Channel selection and switching methods in dynamic spectrum networks: A survey

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ABSTRACT:

The Cognitive Radio (CR) networks architecture is critical for addressing the challenges associated with dynamic spectrum utilization. CR users have the capability to access both licensed and unlicensed bands, enabling efficient spectrum utilization. However, the heterogeneous nature of CR networks presents significant challenges due to coexistence with primary networks and diverse Quality of Service (QoS) requirements. This survey explores spectrum management and adaptive protocols in CR networks, focusing on spectrum handoff. Spectrum handoff involves the transfer of ongoing transmissions from occupied frequency bands to available ones. It discusses target channel selection techniques for spectrum handoff, which are effective for per-slot throughput maximization, latency in spectrum handoff and minimizing cumulative delay in multiple handoffs. The survey also highlights the use of Markov chain models and queueing networks to analyse spectrum handoff schemes and suggests the use of proactive or reactive sensing based on sensing time. A comparison of the effects of spectrum handoff on the data delivery time, channel utilization and latency performance in CR networks was made, offering insights for future research and development in this field.

Keywords: spectrum handoff, reactive handoff, channel utilization, proactive handoff, cognitive radio

INTRODUCTION

The Cognitive Radio (CR) networks architecture plays a crucial role in addressing the challenges associated with dynamic spectrum utilization. CR users possess the capability to access both licensed bands allocated to primary networks and unlicensed bands that become available in the absence of primary users, thanks to wideband access technology. During licensed band operation, CR networks primarily focus on primary user detection. Channel capacity depends on minimizing interference to neighbouring primary users, necessitating CR users to promptly vacate the licensed band and switch to available spectrum whenever primary users appear within the same frequency range. Conversely, for unlicensed band operation, CR users require sophisticated spectrum sharing methods to effectively compete for access to the unlicensed spectrum.

The heterogeneous nature of CR networks presents significant challenges due to their coexistence with primary networks and diverse Quality of Service (QoS) requirements, such as interference avoidance, QoS awareness, and seamless communication. In response to these challenges, the author of (Akyildiz, F. Ian; Lee, Won-Yeol; Vuran, C. Mehmet; Mohanty, Shantidev, 2008) proposed a comprehensive spectrum management process consisting of spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility.

The inherent adaptability of cognitive radios allows for easy adjustment of transmission parameters without the need for hardware modifications. This flexibility enables cognitive radios to adapt swiftly to the dynamic environment. However, changes in the operating frequency by CR users may necessitate modifications to network protocols to align with the new operating parameters. Reconfiguration of transmission parameters may occur at the start or during an ongoing transmission, requiring network stack protocols to adapt accordingly, while considering spectrum handoff and associated latency. Sensing algorithms provide latency information to mobility management protocols, ensuring minimal performance degradation.

Moreover, the current operating frequency may become occupied when a primary user initiates transmission within that frequency during secondary users' ongoing communication. Consequently, the ongoing transmission needs to be transferred to another available frequency band. However, the selection of a new channel may not be immediate, requiring autonomous algorithms to ensure that secondary users' transmissions experience minimal performance degradation during spectrum handoffs. Secondary users often encounter longer communication delays during spectrum handoff due to suspended transmissions. Therefore, an effective spectrum handoff mechanism should facilitate smooth frequency shifts with minimal latency to ensure optimal performance for secondary users.

In the CR networks, unlicensed Secondary Users (SUs) can completely utilize the spectrum in an opportunistic manner without collision with the licensed Primary Users (PUs). To avoid interference with PU, various techniques and protocols are used to access the frequency bands and to manage the channel-control (Maheshwari & Singh, 2014). Usually, the frequency bands of PUs are not always occupied in a cognitive radio network consisting of both PUs and SUs. When the SU occupies the unused frequency band and the PU resurfaces in cognitive radio networks, spectrum handoff occurs such that the SU needs to suspend its on-going transmission, vacate that channel, and determine a new available channel to continue the current transmission (Maheshwari & Singh, 2014). In this case, frequent handoffs may be possible that worsen the performance of SUs and may cause service interruption (Maheshwari & Singh, 2014).

Cognitive radio networks offer unlicensed Secondary Users (SUs) the opportunity to opportunistically utilize the spectrum without causing interference with licensed Primary Users (PUs). To ensure interference avoidance, various techniques and protocols have been developed to facilitate access to frequency bands and manage channel control. However, in cognitive radio networks where both PUs and SUs coexist, the frequency bands assigned to PUs are not consistently occupied. Consequently, when an SU occupies an unused frequency band and a PU re-emerges, spectrum handoff becomes necessary.

During spectrum handoff, the SU must halt its ongoing transmission, vacate the current channel, and identify a new available channel to continue the transmission. Moreover, frequent handoffs in such scenarios can deteriorate the performance of SUs and result in service interruptions. Efficient spectrum handoff hinges on two critical factors: achieving rapid and seamless channel switching to mitigate performance degradation and obtaining accurate information regarding the duration of a spectrum handoff, commonly referred to as handoff delay. In the literature, Markov chain models, switching frequency, blocking probability and outage probability of the SUs have been used to provide the PUs traffic model in both spectrum handoff schemes. For instance, (Wang, Li-Chun; Wang, Chung-Wei, 2008) (Wang, Chung-Wei; Wang, Li-Chun, 2012) (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010) suggested the use of pre-emptive resume priority (PRP) M/G/1 queueing network to analyze the condition by which the reactive or proactive sensing spectrum handoff should be used dependent of sensing time.

This survey aims to provide an in-depth exploration of spectrum management and adaptive protocols in cognitive radio networks. It examines existing approaches, highlights challenges, and proposes potential solutions to optimize spectrum utilization, mitigate interference, and enhance the performance of CR networks during spectrum handoffs.

MODELLING FOR SPECTRUM HANDOFFS

In this study, we examine two decision timing schemes, namely reactive-decision and proactive-decision schemes, for spectrum handoff in CR networks. The reactive-decision spectrum handoff scheme adopts an on-demand approach, where a spectrum handoff is initially requested, and subsequent spectrum sensing is performed to identify idle channels for resuming unfinished data transmission by secondary users. Conversely, the proactive-decision spectrum handoff scheme determines target channels for future spectrum handoffs based on long-term statistics before establishing data connections.

According (Wang, Li-Chun; Wang, Chung-Wei; Feng, Kai-Ten;, 2011), the proactive spectrum handoff exhibits a shorter channel switching delay compared to the reactive spectrum handoff. This is attributed to the fact that the proactive scheme does not require an extensive spectrum search at the time of link transition to determine the target channel. Furthermore, the proactive spectrum handoff scheme effectively addresses the obsolescent channel issue, as the predetermined target channel may not be available at the time a spectrum handoff is requested. The proactive spectrum handoff scheme facilitates consensus on the target channels between transmitters and their intended receivers more easily than the reactive scheme. This is because both the transmitter and receiver possess knowledge of their target channel sequence for future spectrum handoffs prior to data transmission. Hence it is important to study several models to evaluate channel utilization and transmission latency for all handoff schemes under various traffic arrival rates and service time distributions. By examining these models, we aim to gain insights into the performance characteristics of the different spectrum handoff schemes and their impact on channel utilization and transmission latency in CR networks.

A. *Reactive-decision spectrum handoff scheme*

The reactive-decision scheme offers shorter handoff delay by constantly searching for idle channels through spectrum sensing during link transitions. It involves sensing times to identify idle channels and handshaking time for achieving consensus between the transmitter and receiver of a secondary connection. Therefore, different studies focused on characterizing the effects of sensing time and handshaking time on handoff delay in the reactive-decision spectrum handoff scheme. By examining the channel usage behaviours of CR networks, the extent to which channel utilization can be improved with multiple handoffs can be determined. For instance, the ON/OFF random process (Heo, Junghyun; Shin, Jungchae; Nam, Jihee ; Lee, Yutae; Park, Joon Goo; Cho, Ho-Shin, 2008), M/M/m queuing model (Zhang, Yan, 2009), multi-dimensional Markov chain, and M/G/1 queuing model have been utilized. In (Heo, Junghyun; Shin, Jungchae; Nam, Jihee ; Lee, Yutae; Park, Joon Goo; Cho, Ho-Shin, 2008), the ON/OFF random process was employed to model the channel usage behaviours of primary users, considering the geometrically distributed ON (busy) and OFF (idle) periods at each channel. Although this model captured the spectrum opportunities for secondary users during primary users' absence, it did not account for the effects of sensing time. Consequently, an analytical model that examined the impact of sensing time on the extended data delivery time of secondary users was proposed in (Wang, Li-Chun; Chen, Anderson, 2008). However, this model assumed the availability of at least one channel after sensing, overlooking the possibility of all channels being busy. Therefore, the ON/OFF random channel usage model is not applicable for the heterogeneous arrival rates of primary users, various arrival rates of secondary users, and the handoff service time. The M/G/m queuing model was utilized to characterize the channel usage behaviours of primary users in (Zhang, Yan, 2009), considering both opportunistic and negotiated situations. While this model investigated the waiting time for secondary users when no idle channels were available, it did not incorporate the effects of sensing time.

The multiple-dimensional Markov chain proposed by Rashid et al. (Rashid, Mohammad M.; Hossain, Md. Jahangir; Hossain, Ekram; Bhargava, Vijay K., November 2007) described channel state, queue length, and the number of interfered channels but was more suitable for CR networks with homogeneous traffic load rather than the heterogeneous arrival rates of primary and secondary users. Additionally, in (Suliman, Isameldin; Lehtomaki, Janne; Braysy, Timo; Umebayashi, Kenta, September 2009)-[16], a two-dimensional Markov chain model was employed to characterize spectrum usage behaviours in both primary and secondary networks. Blocking probability and forced termination probability were analysed as performance measures for spectrum handoff and secondary users' connections, respectively. In (Suliman, Isameldin; Lehtomaki, Janne; Braysy, Timo; Umebayashi, Kenta, September 2009), (Mihov, Yakim Y.; Tsankov, Boris P., September 2011), blocking probability was studied as a performance measure of the spectrum handoff performance while forced termination probability with instances of queue and no queue was analysed for the performance measures of secondary users' connections in (Tang, Shensheng; Mark, Brian L., November 2007), (Tang, Shensheng; Mark, Brian L., 2009). The case of endless user population was discussed in (Suliman, Isameldin; Lehtomaki, Janne; Braysy, Timo; Umebayashi, Kenta, September 2009) – [14] and blocking probability was derived in (Tang, Shensheng; Mark, Brian L., April 2008), (Wong, Eric W. M.; Foh, Chuan Heng, 2009). However, these models did not fully address the effects of sensing time during reactive-decision spectrum handoff.

To overcome these limitations, a M/G/1 queuing model was proposed in (N, 2007) to characterize secondary user channel usage behaviours in a single-channel CR network. This model assumes that each secondary user can concurrently utilise all idle channels for data transmission. The author suggested using the M/G/1 queuing system to characterize the non-trivially distributed service time. This is because the total number of idle channels depends on the number of channels occupied by the primary users. Also, the service rates of the secondary users are related to the traffic statistics of the primary users that makes the distributed service time non-trivial. This model is applicable for characterizing both heterogeneous arrival rates of primary users and various arrival rates of secondary users on channel utilization and latency performance. However, it did not account for the effects of handoff service time in the reactive-decision spectrum handoff scheme. To address this, (Zhang, Wang, & Li, 2009) introduced a spectrum usage behaviour characterization based on the PRP M/G/1 queuing model in a single-channel CR network. The study investigated the effects of multi-user contention and multiple interruptions on extended data delivery time and latency performance. Although it focused on a non-hopping mode with one candidate channel for spectrum handoff, it did not consider the impact of sensing time during reactive-decision spectrum handoff. Instead, it was assumed that the secondary user must stay on the current operating channel to resume their unfinished transmissions during primary user's interruption.

The PRP M/G/1 queuing network model serves as a unifying model for the reactive-decision spectrum handoff to evaluate channel utilizations of each user under various traffic arrival rates and service time distributions. In (Wang, Chung-Wei; Wang, Li-Chun, 2012), the PRP M/G/1 queuing network model was utilised to characterize the channel usage behaviours at each channel and the extended data delivery time in the context of multiple handoffs. By considering heterogeneous arrival rates of primary users, various arrival rates of secondary users, and the handoff service time, the model provides valuable insights into the dynamics of the network. The network was assumed to be a time-slotted system such that the secondary users perform spectrum sensing at the beginning of each time slot to detect the presence of primary users. Thus, enabling the SUs to utilize idle channels during the remaining duration of the slot whenever the current operating channel is sensed idle. If the current operating channel is sensed as busy, secondary users trigger spectrum handoff procedures to find idle channels and resume their unfinished transmissions. To balance traffic loads across channels, a spectrum algorithm preassigns a default channel to each channel in (Wang, Li-chun; Wang, Chung-wei; Adachi, Fumiyuki, 2011). When establishing a new connection, secondary users transmit handshaking signals at the default channel of the intended receiver. However, if the default channel is busy, the secondary transmitter waits until it becomes available as described in (Zhao, Tong, Swami, & Chen, 2007). Furthermore, the extension of the PRP M/G/1 model to incorporate the effects of false alarm and missed detection is discussed in (Wang, Li-chun; Wang, Chung-wei; Adachi, Fumiyuki, 2011).

Another crucial feature of the PRP M/G/1 queuing network model, as presented in (Wang, Chung-Wei; Wang, Li-Chun, 2012), is its ability to handle both high-priority connections from primary users and low-priority connections from secondary users. The study acknowledges the tendency of secondary connections to experience multiple interruptions from primary users during their transmission period, emphasizing the pre-emptive priority in the model. This pre-emptive priority mechanism characterizes the spectrum usage behaviours between primary and secondary connections during multiple spectrum handoffs across different channels [4].

Another feature of the PRP M/G/1 queuing network model, presented in (Wang, Chung-Wei; Wang, Li-Chun, 2012), is the ability of each channel to serve both high priority connections from the primary users and the low priority connections from the secondary. They stated that secondary connections have the tendency to experience multiple interruptions from the primary users during its transmission period and emphasized the pre-emptive priority in the model. The pre-emptive priority which the primary user must interrupt the transmission of the secondary users was eventually used to characterize the spectrum usage behaviours between primary and secondary connections with multiple spectrum handoffs in different channels in (Wang, Chung-Wei; Wang, Li-Chun, 2012). Building upon the assumptions and key features proposed in (Wang, Chung-Wei; Wang, Li-Chun, 2012), this study investigate the impact of various arrival rates for secondary user connections, heterogeneous arrival rates for primary user connections, and handoff service time on channel utilization and latency performance in both reactive-decision and proactive-decision spectrum handoff schemes. By employing the PRP M/G/1 queuing network model, we can analyse the intricate dynamics of the network and provide valuable insights into optimizing channel utilization and reducing latency in cognitive radio systems.

B. *Proactive-decision spectrum handoff scheme*

In the proactive-decision scheme, secondary users engage in the prediction of future channel availability status prior to establishing a data connection. This approach enables secondary users to proactively carry out spectrum switching and RF reconfiguration pre-emptively, before a primary user occupies the channel. The decision-making process relies on observed channel usage statistics, obtained through periodic observations of all channels over an extended duration. By employing this strategy, both the selection of a target channel and the execution of handoff actions are performed proactively, in anticipation of the triggering event.

To characterize the multiple handoff behaviours in CR networks using the proactive spectrum handoff scheme, a general service time distribution, various operating channels and queuing delay due to channel contention from multiple secondary connections are considered in this study. Numerous studies in the literature have proposed modelling techniques for proactive spectrum handoff behaviours. For instance, Zhao et al. (Zhao, Qianchuan; Geirhofer, Stefan; Tong, Lang; Sadler, Brian M., 2008), introduced the Bernoulli random process to effectively describe the spectrum usage behaviours of primary networks on each channel. They examined the impact of multiple interruptions caused by primary users on the probability of connection maintenance in a connection-based environment. These interruptions serve as the rationale for designing a target channel pool for a series of spectrum handoffs within a secondary connection. Connection-based modelling techniques for spectrum handoff, as defined in (SethuRaman, P.S; Rekha, N; Venkatesan, D, 2013), involve combining the effects of multiple interruptions from primary users in an event-driven manner. On the other hand, slot-based modelling techniques depict interruptions to the secondary user in a time-driven manner. In the time-slot-based multiple channel handoff approach, secondary users are required to perform spectrum sensing at the commencement of each time slot to detect the presence of primary connections before proceeding with the handoff process to complete their ongoing transmissions. If the current operating channel is idle, the secondary user can transmit or receive data during the remaining duration of the time slot. Conversely, if the channel is occupied, the secondary user must initiate spectrum handoff procedures to resume its unfinished transmission on the preselected target channel. In essence, the connection-based method characterizes spectrum handoff only during the periods when the primary user becomes active, whereas the slot-based methods facilitate spectrum handoff at each time slot (Wang, Wang, & Chang, 2012).

In previous studies (Zhao, Tong, Swami, & Chen, 2007), (Zhao, Qianchuan; Geirhofer, Stefan; Tong, Lang; Sadler, Brian M., 2008), (Ma, Rui-Ting; Hsu, Yu-Pin; Feng, Kai-Ten, 2009), a discrete-time two-state Markov chain was proposed to characterize the channel usage behaviours. The dynamics of primary network channel occupancy were represented using the Gilbert-Elliot channel model, which is a discrete-time Markov chain with two states: busy (ON) and idle (OFF) occupancy states. The idle state was considered as a potential spectrum opportunity for secondary users. This Markov chain model was employed as a time-based modelling technique, where the secondary user determines its target channel at each time slot. The model successfully characterized exponentially distributed service times with different operating channels. However, it did not address scenarios involving general service time distributions and multiple secondary connections. While the model allowed a secondary user to preselect the optimal target channel to maximize its immediate reward in the next time slot, such as expected per-slot throughput (Zhao, Tong, Swami, & Chen, 2007), (Zhao, Qianchuan; Geirhofer, Stefan; Tong, Lang; Sadler, Brian M., 2008) or expected waiting time (Ma, Rui-Ting; Hsu, Yu-Pin; Feng, Kai-Ten, 2009), it resulted in frequent spectrum handoffs, even when primary users were not present on the current operating channel.

In contrast, a continuous time ON/OFF random process with arbitrary distributed ON/OFF periods was introduced in (Yang, Cao, & Zheng, 2008), (Song, Yi; Xie, Jiang, 2010), (Min, Alexander W.; Shin, Kang G., 2008) to describe the channel usage behaviours of primary networks on each channel, without assuming the Markov property. This process employed a slot-based modelling technique and enabled secondary users to estimate the service time distributions of the ON (busy) and OFF (idle) periods through long-term observations. At each time slot, secondary users calculated metrics such as the average remaining OFF (idle) periods of primary users (Song, Yi; Xie, Jiang, 2010)or the average throughput of secondary users (Min, Alexander W.; Shin, Kang G., 2008). Once these parameters were determined, secondary users promptly switched to the channel offering the highest reward. This channel usage model was suitable for handling general service time distributions and various operating channels but did not address scenarios involving multiple spectrum handoffs.

In their work, Wang et al. (Wang, Beibei; Ji, Zhu; Liu, Ray K. J., 2009) employed a multidimensional Markov chain to characterize the spectrum usage behaviours of both primary and secondary networks. Each state of the Markov chain represented the actions of individual primary and secondary users, including idleness, queue waiting, or communication. The model assumed that secondary users should remain on their current operating channel after experiencing interruptions from primary users, without switching channels. While this analytical model was suitable for single-channel networks, it did not extend to scenarios involving different operating channels in multiple handoff situations.

The Bernoulli random process, discrete-time two-state Markov chain, and arbitrary ON/OFF random process models discussed earlier did not address the impact of secondary users' traffic loads on channel occupancy statistics. Additionally, these models did not provide a clear methodology for incorporating queuing delays resulting from channel contention among multiple secondary connections. However, the multidimensional Markov chain and M/G/1 queuing models were employed to analyse the effects of spectrum sharing among multiple secondary users. Both models assumed that interrupted secondary users would always remain on their current operating channel and did not consider handoff interactions across different channels.

Building on the key features discussed in (Wang, Chung-Wei; Wang, Li-Chun, 2012), Wang et al. (Wang, Li-Chun; Wang, Chung-Wei; Chang, Chung-Ju, 2012) applied a similar analytical framework to the proactive-decision spectrum handoff, using the M/G/1 queuing network model with the PRP. This approach aimed to characterize the spectrum usage behaviours in connection-based multiple channel spectrum handoffs between primary and secondary connections. The model considered general service time distributions of primary and secondary connections, various operating channels, and the queuing behaviours of multiple secondary connections. In contrast to (Wang, Chung-Wei; Wang, Li-Chun, 2012), where the entire connection would be retransmitted, Wang et al. assumed that interrupted secondary users would resume their unfinished transmission. It was acknowledged that the interrupted secondary connection's target channel might differ from its current operating channel when resuming the transmission. Consequently, the study derived a closed-form expression for the extended data delivery time under various traffic arrival rates, service distributions, and proactively designed target channel sequences using the PRP M/G/1 queuing network model (Wang, Li-Chun; Wang, Chung-Wei; Chang, Chung-Ju, 2012).

C. Target Channel Selection

A secondary connection in a CR network may experience multiple interruption requests during its transmission period. Each interruption triggers spectrum handoff procedures, resulting in the sequential selection of a set of target channels. However, identifying a suitable target channel for secondary users to continue their data transmission during spectrum handoff becomes challenging. This challenge stems from the dependency of secondary users on channel capacity, the availability of channels at the time of handoff, and the likelihood of future channel availability (Christian, Moh, Chung, & Lee, 2012). To address this issue, channel selection schemes are employed to evenly distribute the traffic load of secondary users among multiple channels, thereby increasing channel utilization and mitigating channel contention problems.

In reactive-decision spectrum handoff, on-demand or sensing-based channel selection is utilized to identify available and high-quality target channels. In this approach, both the channel search time and the channel switching time play crucial roles in determining the cumulative delay resulting from multiple handoffs within a connection. The impact of channel search time on the cumulative delay of multiple spectrum handoffs has been investigated in prior studies (Wang, Chung-Wei; Wang, Li-Chun, 2012), (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010) using the PRP M/G/1 queuing approach. These studies have revealed that the spectrum sensing time in on-demand channel selection significantly affects the delay experienced during multiple spectrum handoffs.

On the other hand, proactive-decision spectrum handoff confronts the challenge of dealing with the possibility that the preselected target channel may no longer be available. Therefore, a crucial objective of the proactive-decision handoff scheme is to determine optimal sequences of target channels that minimize the total service time in the system. Christian et al. (Christian, Moh, Chung, & Lee, 2012) have identified the selection of poor target channels as a contributing factor to multiple spectrum handoffs within a single data transmission session, which ultimately degrades the overall system performance. Another approach to determining target channels in the proactive-decision spectrum handoff is the use of predetermined channels based on long-term traffic statistics. This predetermined approach facilitates consensus between the transmitter and receiver regarding the target channel sequence. By leveraging long-term traffic statistics, both the transmitter and receiver can identify their target channel sequences for future spectrum handoffs prior to data transmission. This enables secondary users employing the proactive-decision spectrum handoff method to promptly switch to the predetermined target channel, thereby reducing spectrum sensing time. However, it is crucial to address channel obsolescence concerns when implementing the predetermined channel selection approach to mitigate performance degradation.

The predetermined target channel selection approach for spectrum handoffs can be categorized into two main methods: probability-based channel selection and the utilization of Markov decision processes, as discussed in (Wang, Wang, & Chang, 2012). Song et al. (Song & Xie, ProSpect: a proactive spectrum handoff framework for cognitive radio ad hoc networks without common control channel, 2012) proposed a probability-based prediction strategy for predetermining target channels in the spectrum handoff mechanism. Their approach involved equipping secondary users with a transmitting radio for data and control message transmission, as well as a scanning radio to survey all channels within the frequency band and gather channel occupancy information. The probability-based channel selection methods were further refined in subsequent works such as (Gambini, Simeone, Bar-Ness, Spagnolini, & Yu, 2008) and (Lee, Lin, Hsu, & Feng, 2010). Based on the predetermined probabilities, these studies determined the optimal channel hopping sequences on a packet-by-packet or slot-by-slot basis. Gambini et al. (Gambini, Simeone, Bar-Ness, Spagnolini, & Yu, 2008) developed an optimal channel hopping sequence design for scenarios involving a single secondary user, while Lee et al. (Lee, Lin, Hsu, & Feng, 2010) extended this problem to the multiple-secondary-user scenario. Both approaches aimed to maximize per-slot throughput and achieved optimality in the design of the channel hopping sequence. However, it is worth noting that these designs did not explicitly consider latency issues.

The target channel selection problem in each time slot has been further addressed in (Zhao, Tong, Swami, & Chen, 2007), (Zhao, Qianchuan; Geirhofer, Stefan; Tong, Lang; Sadler, Brian M., 2008), (Ma, Rui-Ting; Hsu, Yu-Pin; Feng, Kai-Ten, 2009), (Yang, Cao, & Zheng, 2008), and (Min, Alexander

W.; Shin, Kang G., 2008). Depending on the channel occupancy state at the current time slot, secondary users preselect their target channels to maximize various metrics such as immediate expected per-slot throughput (Zhao, Tong, Swami, & Chen, 2007), (Zhao, Qianchuan; Geirhofer, Stefan; Tong, Lang; Sadler, Brian M., 2008), (Min, Alexander W.; Shin, Kang G., 2008), idle period (Yang, Cao, & Zheng, 2008), and expected waiting time (Ma, Rui-Ting; Hsu, Yu-Pin; Feng, Kai-Ten, 2009). However, these studies primarily focused on analysing the effects of primary users' channel usage behaviours on channel occupancy and did not consider the impact of secondary users' traffic loads on target channel selection for spectrum handoff.

Wang et al. (Wang, Wang, & Adachi, 2009) introduced the PRP M/G/1 queuing network model to evaluate the total service time for different sequences of target channels and derived optimal target channel sequences. The authors proposed a suboptimal greedy target channel selection scheme to alleviate the challenge of finding the optimal target channels. Their approach involved selecting the channel with the shortest handoff delay as the target channel at each spectrum handoff, assuming that each secondary user must wait on the selected target channel until it becomes idle, following the spectrum handoff protocol. The scheme presented in (Wang, Wang, & Adachi, 2009) is independent of the total number of channels and can effectively reduce the total service time compared to a randomly selected scheme. In (Wang, Wang, & Chang, 2012), an optimization problem was formulated to proactively predetermine the target channel selection. This approach aims to minimize the cumulative delay per connection for each newly arriving secondary user. The study considered both channels switching time and waiting time resulting from the channel obsolescence effect, which occurs due to multiple interruptions from primary users in each secondary user's connection, as well as the varying arrival rates and service times for both primary and secondary users, to ensure Quality of Service (QoS). The authors characterized the channel obsolescence effects and spectrum usage behaviour with a series of interruptions in secondary connections by examining the extended data delivery time of the secondary connections. However, it is important to note that this framework does not determine the optimal target channel sequences for all secondary connections simultaneously.

PERFORMANCE ANALYSIS

Several methods have been proposed in the literature to mitigate performance degradation during spectrum handoff. Zhu et al. [(Zhu, Shen, & Yum, 2007) suggested reserving a specific number of channels for potential spectrum handoff to mitigate long delays. This approach enables secondary users to quickly select a channel from the reserved band when it becomes necessary to switch frequencies. However, reserving too much bandwidth for spectrum handoff can lead to low throughput since primary users may not always reclaim their licensed band in a proactive-decision scheme. Zhu et al. discussed the trade-off involved in optimizing channel reservation for spectrum handoff, aiming to minimize blocking probability and maximize secondary user throughput.

In (Feng, Cao, Zhang, & Liu, 2009), a joint spectrum handoff scheduling and routing protocol was proposed for multi-hop multi-radio cognitive radio networks, with the objective of minimizing total handoff latency while ensuring network connectivity. This protocol extends the spectrum handoff mechanism from a single link to multiple links. To ensure reliable continuous communication among secondary users in the presence of random reclaims by primary users, secondary users should select their channels from different licensed bands owned by different primary users. Kushwaha et al. (Kushwaha, Xing, Chandramouli, & Heffes, 2008) emphasized that the utilization of multi-band spectrum diversity helps reduce the impact of primary user appearances and improve the reliability of spectrum access.

Analytical frameworks play a crucial role in analysing the performance and understanding the operation of spectrum handoffs. However, most prior works on channel allocation in spectrum handoffs (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010), (Yang, Cao, & Zheng, 2008), (Wang, Wang, & Adachi, 2009) have focused on scenarios involving two secondary users. In these scenarios, secondary users greedily select channels based on criteria such as minimum service time (Wang, Wang, & Adachi, 2009) or highest probability of being idle (Yang, Cao, & Zheng, 2008). The proposed models in (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010) and (Wang, Wang, & Adachi, 2009) do not consider interference and interactions among secondary users, which can significantly impact network performance, particularly in terms of total service time for secondary user communications during proactive and reactive-decision spectrum handoffs. Furthermore, these models assume that a secondary user transmitting pair can immediately perform channel switching when a primary user appears on the current channel, without accounting for the associated handoff delay.

To further investigate the performance of spectrum handoff decision schemes, it is necessary to consider the effects of multiple spectrum handoffs on total service time and handoff delay. Wang et al. (Wang, Li-Chun; Wang, Chung-Wei; Chang, Chung-Ju, 2012) defined service time as the period from the start of transmission to its completion, while handoff delay was defined as the period from pausing transmission to the resumption of transmission in (Wang, Li-Chun; Wang, Chung-Wei, 2008). In the case of interruption, the spectrum handoff procedure is initiated immediately, and the interrupted user selects the target channel according to the prescribed handoff schemes to resume the unfinished transmission for both reactive-decision and proactive-decision spectrum handoffs. However, consecutive channel switching increases the total service time and average handoff delay for interrupted users, which can impact the Quality of Service (QoS) for secondary users.

In (Wang, Li-Chun; Wang, Chung-Wei; Feng, Kai-Ten;, 2011), an analytical framework based on the PRP M/G/1 queuing theory to assess the Quality of Service (QoS) performance of spectrum handoff techniques in the hopping mode was presented. The framework addressed the design of a load balancing spectrum decision scheme and evaluated the latency performance of various spectrum handoff schemes. Song et al. (Song & Xie, On the Spectrum Handoff for Cognitive Radio Ad Hoc Networks Without Common Control Channel, 2011) further discussed the possibility of collisions between secondary users and primary users during spectrum handoff. In such cases, an interrupted secondary user may be required to retransmit the entire connection if a packet collides with another transmission. Retransmission in the analysis of spectrum handoff performance in cognitive radio networks remains an open issue and a subject of ongoing research discussion. However, Song et al. proposed a Markov model that incorporated the retransmission of collided packets and assessed the latency performance using transmission policies.

The impact of repeated spectrum handoff delays on the total service time in cognitive radio networks was investigated in [39]. Zahed et al. proposed a prioritized queuing handoff model to effectively manage spectrum usage by primary users, secondary users, and interrupted secondary users. In (Wang, Li-Chun; Wang, Chung-Wei, 2008), (Heo, Junghyun; Shin, Jungchae; Nam, Jihee ; Lee, Yutae; Park, Joon Goo; Cho, Ho-Shin, 2008), (Wang, Wang, & Adachi, 2009), it is possible for interrupted secondary users to switch their operating channel after an interruption event without giving priority to existing secondary users before resuming unfinished transmission on the new target channel. This, however, leads to repeated spectrum handoff and increased handoff delay. Moreover, handoff delay and total service time are further increased when interrupted secondary users are required to join the queue of uninterrupted secondary users on the new channel. While the study in (Zahed, Salah; Awan, Irfan; Min, Geyong, 2012) adopted prioritized schemes that gave higher priority to interrupted users in accessing idle channels over other uninterrupted secondary users, it did not utilize analytical models. Tumuluru et al. (Tumuluru, Vamsi Krishna; Wang, Ping; Niyato, Dusit; Song, Wei, 2012) investigated prioritized secondary user traffic and proposed centralized and distributed schemes to manage different handoff mechanisms for prioritized secondary users in a general setting where primary user transmissions can occur at any time instant. The proposed dynamic spectrum access (DSA) schemes were analysed using continuous-time Markov chains to derive the mean handoff delay for different priority levels of secondary users.

1. *Spectrum Handoff Procedure for CR Networks*

The mechanism of spectrum handoff has been discussed in (Han, C.; Wang, J.; Li, S., 2006) and (Shi, Q.; Taubenheim, D.; Kyperountas, S.; Gorday, P.; Correal, N., 2007). According to (Wang, Li-Chun; Wang, Chung-Wei, 2008), this mechanism involves the following steps:

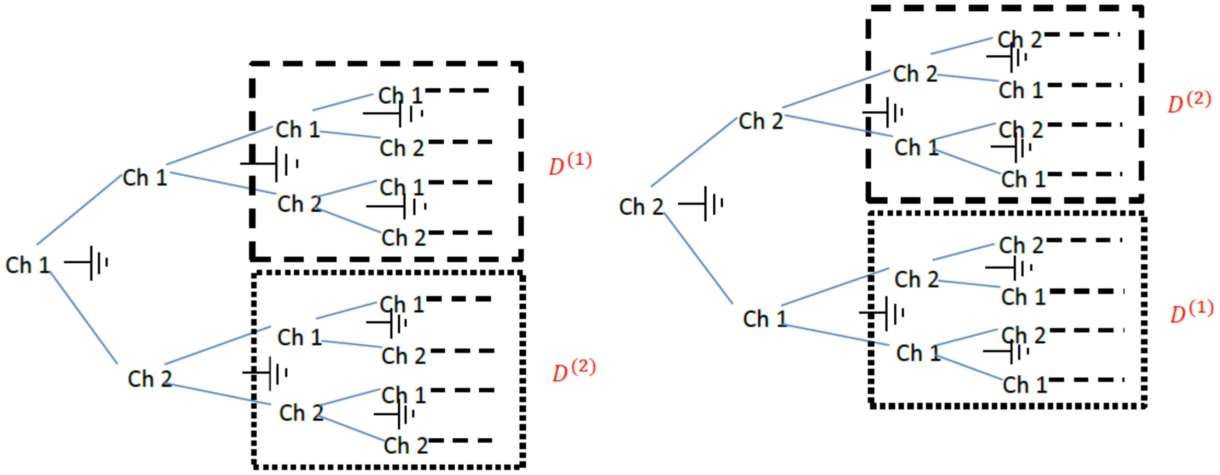
1. Communication on channel Ch1 involves secondary users SU1 and SU2.
2. SU1 is capable of detecting the presence of primary users on Ch1 and prepares to initiate the spectrum handoff procedure.
3. As a result, SU1 temporarily pauses its ongoing communication within a predetermined duration and notifies SU2 of the interruption event within a predefined time interval.
4. Afterwards, SU1 and SU2 can resume their transmission on the selected target channel.
5. This spectrum handoff procedure may be repeated multiple times since the secondary user's transmission could experience numerous interruptions.

Various target channel selection methods for spectrum handoff, as discussed earlier, can be employed to choose the target channel, leading to varying handoff delays.

2. *Delays for Spectrum Handoffs*

The handoff delay experienced by an interrupted secondary user is primarily determined by the chosen target channel. In the context of proactive-decision spectrum handoff, achieving consensus between the transmitter and receiver regarding their target channel can effectively reduce handoff delay compared to reactive-decision spectrum sensing. However, in order to minimize the total service time for proactive-decision spectrum handoff, it becomes necessary to determine the optimal sequence of target channels.

In (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010), the authors derived the cumulative handoff delay in a two-channel system and represented the Markov transition model expression for target channel selection as a tree-structured representation, illustrated in Fig. 1(a) and 1(b). Both figures considered the cases where the secondary connections' default channels were Ch1 and Ch2, respectively. In both cases, the grounding signs indicate the ending of state transition.



(a) Channel 1 (b) Channel 2

Figure 1: Tree-structured representation

3. *PRP M/G/1 Queuing Network*

In this study, the PRP M/G/1 queuing network model, proposed in (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010) and (Wang, Wang, & Adachi, 2009), is employed to analyse the conditions for utilizing reactive-decision and proactive-decision spectrum handoffs based on the sensing time. The model utilizes the following key properties:

1. Pre-emptive priority: Primary users are granted priority to interrupt the ongoing transmission of secondary users.

2. Resumption of unfinished transmission: Rather than retransmitting the incomplete communication, the interrupted secondary user can resume the transmission from where it was interrupted.

It is important to note that the interrupted secondary user's current operating channel may not be the same as its target channel.

In Fig. 2, a prioritization scheme was employed where primary users were assigned to the high-priority queue, while secondary users were allocated to the low-priority queue. When a primary user interrupts the communication of a secondary user, the secondary user has two options: either remain on the current channel or switch to another operating channel. In the case of a channel switch, the unfinished communication is placed at the tail of the low-priority queue of the new channel. If the secondary user chooses to stay on the current channel, the unfinished communication can be placed at the head of the low-priority queue for that channel. The transmission can then resume once the channel becomes idle.

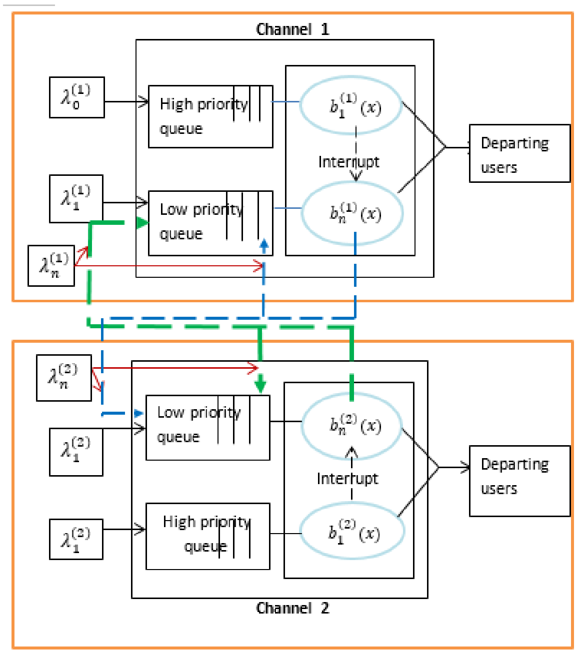


Figure 2: PRP M/G/1 queuing network for two-channel system where n≥1

A crucial parameter in the PRP M/G/1 queuing network model is the effective transmission time, which represents the duration of transmission from the moment a transmission begins or communication resumes until the interruption event occurs (Wang, Li-Chun; Wang, Chung-Wei, 2008). However, it should be noted that when a primary user interrupts a secondary user, the secondary user may only successfully transmit a partial message to the intended receiver. In such cases, the effective transmission time corresponds to the duration of transmission for the partial message. The PRP M/G/1 queuing network model can serve as an effective tool for modelling the spectrum handoff mechanism in cognitive radio networks, as highlighted in (Wang, Li-Chun; Wang, Chung-Wei, 2008).

4. *Analysis of Transmission Latency*

The closed-form expressions for transmission latency in both reactive-decision and proactive-decision spectrum handoffs were derived by the authors in (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010) and (Wang, Wang, & Adachi, 2009). In (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010), the authors simplified the notations by assuming that all channels have the same traffic parameters, thereby dropping the superscript k. Given λ_p and λ_s as the arrival rates of the primary users and secondary users' connections at each channel respectively, and X_p (slots/arrival) is the corresponding service time for the primary users' connection, while X_s (slots/arrival) represents the corresponding service time for secondary users' connection with μ_p and μ_s as exponentially distributed rates for both primary and secondary users' connections respectively. The performance measure that the secondary user's connection will experience is given by (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2009) :

$$E[Y_p] = \frac{E[X_p]}{1 - \lambda_p E[X_p]}, \quad (1)$$

$$p = \frac{\lambda_p}{\lambda_p + \mu_s}, \quad (2)$$

and

$$\rho = \lambda_p E[X_p] + \frac{\lambda_p}{\lambda_p + \mu_s}\left(1 + \frac{\lambda_p}{\mu_s}\right), \quad (3)$$

Assume without generalization that the channel switching time is zero, the cumulative delay can be obtained by equating $E[D^{(1)}] = E[D^{(2)}]$ for the secondary users' connections.

Similar to (Wang, Li-Chun; Wang, Chung-Wei, 2008), suppose a two-channel system where identical traffic parameters is assumed for each channel, k can be eliminated from all the system parameters. Let $\mu_s = 1/E[X_s]$, the transmission latency for reactive-decision spectrum handoff is expressed as (Wang, Li-Chun; Wang, Chung-Wei, 2008):

$$E[L_{reactive}] = E[X_s] + \frac{\lambda_0[t_p\mu_s + (E[X_0])^2\lambda_0\mu_s + E[X_0](\lambda_s - t_p\lambda_0\mu_s)]}{(1 - \lambda_0 E[X_0])(\mu_s{}^2)}, \quad (4)$$

where t_p is the processing time and it is the sum of the channel switching time (t_s) and the channel sensing time (t_f).

It is appropriate to choose the shortest handoff delay as the target channel at each spectrum handoff for the handoff latency to be minimized. In this case, there exists only two possible target channels sequence since each channel has identical traffic patterns. The first possible permutation of target channel sequence is the always-stay case where the interrupted user will always stay on its default channel until it completes its transmission. Therefore, the average transmission latency can be expressed as (Wang, Li-Chun; Wang, Chung-Wei, 2008):

$$E[L_{stay}] = E[X_s] + \lambda_0 E[X_s]\frac{E[X_0]}{1 - \lambda_0 E[X_0]}. \quad (5)$$

The other possibility is the always-change possible permutation of target channel sequence where the target channels will alternatively switch between two channels to reduce the handoff latency. Based on the estimated total service time given in (Wang, Wang, & Adachi, 2009), it is easy to decide which permutation is a better strategy to use. Hence, the average transmission latency for the always-change case is given as (Wang, Li-Chun; Wang, Chung-Wei, 2008):

$$E[L_{change}] = E[X_s] + E[N]\left(\frac{\lambda_0(E[(X_0])^2 + \frac{\lambda_s}{(\lambda_0+\mu_s)\mu_s} + \frac{\rho_0^2}{1-\rho_0}E[X_0]}{1-\rho_0-\rho_s} + t_s\right), \quad (6)$$

where t_s is the switch time of the channel, $\rho_0 = \lambda_0 E[X_0]$, and $\rho_s = \lambda_s E[X_s]$. More so, the optimal transmission latency can be expressed in the proactive-decision scheme as follows:

$$L_{proactive} = \min\{E[L_{stay}], E[L_{change}]\}, \quad (7)$$

NUMERICAL RESULTS

1. *Effects of λ_p on the average cumulative handoff delay*

Fig. 3 shows the effects of λ_p on the average cumulative handoff delay. The result indicate that the cumulative handoff delay increases as λ_p increases. This is because a larger value of λ_p yields a higher interruption probability for a secondary user's connection.

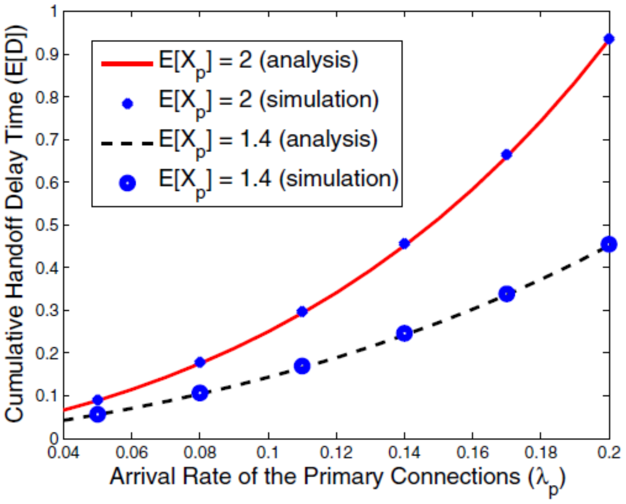


Figure 3: Average cumulative handoff delay of the secondary connections where $\boldsymbol{\delta} = 0$, $\boldsymbol{\lambda_s} = \mathbf{0.15}$ and $\mu_s = \mathbf{0.5}$.

2. *Cumulative handoff delay for different target channel selection schemes*

Fig. 4 illustrates the cumulative handoff delay resulting from different target channel selection schemes, as computed in (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010). The findings indicate that the cumulative handoff delay increases as the mean service time of primary users' connections ($E[X_p]$) increases. This is attributed to the longer delay experienced during each handoff when an interrupted secondary user opts to remain on its current operating channel.

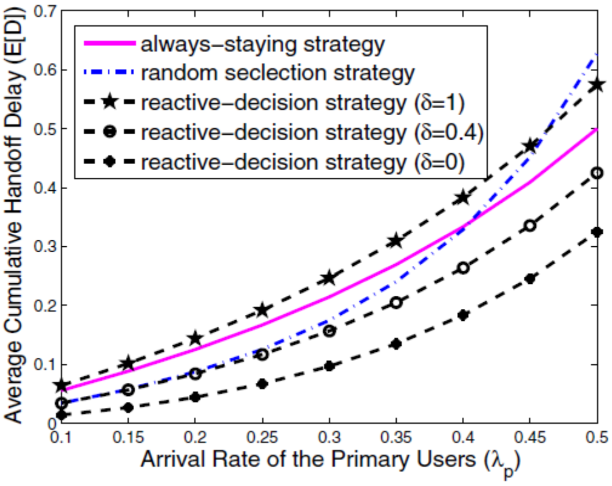


Figure 4: Comparison of the cumulative handoff delay for different target channel selection schemes where $\boldsymbol{\lambda_s = 0.3 E[X_p] = 1}$and $\mu_s = \mathbf{2}$.

The results also demonstrate the effectiveness of the "always-stay" strategy, primarily employed in proactive-decision spectrum handoff, where the interrupted user consistently stays on its default channel to resume its unfinished communication. Comparatively, the random selection strategy, which involves the interrupted user randomly choosing a target channel from all available channels, results in a longer cumulative handoff delay, particularly as the arrival rate of primary users (λ_p) increases. This can be attributed to the higher likelihood of target channels being occupied, necessitating additional waiting time for interrupted users utilizing the random selection method. However, it should be noted that the reactive-decision selection strategy, which leverages spectrum sensing to reliably identify idle channels, may yield the shortest cumulative handoff delay under optimal sensing conditions (Wang, Chung-Wei; Wang, Li-Chun; Adachi, Fumiyuki, 2010). This approach demonstrates its ability to effectively minimize handoff delay by promptly identifying and utilizing idle channels. Nevertheless, as the sensing time increases, the cumulative handoff delay of the reactive-decision spectrum handoff deteriorates, surpassing that of the random selection method. Therefore, it is crucial to consider the trade-off between sensing time and cumulative handoff delay when employing the reactive-decision spectrum handoff scheme. At a certain sensing time, the reactive-decision spectrum handoff can effectively reduce the average cumulative handoff delay compared to the always-stay strategy.

3. *Effect of Primary User Arrival Rate on Total Service Time*

Considering a two-channel system, as depicted in (Wang, Wang, & Adachi, 2009), it can be assumed that high-priority users possess the ability to interrupt the transmission of low-priority users. Furthermore, each channel operates on a collision-free basis, where users of the same priority access the channel using a first-come-first-served (FCFS) scheduling discipline. Comparing the total service time under the always-stay scenario with the always-change situations can be used to evaluate the system's performance. Additionally, the total service time of spectrum handoff can be examined using both the random target channel selection model and the greedy target channel selection approach.

The results, presented in Fig. 5, indicate that a lower value of λ_p (arrival rate of primary users) leads to a reduced total service time when employing the greedy strategy compared to the random selection approach. The greedy strategy, which prioritizes selecting target channels based on a certain criterion, demonstrates its potential to optimize the total service time, particularly under conditions of lower primary user arrival rates. Conversely, the random selection method may yield higher total service time due to the uncertainty associated with randomly chosen target channels. In this context, the impact of employing a greedy target channel selection strategy on the total service time was found to be particularly pronounced under higher values of λ_p. Moreover, when the service rate μ_s for secondary users is small, it was observed that the waiting time for an interrupted user may become prolonged after transitioning to a different channel. Consequently, it is advisable to allow the interrupted user to remain on the same channel to mitigate the potential increase in waiting time. This observation suggests that the choice between changing channels and staying on the current channel should be made based on the specific system parameters, particularly the relative values of λ_p and μ_s in order to optimize the total service time during spectrum handoff.

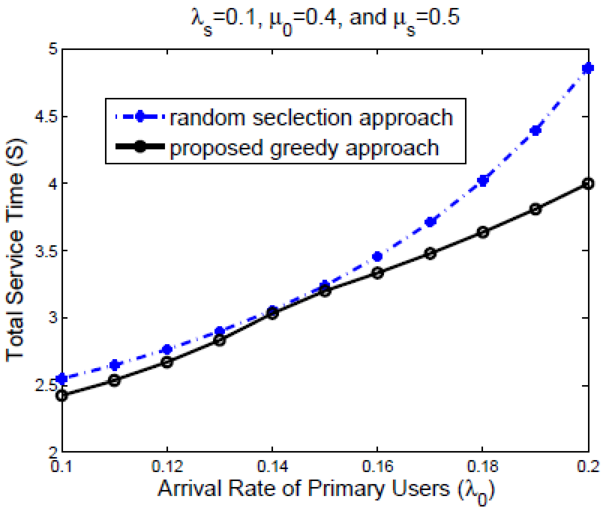


Figure 5: Comparison of total service time for random and greedy strategies. Assume $t_s = 0$

4. *Performance comparison of the transmission latency for reactive and proactive decision schemes*

The performance evaluation of transmission latency in spectrum handoff schemes, including reactive-decision and proactive-decision approaches is shown in Fig. 6, as described in (Wang, Li-Chun; Wang, Chung-Wei, 2008) and (Wang, Li-Chun; Wang, Chung-Wei; Feng, Kai-Ten;, 2011). In the study involving a two-channel system, conducted in (Wang, Li-Chun; Wang, Chung-Wei; Feng, Kai-Ten;, 2011), different arrival rates were considered. By leveraging the PRP M/G/1 queuing network model, a traffic-adaptive proactive-decision handoff scheme was devised, allowing for dynamic adaptation to a more suitable target channel sequence based on the prevailing traffic conditions.

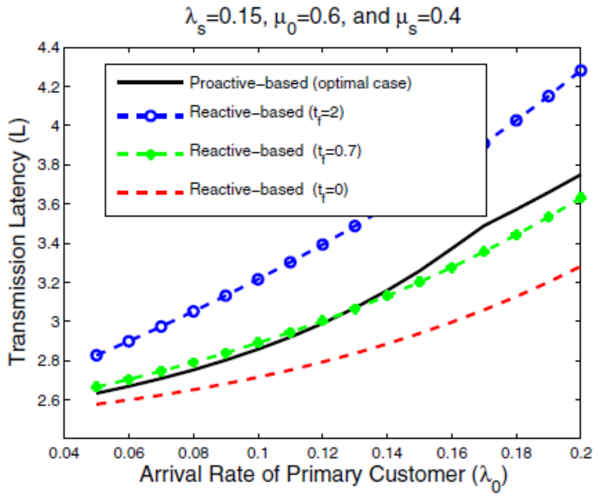


Figure 6: Comparison of transmission latency for different spectrum handoff schemes. $t_s = 0$ and $\mu_0 = 1/E[X_0]$

In the scenario where the ideal case is considered, that is, the sensing time (t_f) for spectrum handoff is assumed to be zero, the transmission latency can be effectively reduced by adopting the reactive-decision spectrum handoff scheme as opposed to the proactive handoff scheme, regardless of the arrival rates of the primary connections. However, it is important to note that an increase in transmission latency associated with the reactive-decision spectrum handoff scheme correlates with an increase in the sensing time. Consequently, this diminishes the performance of the reactive-decision spectrum handoff scheme in terms of transmission latency when compared to the proactive-decision spectrum handoff scheme.

CONCLUSION

This survey has provided a comprehensive exploration of spectrum management and adaptive protocols in CR networks, with a specific focus on spectrum handoff. Spectrum handoff involves the seamless transfer of ongoing transmissions from occupied frequency bands to available ones. The survey has discussed various target channel selection techniques for spectrum handoff, which have proven effective in maximizing per-slot throughput, reducing latency in spectrum handoff, and minimizing cumulative delay in multiple handoffs. Furthermore, the survey has highlighted the utilization of Markov chain models and queueing networks for analysing spectrum handoff schemes. It has also emphasized the importance of employing proactive or reactive sensing strategies based on the sensing time. These analytical approaches enable a deeper understanding of the effects of spectrum handoff on data delivery time, channel utilization, and latency performance in CR networks. As CR networks continue to evolve, further investigations are warranted to enhance the efficiency and effectiveness of spectrum management and adaptive protocols, ultimately contributing to the advancement of dynamic spectrum utilization in CR networks.

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