CRNs, the delay of FSH includes spectrum hole searching delay (t_{search}), spectrum information sharing delay ($t_{sharing}$) among SUs, channel ordering and selection delay ($t_{decision}$), and channel switching delay ($t_{switching}$). With VSH, an SU can overlap the spectrum analysis and sharing time with the ongoing communication. Consequently, the actual communication of the SU continues while preparing for VSH. As a direct result, the communication session is disrupted for shorter periods of time under VSH than under FSH. The session disruption duration for FSH (D_{FSH}) and VSH (D_{VSH}) are $D_{FSH} = t_{search} + t_{sharing} + t_{decision} + t_{switching}$, $D_{VSH} = t_{switching}$.

B. Spectrum Lifetime Estimation

When an SU predicts PU presence (or end of the spectrum lifetime), it switches to a new spectrum band without detecting a PU. The spectrum lifetimes of target channels for VSH are estimated by two algorithms. The proposed algorithms are based on the probability derived from the estimated pdfs with averages ($E\{T^n_{ON}\}$ and $E\{T^n_{OFF}\}$) and variances ($var(T^n_{ON})$ and $var(T^n_{OFF})$) of ON and OFF periods, respectively. For other distributions, pdf estimation methods such as [12] can be adopted. The proposed two algorithms are as follows:

TPS (Transition Probability Selection)

Derivations of transition probabilities for the general ON/OFF processes using Laplace transform are introduced in [10]. In particular, the transitions probabilities for exponentially distributed ON/OFF periods are calculated as

$$\begin{aligned} P_{00}^n(t) &= (1-u^n) + u^n \times e^{-(\lambda_{ON}^n+\lambda_{OFF}^n)t} \\ P_{01}^n(t) &= u^n - u^n \times e^{-(\lambda_{ON}^n+\lambda_{OFF}^n)t}, \end{aligned} \tag{2}$$

where, $u^n = \frac{\lambda_{OFF}^n}{\lambda_{ON}^n+\lambda_{OFF}^n}$. Similarly, the transitions probabilities for Erlang-distributed (k=2) ON/OFF periods are

$$\begin{aligned} &P_{00}^n(t) = 1 - \tfrac{1}{4}\tfrac{(\lambda_{ON}^n-\lambda_{OFF}^n)^2}{\lambda_{ON}^n} e^{-\frac{1}{2}(\lambda_{ON}^n+\lambda_{OFF}^n)t}\tfrac{\sinh(\frac{1}{2}Ct)}{C} \\ &\quad + \tfrac{1}{4}[-4\lambda_{ON}^n\lambda_{OFF}^n - (\lambda_{ON}^n - \lambda_{OFF}^n)^2 e^{-(\lambda_{ON}^n+\lambda_{OFF}^n)t} \\ &\quad + (\lambda_{ON}^n + \lambda_{OFF}^n)^2 e^{-\frac{1}{2}(\lambda_{ON}^n+\lambda_{OFF}^n)t}\cosh(\tfrac{1}{2}Ct)](1-u^n) \\ &P_{01}^n(t) = 1 - P_{00}^n(t), \\ &C = \sqrt{(\lambda_{ON}^n)^2 - 6\lambda_{ON}^n\lambda_{OFF}^n + (\lambda_{OFF}^n)^2} \end{aligned} \tag{3}$$

With the transition probabilities P_{00} (idle to idle transition) and P_{01} (idle to busy transition) from renewal theory, we can estimate spectrum lifetime for VSH. We define the spectrum life time t_n on channel n as

$$t_n = \underset{0<t\leq(t_{Max}-K^n)}{\operatorname{argmax}} \{t | P_{00}^n(t) \geq P_{01}^n(t)\}. \tag{4}$$

In the TPS algorithm, if the probability crossover does not happen due to low PU activity, the SU stays on the same channel and VSH reverts back to FSH. On the other extreme, if a short spectrum lifetime is estimated such as "$0 < t_n \leq$ *one sensing period*", the spectrum lifetime t_n is set to one sensing period and SU switches to a new channel due to the prediction of imminent PU presence only if there are channels with longer spectrum lifetime estimations.

RBS (Reliability Based Selection)

RBS is based on the reliability theory [15] and estimates spectrum lifetime of the OFF periods. To derive a general equation, we define the following; T: time until next primary user detection (r.v.), t: time after the detection of no primary user, $S(t)$: spectrum lifetime function, $F(t)$: cumulative distribution function of T, $f(t)$: probability density function of T. Spectrum lifetime function is defined as $S(t) = P(T > t) = 1 - P(T \leq t) = 1 - F(t)$. $S(t)$ is a curve describing the proportion of spectrum availability as a function of t and expressed in terms of cumulative distribution function $F(t)$ of the OFF process. PU detection rate $\mu(t)$ is defined as the relative rate for spectrum lifetime function decline:

$$\mu(t) = -\frac{dS(t)}{S(t)dt} = -\frac{d}{dt}\ln S(t) \tag{5}$$

From Eq. 5, the spectrum lifetime function is computed as $S(t) = e^{-\int_0^t \mu(u)du}$. For example, for exponentially distributed T_{OFF}^n with rate λ_{OFF}^n, the detection rate can be replaced by constant rate $\mu(t) = -\frac{S'(t)}{S(t)} = \lambda_{OFF}^n = const.$ With the constant PU detection rate, the spectrum lifetime function can be described by the exponential distribution $S(t) = e^{-\lambda_{OFF}^n t}$. Similarly, when T_{OFF}^n is Erlang-distributed, the detection rate is expressed as

$$\mu(t) = \frac{(\lambda_{OFF}^n)^k t^{k-1}/(k-1)!}{\sum_{m=0}^{k-1}(\lambda_{OFF}^n t)^m/m!} \tag{6}$$

With the spectrum lifetime function, the spectrum lifetime t_n on channel n is computed as

$$t_n = \underset{0<t\leq(t_{Max}-K^n)}{\operatorname{argmax}} \{t | S(t) \geq S_{threshold}\}. \tag{7}$$

$S_{threshold}$ determines the aggressiveness of the VSH attempts.

C. Voluntary Spectrum Handoff Process

Under VSH, an SU uses spectrum lifetime estimation to select a potential channel to switch to. The SU selects a channel which has the longest spectrum life time t_n that is estimated by the proposed algorithms. The sequences of events leading to a VSH are as follows:

1) Share the unused spectrum information and estimated spectrum lifetimes t_n between SUs.
2) Decide on a channel which has the maximum spectrum lifetime on both SUs.
3) Share and confirm the decision results.
4) When spectrum lifetime expires, switch to the new channel.

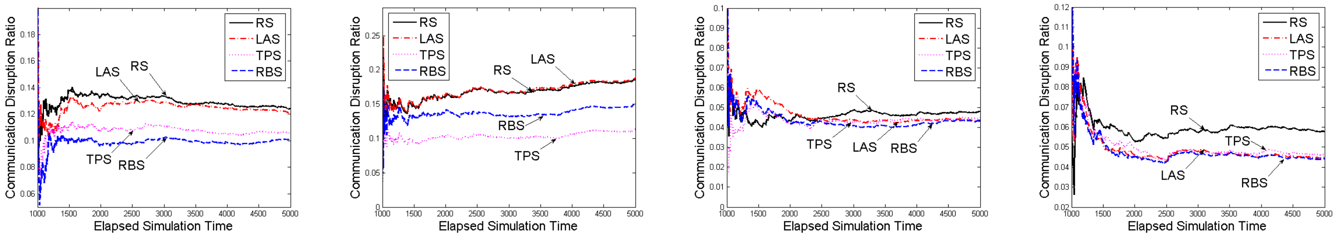
Note that steps 1∼3 occur without disrupting the communication session of the SU under VSH. If a PU is detected before estimated spectrum lifetime, these steps are repeated (as in FSH) in which case all 4 steps contribute to the disruption duration.

V. PERFORMANCE EVALUATION

VSH is evaluated through simulations. We assume N channels and an ON-OFF PU traffic source model. We assume that ON and OFF periods are iid positive random variables with exponential or Erlang distributions. For the spectrum usage estimation and PU detection, SU senses all N channels every second. When an SU detects PU presence, it vacates current spectrum without further transmission and searches for an empty spectrum band. We consider the following two FSH algorithms for comparison:

- *Random Selection (RS)*: When FSH is triggered, an SU randomly selects a channel among currently available ones.
- *Lowest Average Selection (LAS)*: When FSH is triggered, an SU selects the available channel with the lowest average spectrum usage on history window (i.e., lowest BTR [7]).

To evaluate our proposed schemes, we compare TPS and RBS ($S_{threshold}$=0.5) algorithms for VSH with RS and LAS for FSH. In our simulations, we count the numbers of forced and voluntary spectrum handoffs and measure the Communication Disruption Ratio (CDR). CDR is calculated as $disruption\ periods/total\ communication\ time$. In our simulations, the disruption period of SU communication increases when FSHs or VSHs are triggered, or when there is



(a) CDR Comparison in IM (b) CDR Comparison in DM (c) CDR Comparison in SM (d) CDR Comparison in HM

Fig. 1. CDR Comparison with Four Traffic Models

no available channel. In the latter case, the SU waits until a spectrum hole emerges. Simulation results about the channel switching and packet transmission delays are provided in several existing works [6], [7], [16]. In our system model, the delay components of FSH include t_{search}, $t_{sharing}$, $t_{decision}$, and $t_{switching}$. In [6], the channel switching delay including t_{search}, $t_{decision}$, and $t_{switching}$ is reported between 80 msec and 350 msec. In [16], the packet delay of a single hop communication is reported as 100 msec, which can be considered as $t_{sharing}/2$. With these simulation results, we assume that an SU's communication is disrupted for D_{FSH}=500 msec during FSH to detect spectrum holes and connect to another SU. In case of VSH, we assume that SU's communication is disrupted for 50 msec to switch to a new spectrum. We choose a maximum history window size of 1000 sec, which is five times larger than the spectrum sensing window of 200 sec. The total simulation time is 5000 seconds for each configuration. The results have a transient period of 1000 sec, which are ignored when computing averages.

A. Communication Disruption Ratio Comparison

For various communication scenarios, we define 4 traffic patterns with Erlang distribution (k=2) such as Identical Mode (IM), Dense Mode (DM), Sparse Mode (SM), and Hybrid Mode (HM) which have different channel usage. In each mode, the number of channels is 9.

Identical Mode: In identical mode, all 9 channels are configured with $E\{T_{ON}\}$ = 3.0 and $E\{T_{OFF}\}$ = 3.0. In Figure 1(a), VSH schemes have around 10% disruption ratios and FSH methods have around 13%. This means that during 5000 seconds simulation, TPS and RBS with VSH have 150 seconds longer uninterrupted connection time which is caused by 23%∼35% fewer FSHs. The CDR performance is ordered as RBS $>$ TPS $>$ RS $>$ LAS.

Dense Mode: In dense mode, all 9 channels are configured with $E\{T_{ON}\}$ = 9.0 and $E\{T_{OFF}\}$ = 3.0 to simulate high spectrum usage behavior. From Figure 1(b), we can see the TPS and RBS have 11.5% and 14.5% disruption ratios, respectively, whereas RS and LAS have 19% disruption ratios. The 4.5%∼7.5% performance gains of TPS and RBS are obtained from reducing FSH counts and replacing them with VSHs. This means that SUs can have longer uninterrupted connection times with VSH when PU spectrum usage ratio is high. Among VSH schemes, TPS has superior performance over more aggressive VSHs than RBS. The CDR performance is ordered as TPS $>$ RBS $>$ LAS $>$ RS.

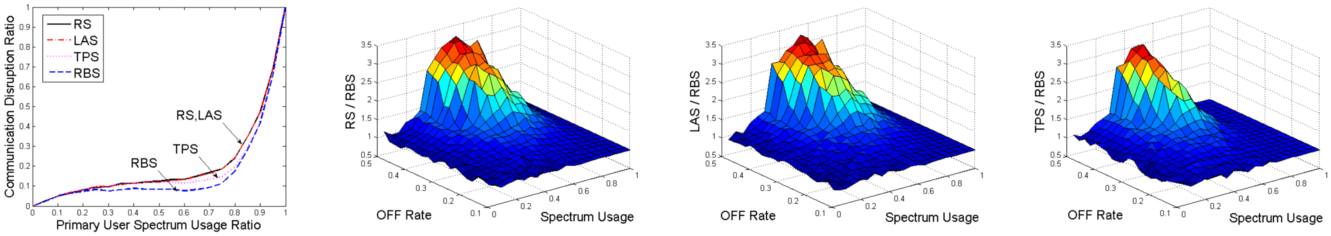
Sparse Mode: In sparse mode, all 9 channels are configured with $E\{T_{ON}\}$ = 3.0 and $E\{T_{OFF}\}$ = 9.0 to simulate low spectrum usage behavior. From Figure 1(c), all spectrum selection algorithms including VSH schemes have similar disruption ratios around 4.3%∼4.8%. This means the TPS and RBS schemes deliver small benefits since FSH occurs before estimated spectrum lifetimes are reached due to low PU spectrum usage.

Hybrid Mode: To simulate heterogeneous spectrum usage behaviors, 3 channels are configured with $E\{T_{ON}\}$ = 3.0 and $E\{T_{OFF}\}$ = 9.0, 3 channels with $E\{T_{ON}\}$ = 6.0 and $E\{T_{OFF}\}$ = 6.0, and 3 channels with $E\{T_{ON}\}$ = 9.0 and $E\{T_{OFF}\}$ = 3.0. In comparison results shown in Figure 1(d), LAS, TPS, and RBS have lower CDR than RS. The CDR performance is ordered as RBS $>$ LAS $>$ TPS $>$ RS.

B. Effect of Primary User Spectrum Usage

To show the effect of PU spectrum usage, we ran simulations with varying PU spectrum usage ratios between 0 (no PU activity) and 1 (permanent PU activity) with exponentially distributed On-Off periods. The PU spectrum usage ratio on a channel n is defined as $E\{T^n_{ON}\}/(E\{T^n_{ON}\} + E\{T^n_{OFF}\})$. For every parameter combination, we average the results for 4000 sec. simulation time.

For CDR comparisons of all spectrum selection algorithms with different PU spectrum usages, the control of PU spectrum usage ratios is achieved using a variable λ_{ON}=$1/E\{T_{ON}\}$ and a fixed λ_{OFF}=$1/E\{T_{OFF}\}$ as $1/3$. Figure 2(a) is the extended version of Figure 1(a) with a different pdf (Exponential) and various PU spectrum usage ratios. Figure 2(a) shows that TPS and RBS have lower disruption ratios in most cases. Between 0.3 and 0.9 of PU spectrum ratio, VSH schemes have benefits from voluntary handoffs by reducing forced handoffs. Between VSH schemes, RBS has better performance in most cases. Between 0.3 and 0.8 of PU spectrum ratio, RBS quite aggressively reduces FSH counts with active VSHs



(a) CDR with $E\{T_{OFF}\} = 3$

(b) CDR with RS/RBS

(c) CDR with LAS/RBS

(d) CDR with TPS/RBS

Fig. 2. CDR Comparisons with PU Spectrum Usage Variation

and has lower disruption ratios than TPS VSH scheme. The aggressive VSHs of RBS are caused by short spectrum lifetime estimations. The sharp increase in CDR between 0.8 and 1 for all schemes is caused by the unavailability of channels.

To compare CDR performance among spectrum selection algorithms, we calculate the CDR ratios of RS/RBS, LAS/RBS, and TPS/RBS. Since RBS has relatively stable and superior performance result with various traffic parameters, we choose RBS as a comparison base. In comparison results, ratios greater than 1 mean that RBS has superior performance. In case of RS and LAS comparisons in Figures 2(b) and 2(c), the ratios are greater than 1 in all ranges. Between PU spectrum usage ratios 0 and 0.3, the CDR ratios increase slowly. Especially, RBS CDR has longer undisrupted connection times between PU spectrum usage ratios 0.3 and 0.9. Beyond PU spectrum usage ratio of 0.9, the CDR ratios converge on 1 because there are no spectrum holes for SUs. In comparison of TPS with RBS in Figure 2(d), RBS has better performance between PU spectrum usage ratios 0.3 and 0.7 with λ_{OFF} $\geq$0.25 by initiating VSHs more aggressively than TPS. The comparison results rapidly converge to 1 between PU spectrum usage ratios 0.7 and 0.8.

VI. CONCLUSIONS

We have introduced a novel spectrum handoff scheme called voluntary spectrum handoff to minimize SU disruption periods during spectrum handoff. To determine voluntary spectrum handoff time, we define spectrum life time which is estimated by two spectrum selection algorithms, i.e., TPS and RBS. For spectrum usage estimation, we propose to use an approach based on a fixed sensing window and a variable history window. Simulation results show that SUs can reduce forced spectrum handoff counts with VSH. With the reduced forced spectrum handoffs, SUs can have longer undisrupted connection times. In the comparisons of each spectrum selection algorithm, while TPS has superior performance for high PU activity, RBS has superior performance in other cases. In general, RBS shows superior performance on various PU spectrum usage ratios. In the future, we would like to explore an estimation of PU spectrum usage distributions from real world data sets such as cellular and WiFi usage statistics to build more realistic system models.

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