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Rendezvous for Heterogeneous Cognitive Radios: Theoretical Foundations

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Abstract

Cognitive radio is proposed to satisfy the huge demand for spectrum by allowing radios to utilize the idle channels opportunistically. Rendezvous, where two radios complete handshaking in an idle channel, is a key step for cognitive radios to start communication. However, none of existing algorithms guarantees rendezvous for heterogeneous cognitive radios, where different radios have different spectrum sensing capabilities. In real life, heterogeneous radios in a wide variety of wireless devices can be seen everywhere. It is crucial to guarantee efficient rendezvous for heterogeneous cognitive radios. In this report, we propose a new channel hopping algorithm, named the HH scheme, that guarantees rendezvous without assuming a universal channel set sensible to all radios. The HH scheme generate CH sequence for a radio based on the radio's own spectrum-sensing capability. To our best knowledge, HH is the first CH scheme that guarantee rendezvous between heterogeneous radios.

I. INTRODUCTION

Wireless devices have extensively spread in recent years, and they bring a huge demand for the radio spectrum. The spectrum resources, such as channels, are relatively limited and the fixed spectrum allocation may not be able to meet the demand. Measurements [1], [15] show that the allocated radio spectrum is rarely utilized by *Primary Users* (PUs) continuously across time and space; in other words, there are spectrum holes consisting of idle channels which can be further utilized. To address this problem, cognitive radio is proposed, which allows the *Secondary Users* (SUs, or simply *radios*) to sense the spectrum ranging within their own device capability and dynamically tunes into different idle channels to communicate with each other opportunistically.

Rendezvous is a key step for cognitive radios to start communication. By rendezvous we mean that two radios complete handshaking (for the purposes of, say, neighbor discovery, data transmission, etc.) in an idle channel. Two common techniques, namely the *Common Control Channel* (CCC) [7], [8], [12], [19], [21], [23] and *Channel Hopping* (CH) schemes [6], [13], [14], [18], [22], [24], [25] are proposed to achieve rendezvous. The CCC predefines a common control channel for (a group of) radios, allowing them to tune into the CCC and rendezvous with each other. On the other hand, the CH schemes divide the time of each radio evenly into *time slots* and requires the radio to hop to some channel at each slot. The sequence of channels that the radio hops to in order is called the *CH sequence*, and is generated by a *CH scheme* programmed in the radio. It is the CH scheme that guarantees rendezvous between the radios using its generated CH sequences. In contrast to the centralized CCC, CH schemes allow radios to obtain their own CH sequences in a distributed manner, thereby walking around a single-point-of-failure. The cost is that CH schemes usually result in longer *Time To Rendezvous* (TTR), since radios hop to channels "blindly" without knowing the others' sequences and rendezvous happens only when two radios to hop to the same channel at the same time, after a period of blind trials.

However, existing works guarantee rendezvous only for *homogeneous cognitive radios* that the spectrum sensing capability of the devises are all the same. Let V_i be a set of channels that a radio i is capable of sensing with. Currently, rendezvous is guaranteed only when $V_i = V_j$ for all i and j. In real-world, there are various types of wireless devices, such as those used for broadcasting, bluetooth, amateur radio, cell phone, different generation of cellular networks, WiFi, NFC, and GPS, etc. *Heterogeneous cognitive radios*, that $V_i \neq V_j$, can be seen everywhere. Ideally, radios i and j having $V_i \cap V_j \neq \emptyset$ should be guaranteed to rendezvous with each other. Unfortunately, existing works cannot be easily extended to provide such a guarantee. For the CCC, there may not exist a common channel in all V_is to be used as the control channel. For CH schemes, simple extensions either results in unacceptably high delay (specifically, the $O(|U|^2)$ *Maximum Time To Rendezvous* (MTTR) if we let $V_i = U$ for all i, where U is the set of universal channels, $|U| \gg |V_i|$) or loss of the guarantee (if we let the CH scheme generate a CH sequence for radio i using V_i directly). It is essential to have a new rendezvous technique for heterogeneous cognitive radios.

In this report, we propose a new CH scheme, named the *Heterogeneous Hopping* (HH) scheme for heterogeneous cognitive radios that guarantees rendezvous between two radios i and j as long as $V_i \cap V_j \neq \emptyset$. The problem we solve is much more complex than existing settings, as unlike in traditional CH schemes a CH sequence can be generated based on U, the HH scheme does not assume the existence of U thus must generate a CH sequence based on each device's own capability V_i. The HH scheme is carefully designed to deal with various overlapping conditions in terms of both device capabilities and time, which are not considered in previous arts. As a result, the MTTR is bound by $O(|V_i||V_j|)$, which is much smaller than that $O(|U|^2)$ returned by extensions of existing works.

II. RELATED WORK

The existing rendezvous schemes for cognitive radios can be classified into two categories: centralized and non-centralized. Centralized schemes [7], [8], [12], [19], [21], [23] predefine a Common Control Channel (CCC) for all or each group of geographically adjacent radios. With a global CCC, radios can easily tune into the global CCC for rendezvous. Despite of its simplicity, it suffers problems that the global CCC is probably in congestion in most of time, it easily leads to single point of failure if the global CCC is not idle, and it is difficult to find a common operable channel for heterogeneous radios. Instead of selecting a global CCC, [10], [11], [17], [20], [28] propose the idea of local CCC. These methods find a CCC for those radios in a proximal cluster or in a regional area. But the cluster is not likely established before communications between radios. Besides, similar to global CCC, it is hard to determine the regional area and find a common operable channel for all heterogeneous radios. We can extend the idea of local CCC to find a local CCC for few kinds of radios with similar capability. However, this prohibits radios with different capabilities from rendezvous when they have operable channels in common. Also, this approach may suffer from congestion if the number of radios, that use the same CCC, is large.

Since CCC are not suitable for cognitive radios, several schemes are proposed without using a

CCC. These method are often referred to as “blind rendezvous”. The typical technique for blind rendezvous is Channel Hopping (CH) [6], [13], [14], [18], [22], [24], [25]. The CH schemes let each radio independently generates a CH sequence and hops to channels of the CH sequence in turn. The main task is to design a generating method of CH sequence. Generally, the objective of the generating method is to guarantee rendezvous for radios with overlaps and guide them to rendezvous as soon as possible. Traditionally, CH schemes for homogeneous radios can be divided into synchronous and asynchronous depend on their environments. In the synchronous environment, the timer is synchronized among all the radios, so that all the radios can start and hop to a channel simultaneously. Kondareddya et al. [18] proposed a protocol called the SYNchronized MAC (SYN-MAC), which guides all radios to follow a common CH sequence to hop. SYN-MAC avoids the single point of failure, but it still suffers from congestion because all radios always hop to the same channel at the same time. Xin et al. [26] proposed ROAT that divides radios into active and passive nodes, with knowing which passive nodes are, active nodes hops to passive nodes’ staying channel to rendezvous. However, passive nodes cannot rendezvous with each other. Bian et al. [5], [6] proposed two CH schemes, the M-QCH and L-QCH schemes respectively, that use the concept of quorum systems to guarantee rendezvous. Shih et al. [24] proposed the DH-MAC scheme that spreads out rendezvous between radios choosing different parameters over all channels in U. Note that DH-MAC employs a concept similar to the parity channels in SSCH [3] (originally proposed for multi-channel 802.11 ad-hoc networks) to ensure rendezvous even when radios accidentally choose the same parameter. Zhang et al. [27] proposed the SYNC-ETCH that pre-construct possible schedules with guaranteed rendezvous, and each radio randomly select a schedule every round to avoid congestion.

However, timer synchronization may not be easily achieved in practice. Asynchronous CH schemes are proposed. Bian et al. [4]–[6] proposed an asynchronous CH scheme called A-QCH. However, this scheme is applicable to the systems with only two channels (that is, $|U| = 2$). The reliability of rendezvous is limited because these two channels may easily be occupied by PUs simultaneously. Moreover, serious congestion may occur because one of the two channels is accessed by at least half of the users. DaSilva et al. [14] proposed another CH scheme under the condition that all radios have the same available channels. But this condition is unlikely to happen in practice as radios may have different device capabilities. Theis et al. proposed yet another CH scheme called the Modular Clock (MC) scheme [25] based on the number theory. The MC scheme cannot guarantee rendezvous if two radios accidentally make the same decision (on the "rate" parameter) to construct their CH sequences. Recently, Lin et al. [22] proposed the Jump-Stay (JS) and Zhang et al. [27] proposed the ASYNC-ETCH. They use an idea similar to the "parity channels" in SSCH and DH-MAC to ensure rendezvous even when two radios generate the same CH sequence. Since the time is not synchronized, the JS and ASYNC-ETCH put extra consideration into the case where the slots for parity channels are not aligned. However, ASYNC-ETCH is not able to pre-construct required overlapping schedules while $V_i \neq V_j$. Without further limitations, JS is the only feasible scheme for heterogeneous radios.

Note that there are some works [4], [6] which assume that senders and receivers are known in advance. However, the assumption may be impractical in a distributed system, where radios cannot know senders and receivers before communication as they can freely join and leave.

III. HETEROGENEOUS HOPPING SCHEME

In this section, we formally define the rendezvous problem for heterogeneous cognitive radios and present the Heterogeneous Hopping (HH) scheme. We also justify the correctness of the HH scheme and analyze the MTTR.

A. *Problem Definition*

Assume that the universal spectrum can be divided into a set $U = \{c_0, c_1, \cdots, c_{|U|-1}\}$ of channels. Each radio i can sense a range of spectrum consisting of a set $V_i = \{c_x, c_{x+1}, \cdots, c_{x+|V_i|-1}\}$ of continuous channels starting from c_x [1], [2], [9], [15], [16]. We denote c_x as $start_i$. Each channel in V_i is either occupied by nearby Primary Users (PUs) or available for opportunistic usage. Two radios i and j are said to have *capability-overlap* if they can sense common channels, i.e., $V_i \cap V_j \neq \emptyset$. The time of each ratio i is divided evenly into *time slots*, denoted as $t_i^{[0]}, t_i^{[1]}, \cdots$. We do *not* assume any timer synchronization between radios. So given an index z, slots $t_i^{[z]}$ and

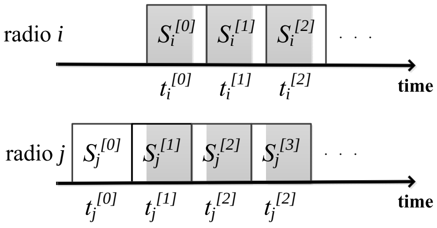

Figure 1. Despite of the asynchronous timers, a slot of radio i must overlap with one slot of radio j over an interval (shaded) longer than half of a slot. For example, the slot $t_i^{[1]}$ is *time-overlapping* with $t_j^{[2]}$, but not $t_j^{[1]}$ and $t_j^{[3]}$.

$t_j^{[z]}$ of two radios i and j may have arbitrary shift in time. We say that two slots $t_i^{[z]}$ and $t_j^{[z]}$ have *time-overlap* if they overlap over an interval longer than half of a slot, as shown in Fig. 1.

We adopt the channel hopping scheme, where each radio hops to a channel at each time slot and waits for rendezvous with other radios. Specifically, given a Channel Hopping (CH) sequence $S_i = [s_i^{[0]}, s_i^{[1]}, \cdots]$, where $s_i^{[z]} \in V_i$, the radio i hops to channel $s_i^{[0]}$ at slot $t_i^{[0]}$, and $s_i^{[1]}$ at slot $t_i^{[1]}$, and so on. Two radios are said to *rendezvous* if they hop to some common available channel at a pair of time-overlapping slots. We assume that the duration of a time slot is set long enough such that the handshaking (for, say, neighbor discovery or data transmission) can be done within half of a slot at which rendezvous takes place [6].

We formally define our problem as follows:

Problem 1. Design a CH scheme such that given any pair of capability-overlapping radios i and j in a network, the scheme is able to return two CH sequences S_i and S_j and guarantee that by following S_i and S_j respectively, the radios i and j will rendezvous within finite time, i.e., $s_i^{[z]} = s_j^{[z']} = c$ for some z, z', and c, where $t_i^{[z]}$ time-overlaps with $t_j^{[z']}$ and c is available in both V_i and V_j.

Note that it is impossible for two radios to rendezvous if they have no available channels in common.

To evaluate the performance of a CH scheme, one common metric is the *Maximum Time to Rendezvous* (MTTR), which measures the maximum time (in number of slots) required for two radios to rendezvous. The shorter the MTTR the better.

It is challenging to design a CH scheme for heterogeneous cognitive radios. Most existing works consider the homogeneous radios where $V_i = V_j = V$ for all i and j. The MTTR is $O(|V|^2)$ in asynchronous environments [22]. To guarantee rendezvous for heterogeneous radios, one naive approach is to let $V_i = V_j = U$ and generate S_i using existing CH schemes. Elements in $U \backslash V_i$ are regarded as "occupied" and during hopping, the radio does nothing if $s_i^{[z]} \in U \backslash V_i$. However, this approach has a serious drawback that the MTTR will be very high, as $|U|$ is generally much larger than $|V_i|$ [1], [2], [9], [15], [16]. Another way is to obtain S_i and S_j directly based V_i and V_j respectively. However, this cannot not guarantee rendezvous. It is still challenging to guarantee rendezvous within acceptable MTTR for heterogeneous cognitive radios.

B. Heterogeneous Hopping Scheme

In this subsection, we propose the *Heterogeneous Hopping* (HH) scheme that solves Problem 1 within the $O(|V_i||V_j|)$ MTTR.

To start, we need to extend the notation for a CH sequence first. A CH sequence $S_i = [s_i^{[0]}, s_i^{[1]}, \cdots]$ can be partitioned evenly into *rounds* $S_i^{[x]} = [s_i^{[x,0]}, s_i^{[x,1]}, \cdots, s_i^{[x,|S_i^{[x]}|]}]$, where $s_i^{[x,y]}$ denotes the y^{th} element in the x^{th} round, as shown in Fig. 2. Note that $s_i^{[z]} = s_i^{[x \cdot |S_i^{[x]}| + y]}$.

In the HH scheme, we partition S_i into rounds of length 3:

$$s_i^{[x,y]} = \begin{cases} f^{[x]}, & y = 0, \\ r^{[x]}, & y = 1, \\ n^{[x]}, & y = 2, \end{cases}$$

and denote the three elements in each round $f^{[x]}$, $r^{[x]}$, $n^{[x]}$ respectively. This effectively divide S_i into three subsequences, namely the *fixed sequence* $F_i = [f_i^{[0]}, f_i^{[1]}, \cdots]$, *rotating sequence* $R_i = [r_i^{[0]}, r_i^{[1]}, \cdots]$, and *insurance sequence* $N_i = [n_i^{[0]}, n_i^{[1]}, \cdots]$ (see Fig. 2).

The fixed sequence F_i is further partitioned into rounds $F_i^{[x]} = [f_i^{[x,0]}, f_i^{[x,1]}, \cdots, f_i^{[x,|F_i^{[x]}|]}]$.

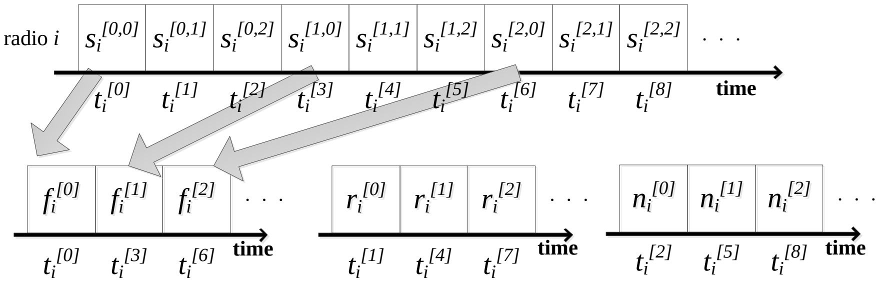

Figure 2. An example CH sequence. S_i is divide into the *fixed* F_i, *rotating* R_i, and *insurance* N_i subsequences.

Let $|F_i^{[x]}|$ be the least prime number larger than $|V_i|$. The HH scheme assigns channels to F_i by

$$f_i^{[x,y]} = \begin{cases} v_i^{(y)}, & x = 0 \text{ and } y < |V_i|, \\ \text{an arbitrary element of } V_i, & x = 0 \text{ and } y \geq |V_i|, \\ f_i^{[x-1,y]}, & \text{otherwise,} \end{cases}$$

where $v_i^{(y)}$ is the y^{th} element in V_i (indexed from 0). An example is shown in Fig. 3. Notice that if $|V_i|$ is a prime already, then $|F_i^{[x]}|$ needs to be the next prime number.

The rotating sequence R_i is also partitioned into rounds $R_i^{[x]} = [r_i^{[x,0]}, r_i^{[x,1]}, \cdots, r_i^{[x,|R_i^{[x]}|]}]$. Let $|R_i^{[x]}| = |F_i^{[x]}|$, the least prime larger than $|V_i|$. The HH scheme assigns channels to R_i by

$$r_i^{[x,y]} = f_i^{[(-x \cdot k_i + y) \bmod |R_i^{[x]}|]},$$

where $k_i = (start_i \bmod (|R_i^{[x]}| - 1)) + 1$. Basically, elements in $R_i^{[x]}$ are rotated k_i slots forward to produce the next round $R_i^{[x+1]}$. An example is shown in Fig. 4. Notice that $r_i^{[x,y]}$ and $r_i^{[x+1,y]}$ must be different since $1 \leq k_i \leq |R_i^{[x]}| - 1$.

Finally, all slots of the insurance sequence N_i is filled in the starting channel $start_i$.

C. Correctness of Heterogeneous Hopping Scheme

In this subsection, we verify the correctness of our heterogeneous hopping scheme. Since we do not assume timer synchronization between radios, we need to deal with timer shifts. However, as we have shown in Fig. 1, a time slot of radio i must *time-overlap* with exactly one

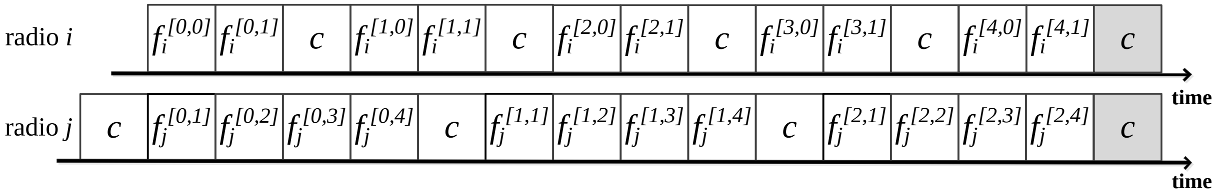

Figure 3. Rounded fixed sequences F_i and F_j with a common available channel c, where $|F_i^{[x]}| = 3$, $|F_j^{[x]}| = 5$. The MTTR is bounded by $O(|F_i^{[x]}||F_j^{[x]}|)$ time slots.

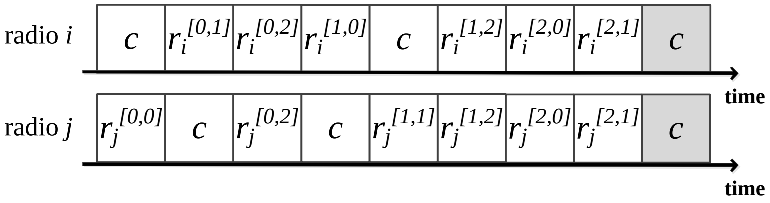

Figure 4. Rounded rotating sequences R_i and R_j with a common available channel c, where $|R_i^{[x]}| = |R_j^{[x]}| = 3$, $k_i = 1$, and $k_j = 2$. The MTTR is bounded by $O(|R_i^{[x]}||R_j^{[x]}|)$ time slots.

slot of another radio j (for an interval longer than half of a time slot). Therefore, in terms of time-overlapping, we only need to consider the shifts that are multiples of a slot.

Without loss of generality, we consider two possible time-overlapping cases: (i) F with F, R with R, and N with N, and (ii) F with R, R with N, and N with F. Notice that the case (iii) in Fig. 5 is covered by the case (ii) as we don't distinguish radios i and j.

Without loss of generality, each of the above cases can be further classified into three subcases in terms of capabilities of radios i and j: (a) $|V_i| \neq |V_j|$, (b) $|V_i| = |V_j| \wedge start_i \neq start_j$, and (c) $|V_i| = |V_j| \wedge start_i = start_j$. Since $|F_i^{[x]}|$ depends on $|V_i|$, we can re-classify the cases into: (a) $|F_i^{[x]}| \neq |F_j^{[x]}|$, (b) $|F_i^{[x]}| = |F_j^{[x]}| \wedge start_i \neq start_j$ (c) $|F_i^{[x]}| = |F_j^{[x]}| \wedge start_i = start_j$. We verify the correctness of the HH scheme for each of these subcases.

Case (i-a): we can use the time-overlapping slots between F_i and F_j to guarantee rendezvous , and the MTTR is $O(|V_i||V_j|)$.

Lemma 2. *Let p be a prime and m be an integer coprime with p. Then for any d, the integers*

$d,\ d+m,\ d+2m,\ \cdots,\ d+(p-1)m$ are all distinct under modulo-p arithmetic.

Proof: Suppose on the contrary that $d+xm \equiv d+ym \pmod{p}$, for some $0 \le x < y \le p-1$. This implies that $(y-x)m \equiv 0 \pmod{p}$, which is a contraction since p is a prime and both $y-x$ and n are coprime with p. ■

By lemma 2, we show that two CH sequences guarantee rendezvous if $|F_i^{[x]}| \ne |F_j^{[x]}|$. As an example, suppose that $f_i^{[0,a]}$ is a common available channel of radios i and j. Let $p = |F_i^{[x]}|$, $m = |F_j^{[x]}|$ and $p,\ m$ coprime. If $f_i^{[0,a]}$ has the first time-overlap with $f_j^{[0,b]}$, then when i hops to $f_i^{[x,a]}$ in the following rounds, $0 \le x < m$, $f_i^{[x,a]}$ will have time-overlap with $f_j^{[0,\,b]}$, $f_j^{[1,\,b+p \pmod{m}]}$, $f_j^{[2,\,b+2p \pmod{m}]}$,$\cdots$, $f_j^{[p-1,\,b+(m-1)p \pmod{m}]}$ in term. These elements in $F_j^{[x]}$ are all distinct under modulo-p arithmetic by Lemma 2, so that one of them must exist a channel same as some $f_i^{[x,a]}$. The rendezvous will occur within the MTTR of $O(|F_i^{[x]}||F_j^{[x]}|) = O(|V_i||V_j|)$. This leads to the following theorem:

Theorem 3. *Given that two radios i and j with common available channels that adopt two CH sequences generated by the HH scheme. The MTTR between i and j is bounded by $O(|V_i||V_j|)$ as long as $|F_i^{[x]}| \ne |F_j^{[x]}|$.*

Case (i-b): we can use the time-overlapping slots between R_i and R_j to guarantee rendezvous, and the MTTR is bounded by $O(|V_i||V_j|)$.

In this case, $R_i^{[x]}$ and $R_j^{[x]}$ have the same length equal to a prime number but distinct rotating amounts $k_i \ne k_j$. Suppose that radios i and j have a common channel c. Let $p = |R_i^{[x]}| = |R_j^{[x]}|$ and $m = k_i - k_j$. By definition of the HH scheme, we have $k_i, k_j \in [1,\ p-1]$. This implies that $k_i \not\equiv k_j \pmod{p}$, so that m is coprime with p. If the radio i hops to c at slot $r_i^{[0,a]}$ having the first time-overlap with $r_j^{[0,b]}$, then $r_i^{[x,a]}$ in the following p rounds will have time-overlaps with $r_j^{[0,\,b \pmod{p}]}$, $r_j^{[0,\,b+m \pmod{p}]}$, $r_j^{[0,\,b+2m \pmod{p}]}$, $\cdots$, $r_j^{[0,\,b+(p-1)m \pmod{p}]}$ in term. By Lemma 2, these elements are all distinct under the modulo-p arithmetic. So that one of them must be channel c and rendezvous occurs. The MTTR is $O(|R_i^{[x]}||R_j^{[x]}|) = O(|V_i||V_j|)$. This leads to the following theorem:

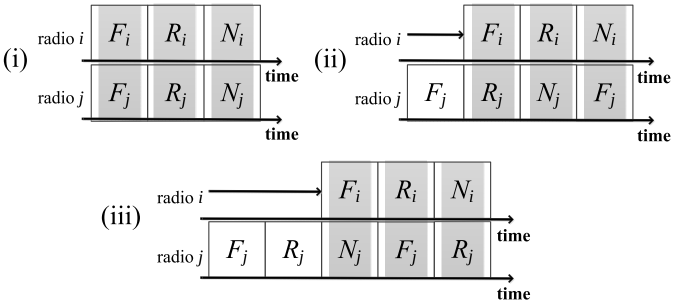

Figure 5. Timer shifts between two CH sequences of the HH scheme. Based on Fig. 1, we only need to consider the time-overlapping slots and regard shifts as multiples of a time slot.

Theorem 4. *Given that two radios i and j with common available channels that adopt two CH sequences generated by the HH scheme. The MTTR between i and j is bounded by $O(|V_i||V_j|)$ as long as $|R_i^{[x]}| = |R_j^{[x]}|$ and $k_i \neq k_j$.*

Case (i-c): we can use the time-overlapping slots between N_i and N_j to guarantee rendezvous. Since $start_i = start_j$, N_i and N_j are filled with the same channel by definition of the HH scheme. The MTTR is bounded by $O(1)$.

Case (ii-a): we can use the time-overlaps of R_i and N_j together with N_i and F_j to guarantee rendezvous. Notice that $V_i \cap V_j \neq \emptyset$ implies that either $start_i \in V_j$ or $start_j \in V_i$ must be true. If $start_i \in V_j$, then rendezvous must occur between the time-overlaps of N_i and F_j within $O(|V_j|)$ slots as each $F_j^{[x]}$ will iterate over all channels in V_j. Otherwise if $start_j \in V_i$, then rendezvous must occur between the time-overlaps of R_i and N_j within $O(|V_i|)$ slots. The MTTR is bounded by $\max\{O(|V_i|), O(|V_j|)\}$.

Case (ii-b): we can use the time-overlaps of F_i and R_j to guarantee rendezvous by regarding each $F_i^{[x]}$ as a rotating sequence with rotating amount $k_i = 0$. Since $k_j \in [1, |R_j| - 1]$ and $k_i \neq k_j$, the argument in case (i-b) applies here, and the MTTR is $O(|V_i||V_j|)$.

Case (ii-c): the argument in case (ii-a) applies here.

In summary, the HH scheme can guarantees rendezvous in asynchronous, heterogeneous cognitive radios, and the MTTR is bounded by $O(|V_i||V_j|)$.

IV. CONCLUSION

In this report, we proposed the HH scheme, an efficient channel hopping scheme which guarantees rendezvous between radios in different scenarios of device capabilities without the need of timer synchronization. Next, we will conduct simulations to evaluate the performance of the HH scheme, based on metrics including the rendezvous guarantee, average TTR and the MTTR in the worst case. Also, we are planning to implement the HH scheme on real wireless devices to verify its practicality. In the future, we try to investigate some topics that have not been attentively explored, e.g., we try to design rules on how the communication starts between two rendezvoused radios, how a cognitive radio network forms, how the network is updated and maintained, and how the data flows in a cognitive radio network. This work is a crucial basis of our future research. We welcome comments from interested readers.

REFERENCES

[1] I.F. Akyildiz, W.Y. Lee, M.C. Vuran, and S. Mohanty. Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. *Computer Networks*, 50(13):2127–2159, 2006.

[2] R. Bagheri, A. Mirzaei, S. Chehrazi, M. Heidari, M. Lee, M. Mikhemar, M. Tang, and A. Abidi. An 800mhz to 5ghz software-defined radio receiver in 90nm cmos. In *IEEE Int'l Solid-State Circuits Conference (ISSCC)*, pages 1932–1941, 2006.

[3] P. Bahl, R. Chandra, and J. Dunagan. Ssch: slotted seeded channel hopping for capacity improvement in ieee 802.11 ad-hoc wireless networks. In *Proc. of ACM Int'l Conf. on Mobile computing and networking (MobiCom)*, pages 216–230, 2004.

[4] K. Bian and J.M. Park. Asynchronous channel hopping for establishing rendezvous in cognitive radio networks. In *Proc. of IEEE Int'l Conf. on Computer Communications (INFOCOM)*, pages 236–240, 2011.

[5] K. Bian, J.M. Park, and R. Chen. A quorum-based framework for establishing control channels in dynamic spectrum access networks. In *Proc. of ACM Int'l Conf. on Mobile computing and networking (MobiCom)*, pages 25–36, 2009.

[6] K. Bian, J.M. Park, and R. Chen. Control channel establishment in cognitive radio networks using channel hopping. *IEEE Journal on Selected Areas in Communications*, 29(4):689–703, 2011.

[7] V. Brik, E. Rozner, S. Banerjee, and P. Bahl. Dsap: a protocol for coordinated spectrum access. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pages 611–614, 2005.

[8] M.M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans. Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum. In *IEEE Int'l Symp. on World of Wireless Mobile and Multimedia Networks (WoWMoM)*, pages 78–85. Ieee, 2005.

[9] D. Cabric, S.M. Mishra, and R.W. Brodersen. Implementation issues in spectrum sensing for cognitive radios. In *Proc. of Asilomar Conf. on Signals Systems and Computers*, pages 772–776, 2004.

[10] T. Chen, H. Zhang, M.D. Katz, and Z. Zhou. Swarm intelligence based dynamic control channel assignment in cogmesh. In *IEEE Int'l Conf. on Communications (ICC) Workshops*, pages 123–128, 2008.

[11] T. Chen, H. Zhang, G.M. Maggio, and I. Chlamtac. Cogmesh: a cluster-based cognitive radio network. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pages 168–178, 2007.

[12] C. Cordeiro, K. Challapali, D. Birru, and N. Sai Shankar. Ieee 802.22: the first worldwide wireless standard based on cognitive radios. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pages 328–337, 2005.

[13] C. Cormio and K.R. Chowdhury. Common control channel design for cognitive radio wireless ad hoc networks using adaptive frequency hopping. *Ad Hoc Networks*, 8(4):430–438, 2010.

[14] L.A. DaSilva and I. Guerreiro. Sequence-based rendezvous for dynamic spectrum access. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pages 1–7, 2008.

[15] A. Ghasemi and E.S. Sousa. Spectrum sensing in cognitive radio networks: requirements, challenges and design trade-offs. *IEEE Communications Magazine*, 46(4):32–39, 2008.

[16] M. Ingels, V. Giannini, J. Borremans, G. Mandal, B. Debaillie, P. Van Wesemael, T. Sano, T. Yamamoto, D. Hauspie, J. Van Driessche, et al. A 5 mm^2 40 nm lp cmos transceiver for a software-defined radio platform. *IEEE Journal of Solid-State Circuits*, 45(12):2794–2806, 2010.

[17] M.R. Kim and S.J. Yoo. Distributed coordination protocol for common control channel selection in multichannel ad-hoc cognitive radio networks. In *IEEE Int'l COnf. on Wireless and Mobile Computing, Networking and Communications (WIMOB)*, pages 227–232, 2009.

[18] Y.R. Kondareddy and P. Agrawal. Synchronized mac protocol for multi-hop cognitive radio networks. In *Proc. of IEEE Int'l Conf. on Communications (ICC)*, pages 3198–3202, 2008.

[19] S. Krishnamurthy, M. Thoppian, S. Venkatesan, and R. Prakash. Control channel based mac-layer configuration, routing and situation awareness for cognitive radio networks. In *IEEE Military Communications Conference (MILCOM)*, pages 455–460, 2005.

[20] L. Lazos, S. Liu, and M. Krunz. Spectrum opportunity-based control channel assignment in cognitive radio networks. In *IEEE Communications Society Conf. on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pages 1–9, 2009.

[21] L. Le and E. Hossain. A mac protocol for opportunistic spectrum access in cognitive radio networks. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1426–1430, 2008.

[22] Z. Lin, H. Liu, X. Chu, and Y.W. Leung. Jump-stay based channel-hopping algorithm with guaranteed rendezvous for cognitive radio networks. In *Proc. of IEEE Int'l Conf. on Computer Communications (INFOCOM)*, pages 2444–2452, 2011.

[23] J. Pérez-Romero, O. Salient, R. Agustí, and L. Giupponi. A novel on-demand cognitive pilot channel enabling dynamic spectrum allocation. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pages 46–54, 2007.

[24] C.F. Shih, T.Y. Wu, and W. Liao. Dh-mac: A dynamic channel hopping mac protocol for cognitive radio networks. In *Proc. of IEEE Int'l Conf. on Communications (ICC)*, pages 1–5, 2010.

[25] N.C. Theis, R.W. Thomas, and L.A. DaSilva. Rendezvous for cognitive radios. *IEEE Transactions on Mobile Computing*, 10(2):216–227, 2011.

[26] C. Xin, M. Song, L. Ma, and C.C. Shen. An approximately optimal rendezvous scheme for dynamic spectrum access networks. In *Proc. of IEEE Int'l Conf. on Gloal Telecommunications (GLOBECOM)*, pages 1–5, 2011.

[27] Y. Zhang, Q. Li, G. Yu, and B. Wang. Etch: Efficient channel hopping for communication rendezvous in dynamic spectrum access networks. In *Proc. of IEEE Int'l Conf. on Computer Communications (INFOCOM)*, pages 2471–2479, 2011.

[28] J. Zhao, H. Zheng, and G.H. Yang. Distributed coordination in dynamic spectrum allocation networks. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, pages 259–268, 2005.