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An Expository Inquiry into Spectral Handoff Mechanisms for the Cognitive Radio Network

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Abstract
In a cognitive radio network, the cognitive radio (CR) devices, also known as secondary users (SUs), necessitate altering their operational frequency when a primary user (PU) enters that frequency band. Consequently, when a PU enters a frequency band and requests a channel within it, it acquires that band, potentially occupying a channel that an SU is currently using. In such a scenario, the SU must search for an alternative channel in a different frequency band, resulting in what is termed a "spectral handoff." Therefore, in addition to location-based handoffs for SUs, spectral handoffs also come into play. The SU may undergo multiple spectral handoffs in this process, prompting an in-depth investigation of the handoff mechanism. This paper undertakes a comprehensive survey of the various types of handoffs and the mechanisms that have already been conceptualized.

Keywords: Cognitive Radio, handoff, spectral handoff, spectrum sensing, proactive, reactive.

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I. INTRODUCTION

In a cognitive radio network, the cognitive radio (CR) devices, denoted as secondary users (SUs), are unregistered users, while the registered devices are the primary users (PUs) in the underlying technology. The frequency resource utilized for communication experiences sporadic usage, signifying periods of over-utilization and underutilization across time and regions. SU devices adhere to two fundamental rules when using this frequency resource for communication: 1. SUs must avoid creating interference to nearby PUs. 2. SUs are required to vacate an occupied frequency channel if it is demanded by a PU.

These regulations, specified by the FCC (Federal Communication Commission) [1], enable the coexistence and operation of cognitive radio devices in close proximity to PUs, thereby granting the SUs a lower priority for resource consumption compared to registered primary users.

In general, for a PU, a handoff occurs when the device changes its cell, meaning it changes its location, resulting in a handoff primarily limited to a spectral shift due to the cell change. Consequently, this handoff is referred to as a location-based handoff rather than a spectral handoff. On the other hand, for SUs, two distinct scenarios arise: 1. SUs change location to experience a spectral handoff. 2. SUs, even when stationary, may undergo a spectrum shift due to the inclusion of a PU in close proximity.

These situations necessitate frequent operating frequency changes for SUs to maintain operation, leading to handoffs termed "spectral handoffs" rather than location-based handoffs. The structure of this paper further unfolds as follows: firstly, it describes the spectrum handoff procedure, followed by an exploration of different handoff categories. Next, various handoff techniques are expounded upon, and finally, the paper concludes with a comprehensive summary.

II. LITERATURE REVIEW

Cognitive radio systems undergo spectrum handoff when primary users (PU) emerge in channels occupied by secondary users (SU). In such instances, the SU must promptly engage in a handoff process, transitioning or switching from the current channel to a target channel. The selection of this target channel is determined either autonomously by the SU or assigned by the base station, relying on sensing techniques and received signal strength. Notably, centralized sensing and distributed sensing are among the sensing techniques employed.

Upon the SU's decision to initiate a spectral handoff, a handoff delay arises, measured from the moment the SU pauses its transmission until it successfully switches to the target channel and prepares to resume transmission. To illustrate this process, consider a scenario where two SUs, SU1 and SU2, are communicating over channel Ch1. When a PU appears on Ch1 while this communication is ongoing, SU1 detects this event and readies itself to execute the spectrum handoff procedure. In response, SU1 promptly suspends its current communication within a predefined duration and notifies SU2 of the interruption event before another predetermined time interval. Additionally, SU1 informs SU2 about the target channel to be used for their resumed transmission. Subsequently, both SU1 and SU2 can proceed with the resumption of their transmission activities on the selected target channel.

III. COGNITIVE RADIO HANDOFF TYPES

The handoff type described herein pertains to the process of identifying and selecting the target channel for completing the handoff procedure. In this context, comprehensive techniques for target channel selection are presented, primarily focusing on two methods: proactive and reactive selection. The resulting handoffs based on these methods are referred to as:

A. Proactive Spectrum Sensing Handoff:

In the proactive-sensing spectrum handoff, secondary users proactively prepare target channels for spectrum handoff ahead of their actual transmission needs. In this approach, secondary users periodically monitor all available channels to gather channel usage statistics and discern a candidate set of target channels for spectrum handoff based on long-term observation outcomes. Subsequently, this observation data is transmitted to the base station, which ultimately determines the optimal target channel for the secondary user.

B. Reactive Spectrum Sensing Handoff:

In the reactive-sensing spectrum handoff, the target channels are sought on demand. In this scenario, instantaneous results from wideband sensing are utilized to determine the target channel selection for the spectrum handoff. Once the suitable channel is identified, the secondary user acquires it from the base station for execution of the handoff process.

IV. DIFFERENT SPECTRUM HANDOFF TECHNIQUES

Li-Chun Wang and Chung-Wei Wang [2] have put forth an in-depth analysis of a PRP M/G/1 queuing network model to determine the optimal conditions for implementing either reactive- or proactive-sensing spectrum handoffs. In their model, each channel maintains a priority-based queue for users, distinguishing between low and high priority queues. As primary users hold higher priority than secondary users, they can acquire channels already occupied by the latter. The study presents two scenarios wherein secondary users can either remain on their current channel or switch to another.

In the first case, unfinished data is placed at the tail of the low-priority queue of another channel. Conversely, in the second case, when the secondary user stays on the current channel, the unfinished data is inserted at the head of the low-priority queue of that channel. Transmission resumes in both cases once the channel becomes idle.

Moreover, the paper accounts for the arrival rate of primary users ($\lambda 0$) and utilizes its mean value to calculate the transmission latency for reactive- and proactive-sensing spectrum handoffs. Two transmission latencies are derived: the "always-stay" and "always-change" cases. The "always-stay" case refers to the scenario where the interrupted secondary user remains on its default channel until its packet is fully transmitted. In contrast, in the "always-change" case, the target channels alternate between two channels.

A lower value of arrival rate for primary users leads to a preference for channel change by the interrupted secondary user. Conversely, with a larger $\lambda 0$, the interrupted customer prefers the "always-stay" strategy. C.-W. Wang, L.-C. Wang, and F. Adachi [3] have proposed a Markov transition model integrated with the PRP M/G/1 queuing network to characterize the delay involved in multiple handoffs. Secondary users may undergo several spectral handoffs during the entire transmission period, owing to interruptions by primary users. Consequently, a secondary user should have a series of target channels to be used sequentially when needed. The proposed reactive decision spectrum handoff scheme employs a Markov transition model, further integrated with the PRP M/G/1 queuing network to extract a sequence of target channels.

The Markov chain encompasses L stages, with L representing the maximum number of interruptions for secondary connections, and M denoting the maximum number of states. State "Chk" signifies that channel k is selected as the target channel, where $1 < k < M$. The Markov model includes both start and end states. Based on this model, the transition probability from state i to j (denoted as Pi,j) and transition cost (denoted as Ci,j) are calculated. The sequence of target channels is then derived, and the mean of cumulative handoff delay, E[D(k)], is computed. M. Kalil, H. Al-Mahdi, A. Mitschele [4] have proposed the Opportunistic Spectrum Access with Backup (OSAB) channel. Typically, spectrum handoffs occur in licensed bands, but this paper introduces the use of unlicensed bands as backup channels.

The spectrum handoff is conducted proactively, with each SU maintaining a list of available channels in both bands, to be used in case primary users appear. In licensed bands, primary users possess higher priority over secondary users, while in unlicensed bands, both primary and secondary users have the same priority. The link maintenance probability is calculated, representing the likelihood of successfully maintaining a link when the SU abandons a channel. The performances of the link maintenance probability and the expected number of spectrum handoffs for SUs are evaluated under two scenarios: one with six licensed channels (LCs) and zero unlicensed channels (UCs), and another with four LCs and two UCs.

Additionally, three traffic load conditions are assessed: low, moderate, and high traffic. Experimental results demonstrate that OSAB yields superior results compared to just opportunistic spectrum access (OSA). L. Ch. Wang, W. Chung [5] have employed a PRP M/G/1 queuing model to derive performance indicators for quality of service (QoS) in cognitive radio networks. The study evaluates spectrum sensing, spectrum sharing, spectrum decision, and spectrum handoff to design improved spectrum management policies that satisfy the QoS requirements of secondary users in CR networks. The proactive spectrum handoff results are compared against the reactive spectrum handoff, with the findings indicating that proactive spectrum handoff exhibits lower time consumption than reactive spectrum handoff. Soumaya Dahi, Sami Tabbane [6] utilize a sigmoid S-shaped curve to represent the life cycles of cognitive radios, consisting of incipient, maturing, and declining phases. Here, the SU selects a channel with the highest holding time (HT), representing the idle time of the channel learned from long observations. Using QoS and HT parameters, the SU chooses a channel for handoff.

However, if the selected channel has high HT but poor quality, the transmission may be interrupted due to unacceptable quality even in the absence of PU activity. In such cases, the SU should opt for a channel with a smaller HT but better quality to resume transmission during the entire provided holding time. This type of handoff is also considered proactive spectral handoff. Lu Li, Yanming Shen, Keqiu Li, Kai Lin [7] have proposed a novel proactive spectrum handoff approach based on time estimation (TPSH). In this approach, two probabilities, namely busy-to-idle and idle-to-busy, are calculated at every time slot. The idle period vectors are used to update the remaining idle time for the SU.

Only channels with idle probabilities exceeding 50% are considered, rather than considering the average case. If the SU's remaining task duration is shorter than the current channel's remaining idle period, and a PU is detected, the SU selects a target channel using the proposed algorithm and triggers a reactive handoff. J. Guo, H. Ji, Y. Li, X. Li [8] have proposed a support vector machine (SVM) model to predict the handoff point, enabling the SU to prepare for handoff before the channel is occupied by the PU. This proactive spectrum handoff method involves learning from neighboring nodes' broadcast information to predict the handoff point and identify idle spectrum channels for SUs. The spectrum handoff scheme comprises three parts: a cooperative spectrum sensing mechanism, the use of SVM to predict the handoff point, and the selection of an idle spectrum channel for handoff.

The input to the system includes node information such as node position, speed, and currently used spectrum, while the output indicates whether the SU should prepare for handoff (-1) or not (+1). The SVM model considers only two spectrum bands with frequencies f1 and f2, and the output of the SVM is unified to calculate Gc, representing the handoff point. Yuh-Shyan Chena, Ching-Hsiung Choa, Ilsun Youb, Han-Chieh Chaoc [9] have proposed a cross-layer protocol of spectrum mobility and handover, divided into three phases: (1) environment observation phase, (2) computation and analysis phase, and (3) evaluation and transmission phase. In the environment observation phase, each SU senses all spectrum bands within the transmission coverage of the current serving base station periodically. If a frequency channel resource reclaimed by a PU is detected, the SU performs handoff to another frequency channel that was identified as unused during environment observation. The computation and analysis phase distinguish between non-overlapping and overlapping areas. In the third phase, the actual handoff takes place based on the earlier phases. The proposed protocol reduces total handoff delay and minimizes the number of handoffs, providing the SU with more time to remain on the current spectrum hole. This protocol is also of the proactive spectrum handoff type.

V. CONCLUSIONS

Based on the survey conducted on handoffs in cognitive radio networks, the handoff mechanism is categorized into two fundamental classes: proactive and reactive spectrum handoffs. The findings from the survey underscore that the proactive spectrum handoff exhibits remarkable advantages in terms of both handoff delay and communication reliability compared to the reactive spectrum handoffs. Nonetheless, the research in this domain acknowledges the significance of considering traffic loads; however, it fails to address the potential occurrence of a ping-pong effect that might emerge in scenarios characterized by heavy traffic loads. Consequently, a prospective avenue for investigation entails the development of an algorithmically-based approach to tackle and ameliorate this effect.

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