Spectrum Mobility in Cognitive Radio Networks

Ivan Christian, Sangman Moh, Ilyong Chung, and Jinyi Lee, Chosun University

ABSTRACT

Cognitive radio networks (CRNs) offer a promising solution for spectrum scarcity problem by means of dynamic spectrum access. So long as in highly dynamic environments, the secondary user (SU) communication is often interrupted, spectrum mobility is a key feature enabling continuous SU data transmission. Namely, SU performs spectrum handoff by transferring ongoing communication to a vacant channel. This article discusses some important features of spectrum mobility in CRNs. Qualitative comparison of various handoff strategies is considered with regard to handoff latency. Furthermore, essential design issues and associated research challenges are also addressed.

INTRODUCTION

Rapid development of wireless networking technology has raised a large demand for spectrum band. Whereas the number of devices utilizing unlicensed industrial, scientific, and medical (ISM) band is growing, the allocated spectrum remains the same. This spectrum scarcity problem happens because the current static spectrum allocation policy used by governmental agencies is unable to accommodate the growing bandwidth demand. In fact, exclusively allocated licensed spectrum bands whose availability varies both spatially and temporally, are proved to be underutilized. Meanwhile, a large portion of spectrum in UHV and VHF range will become available in the future upon completing the transition to digital TV [1]. This so-called TV white space calls large interest because radio frequency of the respective spectrum bands has a number of advantageous characteristics that would open numerous new wireless applications in the future.

Cognitive radio (CR) is a key enabling technology in dynamic spectrum access (DSA). CR networks (CRNs) can maximize the use of bandwidth resources without changing well-established regulation of spectrum allocation. Owing to spectrum awareness, CR enabled devices or secondary users (SUs) can make use of unoccupied licensed spectrum bands opportunistically when the legacy devices or primary users (PUs) are idling. Thus, CRN becomes a compelling solution to the spectrum scarcity problem.

In [2, 3], spectrum management framework is introduced, where a CRN system executes four interrelated functions: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. In spectrum sensing, CR nodes search for spectrum holes in licensed spectrum bands that can be used for SU communication. Based on spectrum sensing results, CR nodes decide on the best available communication channel. Spectrum sharing coordinates channel access among the CR nodes. Finally, when a PU reclaims a licensed channel temporarily occupied by a SU, spectrum mobility suspends the transmission, vacates the channel, and resumes ongoing communication using another vacant channel.

Spectrum mobility is a challenging topic for various research activities related to heterogeneous networks and CRNs. In this article, spectrum mobility in CRNs is examined with respect to spectrum handoff. Various spectrum handoff strategies are reviewed and compared qualitatively. The comparison shows that even a simple strategy can achieve satisfactory performance for sparse communication needs, whereas more advanced adaptive handoff strategies are required to gain highest benefit as a trade-off for higher computation effort. Then, we discuss current issues and research challenges in spectrum mobility.

The rest of the article is organized as follows: In the following section, some background concepts are overviewed. We introduce design issues in spectrum mobility. Different spectrum handoff strategies are classified, technically reviewed, and qualitatively compared. We discuss current issues and research challenges. Finally, the conclusions of the article are presented.

PRELIMINARIES

COGNITIVE RADIO NETWORK ARCHITECTURE

From network architecture standpoint, CRN differs from legacy wireless networks in that it considers spatial and temporal spectrum heterogeneity and distinguishes legacy (PU) and opportunistic (SU) users. A general classification of CRNs is illustrated in Fig. 1 where infrastructure-based and non-infrastructure-based CRNs [3] are depicted.

Infrastructure-based CRNs have a base CR station (i.e., a local centralized entity), which organizes CR communication in a single-hop

0163-6804/12/$25.00 © 2012 IEEE

environment, in much the same way it works in cellular systems. As a rule, CR nodes are responsible for spectrum sensing and the base station performs other functions such as spectrum decision, spectrum sharing, and spectrum mobility.

On the other hand, in non-infrastructure-based CRNs, which are also known as CR ad hoc networks (CRAHNs), distributed communication is performed between CR nodes in a multihop environment. Having no centralized entity to organize the network, CR nodes are responsible for performing all spectrum-related functions by means of collaboration. As a consequence, cooperation between CR nodes is of great importance for high performance CRAHNs.

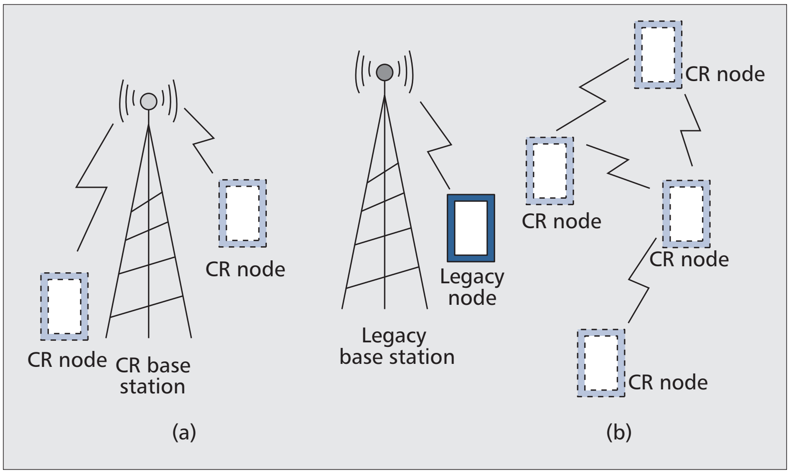

Figure 1. *A legacy network together with: a) a cognitive radio network (CRN) and b) a cognitive radio ad hoc network (CRAHN).*

Spectrum Handoff

The primary objective of spectrum mobility in CRNs is to perform seamless channel switchover while sustaining performance of ongoing SU communication. To this end, spectrum mobility is divided into two processes: spectrum handoff and connection management. Spectrum handoff is the process of transferring ongoing data transmission from the current channel to another free channel. This naturally causes additional latency to SU communication that eventually affects SU performance. To compensate the unavoidable handoff delay, connection management process manages and adjusts protocol stack parameters depending on current situation.

There are two PU related events that can trigger spectrum handoff in CRNs. First, PU arrival in the licensed channel necessarily forces SU to perform spectrum handoff. Second, spectrum handoff can occur because of CR user mobility. As CR users moves spatially, there is a chance that transmission coverage of the SU overlaps with a PU currently using the same channel band. Being opportunistic users in licensed spectrum bands, SUs' activity in legacy networks shall conform to the ground rule: PUs always have higher priority in using licensed spectrum than SUs. As a consequence, if SU arrival causes interference to PU data transmission, the SU shall leave the licensed channel immediately.

In addition, SUs can also perform spectrum handoff because of link quality degradation. Since the radio spectrum of CRNs is predominantly occupied by users outside the control of SUs, the quality of the communication channel in CRNs may in particular vary dynamically over time and space. Thus, it is important for SUs to monitor and analyze periodically the quality of the channel being used for data transmission. If channel quality tends to degrade in the future, spectrum handoff is required to maintain the QoS level.

Spectrum handoff can be explained as cyclic process as shown in Fig. 2. It consists of two phases [4]: evaluation phase and link maintenance phase. In evaluation phase, SU observes the environment and analyzes whether handoff triggering events occur. Once SU decides to perform spectrum handoff, it goes into link maintenance phase. In this phase, SU first pauses the ongoing transmission. Then SU hands over the reclaimed channel to PU and resumes data transmission session over another free channel. Finally, SU leaves link maintenance phase and resumes the cycle. Note that backup target channel can be searched either in evaluation or in link maintenance phase depending on whether proactive or reactive handoff is used.

Performance Measurement

To measure spectrum mobility performance, several parameters have been proposed [4, 5]. The number of spectrum handoff is defined as the number of handoffs occurring during one session of SU data transmission. Link maintenance probability is the probability that the communication link is successfully maintained when SU vacates the channel. Handoff latency is defined as the delay resulting from spectrum handoff process, and effective data rate is the average amount of data which is successfully transferred between two communicating SUs in each session. Among these parameters, link maintenance probability and handoff latency are key performance metrics for spectrum mobility.

The correlation between these parameters is explained as follows: From SU point of view, increasing the number of spectrum handoffs increases link maintenance probability. However, at the same time, this also reduces effective data rate per connection. On the other hand, from PU point of view, handoff latency becomes the main concern. The greater the handoff latency to the SU is, the greater the interference to the PU is.

In general, spectrum mobility techniques with higher link maintenance probability and lower handoff latency give better spectrum agility to CRNs. In order to achieve high performance in spectrum mobility, multiple spectrum handoffs should be avoided if possible.

Design Issues in Spectrum Mobility

This section briefly discusses design issues in spectrum mobility.

PU Detection

Sensing speed and accuracy in spectrum sensing are two important factors for efficient spectrum mobility. In fact, there is a trade-off between the two. Fast sensing speed would lead to less accu-

Sensing speed and accuracy in spectrum sensing are two important factors for efficient spectrum mobility. In fact, there is a trade-off between the two. Fast sensing speed would lead to less accurate sensing output. In addition, recent spectrum sensing techniques are also prone to imperfect sensing results.

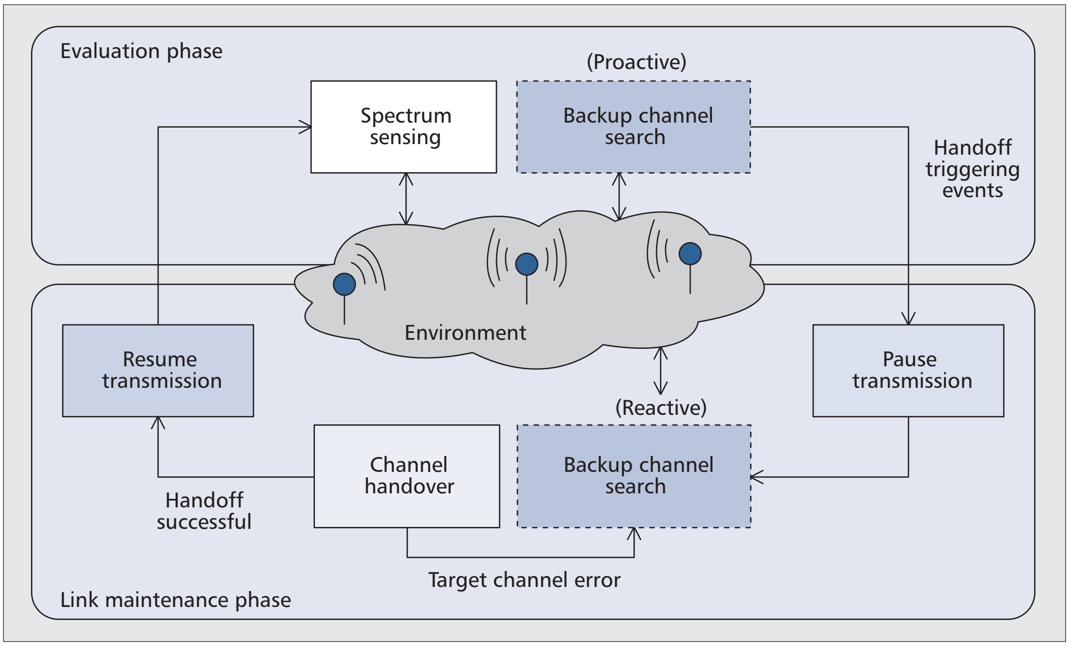

Figure 2. *Spectrum handoff process.*

rate sensing output. In addition, recent spectrum sensing techniques are also prone to imperfect sensing results due to radio propagation effects, such as channel fading or shadowing.

To increase sensing speed and accuracy, CR nodes can select other idle CR nodes as partners to perform cooperative spectrum sensing instead of local sensing. In [6], a cross-layer protocol called ESCAPE (Embedded Spectrally Agile Radio Protocol for Evacuation) using cooperative spectrum sensing in CRAHNs was suggested. Specifically, CR nodes are divided into evacuation groups and each group shares the same CDMA spreading code. If PU arrival is detected, warning messages are spread periodically to the entire group.

Handoff Decision

Generally SUs use spectrum overlay technique where radio signals are transmitted with a power above PU noise level. In contrast, SUs with underlay technique transmit radio signals with a power below PU noise level so that both SU and PU can use the same licensed band at the same time. Nevertheless, if the aggregate interference to the PU exceeds a certain threshold, SU should leave the licensed band. Therefore, spectrum handoff decision is an important issue even in CRNs with spectrum underlay technique.

In [7], fuzzy logic based spectrum handoff algorithm in multihop underlay CRAHNs is proposed. Using fuzzy logic controller, SU will first adjust the transmitting power of the radio signal. If power adjustment is unlikely to lower the aggregate interference, then SU should do spectrum handoff.

Target Channel Selection

Finding a suitable target channel over which a SU can continue data transmission session is the most pressing issue in CR research related to spectrum mobility. In fact, target channel selection for spectrum handoff is a non-trivial task, because it depends on many factors, such as channel capacity, channel availability at the time of handoff, and probability of channel being available in the future. Poor target channel selection can cause multiple spectrum handoffs in a single data transmission session that degrades overall performance.

The most common approach to this issue is using backup channel list (BCL). SU anticipates spectrum handoff by listing potential target channels into BCL and maintaining it periodically between communicating peers. IEEE 802.22 Wireless Regional Area Network (WRAN) Standard adopts this approach [8]. Another approach is predicting target channel availability. Using prediction, partial spectrum sensing rather than conventional full sensing can be performed to reduce sensing delay during spectrum handoff [9]. Also, instead of relying only on sensing result, SU can get accurate target channel selection based on historical spectrum statistics. In [10], a proactive channel access algorithm using both spectrum sensing results and spectrum statistics to determine a handoff target channel is suggested. Assuming that PU arrival pattern is not statistically random (because it depends on human behavior) PU traffic can be modeled so that SU can estimate both channel availability and the length of time that channels will be available. As a result, intelligent target channel selection can be performed.

Routing Recovery

Routing recovery is another important issue in spectrum handoff that requires careful planning. Spectrum handoff is likely to cause route breaking. Accordingly, SU is required to recover the routing table to maintain network connectivity. In fact, routing recalculation is a costly process in terms of time and resource consumption. Therefore, routing recovery process should be integrated in spectrum handoff schemes.

A few works in CR routing have been proposed to anticipate spectrum handoff, all of which attempt to keep network connectivity. One approach is to recalculate a new route and to perform spectrum handoff once a new routing table is ready. Another approach is to avoid routing recalculation by preparing two redundant channels (data channel and backup channel) before starting data transmission. SU maintains the backup channel periodically so that the communication link can be immediately transferred to the backup channel upon spectrum handoff event.

SPECTRUM HANDOFF STRATEGY

Among other issues discussed in this section, spectrum handoff strategy is considered as the main issue in spectrum mobility. Since each module involved in spectrum handoff process is subject to imperfect performance, spectrum handoff strategy plays an important role in compensating the deficiency of the related modules. Thus, applying proper handoff strategy to the specific PU network can give optimal result to spectrum mobility performance.

The next section discusses spectrum handoff strategies in greater detail.

COMPARISON OF HANDOFF STRATEGIES

Spectrum handoff strategies are characterized by identifying when spectrum sensing and handoff are performed with regard to handoff triggering event occurrence. Spectrum sensing can be performed either before or after spectrum handoff triggering events happens [11], and so can be handoff action [10]. The combination of the two parameters above, gives four spectrum handoff strategies: non-handoff, pure reactive handoff, pure proactive handoff, and hybrid handoff strategy. These cases are shown in Fig. 3.

NON-HANDOFF STRATEGY

In non-handoff strategy, SU keeps staying in original channel and being idle until the channel becomes free again. In other words, SU selects the current licensed channel as the next target channel. After PU leaves the licensed channel, SU resumes the data transmission again.

The major disadvantage of this approach is that it causes high waiting latency to SU because the delay is as long as PU is active in the corresponding channel. In delay sensitive applications, this method would fail to meet QoS requirements. Also, it is obvious that time is badly wasted during SU waiting period.

PURE REACTIVE HANDOFF STRATEGY

In pure reactive handoff strategy, SU applies reactive spectrum sensing and reactive handoff action approach. Once a handoff triggering event occurs, SU performs spectrum sensing to find target backup channel. Afterward, link communication is transferred to the new target channel. In other words, both target channel selection and handoff action are performed reactively after a triggering event happens.

The advantage of this approach is that SU can get an accurate target channel since spectrum sensing is performed in the most relevant spectrum environment. Nevertheless, it comes at a cost of longer handoff latency due to on-demand spectrum sensing. Since SU performs spectrum sensing after detecting the handoff event, spectrum sensing becomes the major delay in the handoff process.

PURE PROACTIVE HANDOFF STRATEGY

In pure proactive handoff strategy, SU uses proactive spectrum sensing and proactive handoff action approach. SU performs spectrum sensing to find a backup target channel before a handoff triggering event happens. Based on the knowledge of PU traffic model, SU is able to predict PU arrival so that SU evacuates the channel beforehand. In other words, both target channel selection and handoff actions are performed proactively before the triggering event happens.

There are several advantages in using pure proactive strategy. First, handoff latency can be very short because everything can be planned in advance. Second, the possibility of multiple spectrum handoffs can be minimized by considering future target channel usage when selecting backup target channel. However, the drawback of this strategy is that backup target channel can remain obsolete. There is a chance that prepared backup channel is already occupied by other users at handoff time. In addition, accurate PU traffic model also becomes a key factor in this strategy. Poor prediction caused by inaccurate PU traffic model may badly degrade the overall spectrum mobility performance.

HYBRID HANDOFF STRATEGY

Hybrid handoff strategy combines pure reactive and pure proactive strategy by applying proactive spectrum sensing and reactive handoff action. Target channel selection is prepared beforehand or during SU data transmission while spectrum handoff is performed after a handoff triggering event happens. In other words, target channel selection is performed proactively and handoff action is performed reactively.

Hybrid handoff strategy is a reasonable compromise between pure reactive and pure proactive strategy. Faster spectrum handoff time can be achieved as spectrum sensing time is not performed during the handoff process. However, target channel can stay obsolescent as it does in pure proactive approach.

Comparison between various spectrum handoff strategies is summarized in Table 1.

DISCUSSION

In terms of handoff latency, pure proactive handoff strategy has superior performance, followed by hybrid handoff, pure reactive handoff, and non-handoff strategy, respectively. This can be explained by examining handoff latency factor diagram shown in Fig. 4.

Handoff phase is defined as a period of time from the occurrence of a handoff triggering event to the time when SU can resume its data transmission. In principle, handoff latency is directly proportional to the number of sequen-

Since each module involved in spectrum handoff process is subject to imperfect performance, spectrum handoff strategy plays an important role in compensating the deficiency of the related modules. Thus, applying proper handoff strategy to the specific PU network can give optimal result to spectrum mobility performance.

In the case of well-modeled PU networks, pure proactive strategy would be the best. On the other hand, pure reactive handoff strategy and hybrid handoff strategy are good for CRNs in general PU networks where PU arrival is considered to be random, such as in battlefield and natural disaster evacuation.

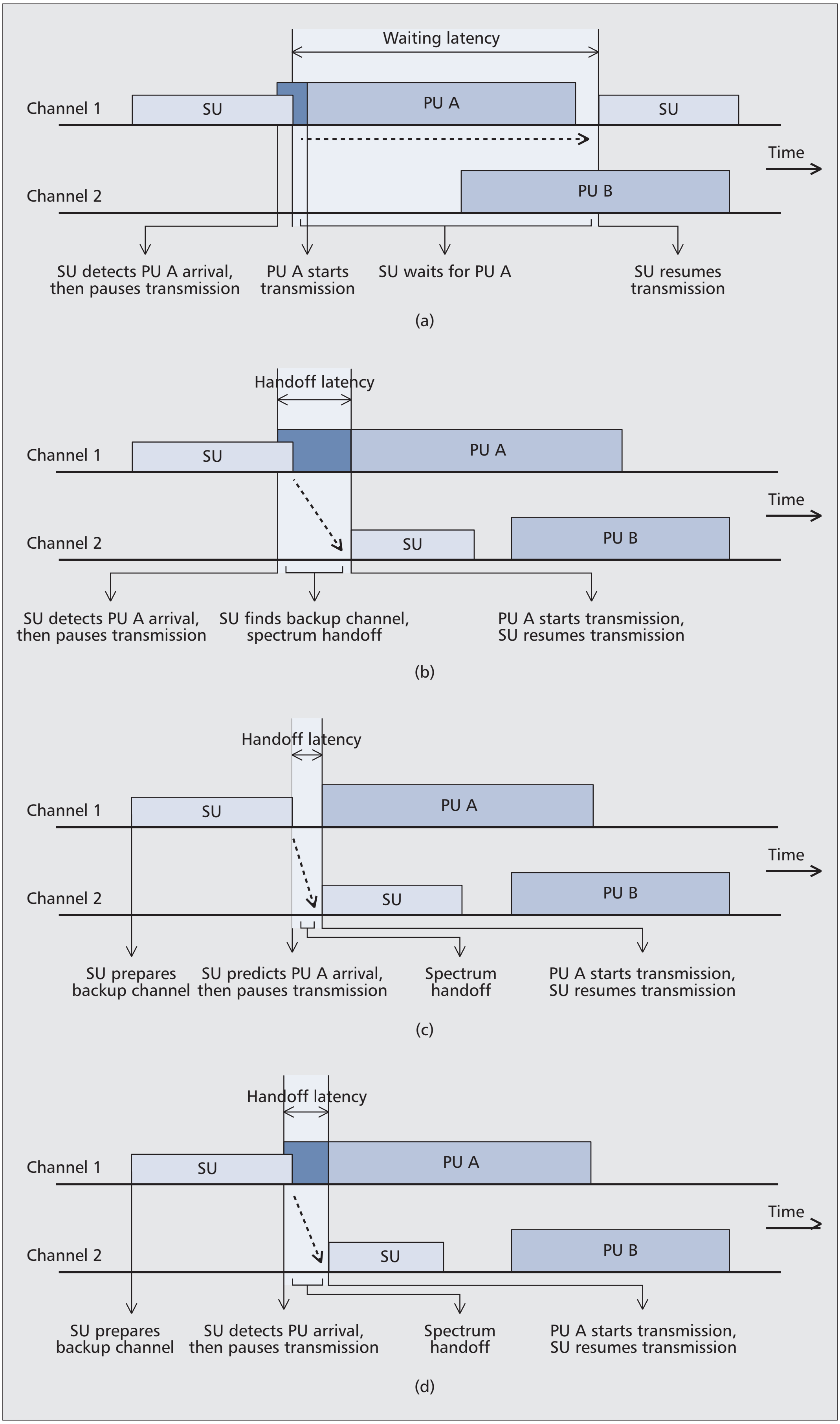

Figure 3. *Spectrum handoff strategies: a) non-handoff; b) pure reactive handoff; c) pure proactive handoff; and d) hybrid handoff.*

Strategy	Non-handoff	Pure reactive	Pure proactive	Hybrid
Main idea	Stay and wait	* Reactive sensing * Reactive action	* Proactive sensing * Proactive action	* Proactive sensing * Reactive action
Advantages	Very low PU interference	Accurate target channel selection	* Fastest response * Smart target channel selection	Fast response
Disadvantages	Very high SU interference	Slow response	* Outdated target channel selection * High computational requirement	Outdated target channel selection
Handoff latency	Unpredictably high latency	Medium latency	Very low latency	Low latency
Dependency	PU activity	Spectrum sensing	* Backup channel relevancy * Accurate PU traffic model	Backup channel relevancy
Best suited environment	Short data transmission PU network	General PU network	Well-modeled PU network	General PU network

Table 1. *Comparison of spectrum handoff strategies.*

tial tasks performed by SU during the handoff phase. Each task requires specific period of time to finish that is translated into delay to PU side. The delays are accumulated together and become handoff latency. Therefore, more tasks performed by SU in handoff phase lead to longer handoff latency to the SU, and, in turn, greater interference to PU.

In non-handoff strategy, PU data transmission becomes a major delay source to SU. While handoff decision task completion can be estimated, it is not the case for PU activity where its completion tends to be random in nature. Therefore, non-handoff strategy suffers from unpredictable waiting latency.

For other spectrum handoff models, major delay sources to SU come from spectrum sensing, handoff decision, and channel switching task; among which spectrum sensing is considered the most time-consuming. In pure reactive handoff strategy all three tasks are performed during the handoff phase. On the contrary, in pure proactive handoff strategy spectrum sensing and handoff decision task are excluded from handoff phase. In hybrid handoff strategy spectrum decision and channel switching tasks are performed during handoff phase, while spectrum sensing is excluded from handoff phase. As a result, pure proactive handoff strategy features the fastest response in spectrum mobility, while pure reactive handoff strategy exhibits relatively slow response and hybrid handoff strategy has moderate response.

It is important to note that the application of spectrum handoff strategy depends on unique characteristics of the PU network. Non-handoff strategy can be suitable for the PU network with short data transmission pattern and in the situation where other licensed spectrum bands are highly congested. In the case of well-modeled PU networks, pure proactive strategy would be the best. On the other hand, pure reactive handoff strategy and hybrid handoff strategy are good for CRNs in general PU networks where PU arrival is considered to be random, such as in battlefield and natural disaster evacuation.

Current Issues and Research Challenges

This section lists current issues and research challenges in the field of spectrum mobility.

Current Issues-

Parallel Multichannel Transmission — Parallel multichannel transmission is used in wireless networks to improve channel capacity. Instead of using a single channel, data is transmitted over multiple channels simultaneously so that the throughput is maximized. In CRNs, the same technique is adopted to minimize spectrum handoff effect.

This approach is used in the CORVUS (Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum) architecture where licensed spectrum bandwidth is divided into fine-grained subchannels [12]. Each SU data link makes use of multiple scattered subchannels to minimize spectrum handoff effects. In [13], a link maintenance protocol with OFDM (Orthogonal Frequency Division Multiplexing) modulation scheme in CRNs is proposed to provide a mechanism for exchanging spectrum information, maintaining backup subchannels, and switching the subchannels when required.

The CORVUS concept can reduce spectrum handoff effect and lower the risk of route recovery. However, its effectiveness is closely related to PU bandwidth usage. The wider the PU bandwidth is, the more effective is this technique. In addition, CORVUS requires a large number of radios that can be impractical in mobile networks with limited hardware support. Nevertheless, the application of CORVUS-like concept in mobile networks is worth researching.

Channel Contention During Spectrum Handoff — PU arrival may cause simultaneous spectrum handoffs. So, there is a chance that SUs will contend with each other to reserve target channels that can decrease spectrum handoff success rate and degrade spectrum mobility per-

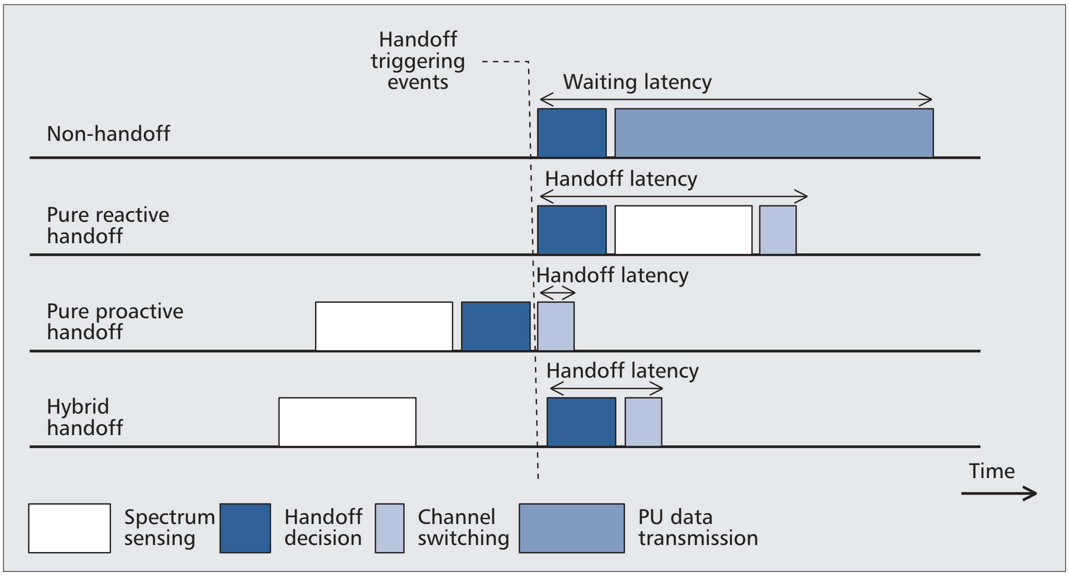

Figure 4. *Handoff latency factors.*

Ideally a SU should know the PU traffic pattern and apply the most suitable handoff strategy. When PU traffic pattern changes, SU would notice the change and adapt its handoff strategy accordingly. Therefore, future spectrum handoff strategy should consider spectrum learning factor in the design process.

formance. In fact, most of current works in spectrum mobility consider a pair of SUs instead of multiple SUs.

To date, only few research activities consider channel contention for multiple SU spectrum handoffs. In [14], a distributed channel selection algorithm is employed, where a SU that needs to perform spectrum handoff selects available channels according to randomized selecting channel sequence. Thus, the target channel contention problem can be mitigated in case of simultaneous spectrum handoff among multiple SUs.

Since this issue is practically important for successful spectrum handoff, the target channel selection algorithm for spectrum handoff has to account for channel contention as well.

RESEARCH CHALLENGES

Adaptive Spectrum Handoff Strategy — Current works are mostly focused on single spectrum handoff strategy. Since each spectrum handoff strategy is best suited for different PU networks, a new adaptive spectrum handoff algorithm with multiple spectrum handoff strategies is required. Ideally a SU should know the PU traffic pattern and apply the most suitable handoff strategy. When PU traffic pattern changes, SU would notice the change and adapt its handoff strategy accordingly. Therefore, future spectrum handoff strategy should consider spectrum learning factor in the design process.

Cross-Layer Link Maintenance Protocols — Link maintenance is at the heart of spectrum mobility. The related design issues are spread over physical, MAC and network layers. Therefore, cross layer approach between the three layers is required to address this issue efficiently. Most of the research works propose cross-layer solutions, either between physical and MAC layers or between MAC and network layers. Although the proposed solutions are aware of spectrum handoff, they are ineffective to some extent because some important spectrum handoff issues are overlooked. For example, routing algorithms with cross-layer approach between MAC and network layers usually do not address PU detection issue. On the other hand, MAC algorithms with cross-layer approach between physical and MAC layers hardly address the problem of routing recovery. Therefore, it is necessary to design a cross-layer link maintenance protocol that would efficiently address spectrum mobility issues in physical, MAC, and network layers to get optimal solution.

Energy Efficiency — In CRAHN, energy efficiency becomes a major constraint due to the limited resources of CR nodes. On the other hand, spectrum mobility methods usually rely on frequent spectrum information update and spectrum sensing that take significant power. Therefore, energy efficient spectrum mobility is still a challenge.

CONCLUSIONS

Spectrum mobility is one of main functionalities in CRNs that gives agility to CR nodes. Design issues in spectrum mobility include PU detection, handoff decision, target channel selection, routing recovery, and spectrum handoff strategy. Among these issues, spectrum handoff strategy plays an important role in spectrum mobility performance. Various handoff strategies are classified into four models: non-handoff, pure reactive, pure proactive, and hybrid handoff strategy. Qualitative comparison between the four models is made in terms of handoff latency performance metric. The analysis of handoff latency factors shows that pure proactive handoff strategy has the lowest handoff latency, while hybrid handoff and pure reactive handoff strategies have moderate and long handoff latency, respectively. These characteristics will determine their suitability for various applications in PU networks. In addition, reducing spectrum handoff effect using parallel multichannel transmission and mitigating channel contention between multiple SUs during spectrum handoff remain open issues in spectrum mobility. We also consider adaptive spectrum handoff strategy, cross-layer link maintenance protocols, and energy efficiency as research challenges in spectrum mobility.

Finally, we would like to share our perspective regarding research directions in spectrum mobility. First, there is a tendency to exhibit cognitive behavior in dynamic spectrum environment by integrating various learning methods in a spectrum handoff algorithm. Properly applied learning techniques would benefit in many aspects, especially in obtaining spectrum usage information in more independent way rather than relying on predefined static information. Second, from handoff strategy standpoint, the focus of spectrum mobility will be shifted from a single static handoff strategy towards the adaptive multiple handoff strategies approach. As a result, spectrum handoff behavior can change dynamically over time from reactive to proactive approach to achieve optimal performance in dynamic spectrum environment.

Acknowledgements

This work was supported by research funds from Chosun University while Dr. Jinyi Lee's work was also supported in part by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency) (NIPA-2012-H0301-12-2008). Correspondence should be addressed to Dr. Sangman Moh (smmoh@chosun.ac.kr).

References

[1] C.-J. Kim *et al.*, "Dynamic Spectrum Access/Cognitive Radio Activities in Korea," *Proc. IEEE Symp. New Frontiers in Dynamic Spectrum*, Apr. 2010.

[2] I. F. Akyildiz, W.-Y. Lee, and K. Chowdhury, "CRAHNs: Cognitive Radio Ad Hoc Networks," *Ad Hoc Networks*, vol. 7, No. 5, July 2009, pp. 810–36.

[3] I. F. Akyildiz *et al.*, "A Survey on Spectrum Management in Cognitive Radio Networks," *IEEE Commun. Mag.*, vol. 46, no. 4, Apr. 2008, pp. 40–48.

[4] Y. Zhang, "Spectrum Handoff in Cognitive Radio Networks: Opportunistic and Negotiated Situations," *IEEE Int'l. Conf. Commun. (ICC)*, June 2009.

[5] L.-C. Wang and A. Chen, "On the Performance of Spectrum Handoff for Link Maintenance in Cognitive Radio," *Proc. Int'l. Symp. Wireless Pervasive Computing (ISWPC)*, May 2008.

[6] X. Liu and Z. Ding, "ESCAPE: A Channel Evacuation Protocol for Spectrum Agile Networks," *Proc. IEEE Int'l. Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Apr. 2007.

[7] L. Giupponi and A. I. Perez-Neira, "Fuzzy-based Spectrum Handoff in Cognitive Radio Networks," *Proc. Int'l. Conf. Cognitive Radio Oriented Wireless Networks and Commun. (CrownCom)*, May 2008.

[8] G. Ko *et al.*, "Channel Management in IEEE 802.22 WRAN Systems," *IEEE Commun. Mag.*, vol. 48, no. 9, Sept. 2010, pp. 88–94.

[9] R. Ma, Y. Hsu, and K. Feng, "A POMDP-Based Spectrum Handoff Protocol for Partially Observable Cognitive Radio Networks," *Proc. IEEE Wireless Commun. and Net. Conf. (WCNC)*, Apr. 2009.

[10] L. Yang, L. Cao, and H. Zheng, "Proactive Channel Access in Dynamic Spectrum Networks," *Physical Communication (Elsevier)*, vol. 1, June 2008, pp. 103–11.

[11] L.-C. Wang and C.-W. Wang, "Spectrum Handoff for Cognitive Radio Networks: Reactive-Sensing or Proactive-Sensing?," *Proc. IEEE Int'l. Conf. Performance, Computing and Commun. (IPCCC)*, Dec. 2008.

[12] D. Cabric *et al.*, "A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum," *Proc. 14th IST Mobile and Wireless Commun. Summit*, June 2005.

[13] Q. Shi *et al.*, "Link Maintenance Protocol for Cognitive Radio System with OFDM PHY," *Proc. IEEE Int'l. Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Apr. 2007.

[14] Y. Song and J. Xie, "Common Hopping Based Proactive Spectrum Handoff in Cognitive Radio Ad Hoc Networks," *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2010.

Biographies

IVAN CHRISTIAN (chris.ivan@gmail.com) received his B.E. degree in electrical engineering from Bandung Institute of Technology, Indonesia in 2005. From 2006 to 2010, he worked at PT Siemens Indonesia, Jakarta, Indonesia. In 2010, he was selected as a Korean Government Scholarship Program (KGSP) grantee. Currently, he is a graduate student in the Dept. of Computer Engineering, Chosun University, South Korea. His current research interests include cognitive radio networks and cognitive radio ad hoc and sensor networks.

SANGMAN MOH (smmoh@chosun.ac.kr) received the Ph.D. degree in computer engineering from Korea Advanced Institute of Science and Technology (KAIST), South Korea in 2002. Since late 2002, he has been a faculty member in the Dept. of Computer Engineering at Chosun University, South Korea. From 1991 to 2002, he had been with Electronics and Telecommunications Research Institute (ETRI), South Korea. His research interests include mobile computing and networking, ad hoc and sensor networks, and cognitive radio networks.

ILYONG CHUNG (iyc@chosun.ac.kr) holds Ph.D. degrees in Computer Science from City University of New York. From 1991 to 1994, he was a senior technical staff of Electronic and Telecommunication Research Institute (ETRI), Dajeon, Korea. Since 1994, he has been a Professor in Department of Computer Science, Gwangju, Korea. His research interests are in computer networking, security systems and coding theory.

JINYI LEE (jinyilee@chosun.ac.kr) received the bachelor degree in mechanical design from Chonbuk University, Korea. Also he received the master and Ph.D. degree from Tohoku University, Japan. He is an Associate Professor of Chosun university, Korea and director of IT-NDT Center. He is the author or coauthor of thirty patents and over 60 scientific papers. His research interest is in development of magnetic camera.

The analysis of handoff latency factors shows that pure proactive handoff strategy has the lowest handoff latency, while hybrid handoff and pure reactive handoff strategies have moderate and long handoff latency, respectively. These characteristics will determine their suitability for various applications in PU networks.