Multiple Radios for Effective Rendezvous in Cognitive Radio Networks

Lu Yu[1], Hai Liu[1], Yiu-Wing Leung[1], Xiaowen Chu[1], and Zhiyong Lin[2,1]
[1]Dept of Computer Science, Hong Kong Baptist University, Hong Kong
[2]Dept of Computer Science, GuangDong Polytechnic Normal University, GuangZhou, China
{lyu, hliu, ywleung, chxw, zylin}@comp.hkbu.edu.hk

Abstract—**Rendezvous is a fundamental operation in cognitive radio networks (CRNs) for establishing a communication link on a commonly-available channel between cognitive users. The existing works on rendezvous implicitly assume that each cognitive user is equipped with one radio (i.e., one wireless transceiver). As the cost of wireless transceivers is dropping, this feature can be exploited to significantly improve the rendezvous performance at low cost. In this study, we investigate the rendezvous problem in CRNs where cognitive users are equipped with multiple radios and different users may have different number of radios. We first study how the existing rendezvous algorithms can be generalized to use multiple radios for faster rendezvous. We then propose a new rendezvous algorithm, called *role-based parallel sequence* (*RPS*), which specifically exploits multiple radios for more efficient rendezvous. Our basic idea is to let the cognitive users stay in a specific channel in one *dedicated radio* and hop on the available channels with parallel sequences in the remaining *general radios*. We prove that our algorithm provides guaranteed rendezvous and derive the maximum time-to-rendezvous (TTR) and upper-bounds on the expected TTR. Extensive experiments are conducted to evaluate the proposed solutions.**

Keywords – wireless networks; cognitive radio networks; rendezvous.

I. INTRODUCTION

With the traditional static spectrum management, a majority of the licensed spectrum is underutilized in most of time while the unlicensed spectrum is over-crowded due to the growing demand for wireless radio spectrum from exponential growth of various wireless devices [1]. Dynamic Spectrum Access (DSA) is a new technology which exploits the wireless spectrum in a more intelligent and flexible way. Cognitive radios, devices which can sense the spectrum for idle channels and further access them by adaptively adjusting the transmission parameters, have been envisioned as a promising enabler for DSA. With cognitive radios, the unlicensed users (or cognitive users, or secondary users (SUs)) can opportunistically identify and access the vacant portions of the spectrum of the licensed users (or primary users, PUs).

In cognitive radio networks (CRNs), SUs are even not aware of the presence of each other beforehand. The process of two or more radios of SUs to meet and establish a link on a commonly-available channel is referred to as "rendezvous" [1]. Rendezvous is a fundamental and essential operation for establishing communication links of SUs. Channel-hopping (CH) is one of the most representative techniques for rendezvous. With CH technique, each user of a CRN selects a set of available channels and hops among these channels for rendezvous with its potential neighbors. If all users have the same available channels, we call it *symmetric model*. We call it *asymmetric model* otherwise, i.e., different users might have different available channels. Basically, the existing CH algorithms can be classified into two categories based on their structures: i) centralized systems, and ii) decentralized systems. The decentralized systems can be further classified into two subcategories depending on whether employing the common control channel (CCC) or not. Because of space limitation, we refer the readers to [2] for a survey and taxonomy of the existing rendezvous algorithms.

To the best of our knowledge, all the existing rendezvous algorithms [2-15] implicitly assume that each user is equipped with one radio (i.e., one wireless transceiver). As the cost of wireless transceivers is dropping, this feature can be exploited to significantly improve the rendezvous performance at low cost. In particular, when a SU is equipped with multiple radios, the time-to-rendezvous (TTR, i.e., the time required by the rendezvous operation) can potentially be reduced by a large amount while the additional cost (i.e., cost of the extra radios) is low.

In this paper, we study the rendezvous problem in CRNs where each SU is equipped with multiple radios and different SUs may have different number of radios. We make three contributions.

i) We investigate a new approach (i.e., exploiting multiple radios per user) to significantly improve the rendezvous performance at low cost.

ii) We generalize the random algorithm and the existing rendezvous algorithms in order to use multiple radios for faster rendezvous.

iii) We propose a new rendezvous algorithm, called *role-based parallel sequence* (*RPS*), which specifically exploits multiple radios for more efficient rendezvous. We derive the maximum TTR (MTTR) and upper bounds on the expected TTR (E(TTR)) of this algorithm. We conduct extensive simulation to demonstrate that its MTTR and E(TTR) decrease significantly with the number of radios.

Table I summarizes the differences between the proposed algorithm and the existing rendezvous algorithms.

TABLE I. COMPARISON OF OUR ALGORITHM AND THE EXISTING RENDEZVOUS ALGORITHMS UNDER THE SYMMETRIC MODEL

	RPS	Existing Algorithms
Applicable to CRNs with multiple radios	yes	no
Applicable to heterogeneous CRNs	yes	no
MTTR	$\left\lceil 2\times\left\lceil\frac{P}{max\{m,n\}}\right\rceil-1\right\rceil$	$\geq 3P$
E(TTR)	$\left\lceil\frac{P}{max\{m,n\}-1}\right\rceil + \frac{\left(\left\lceil\frac{P}{max\{m,n\}-1}\right\rceil-1\right)^2}{2\times\left\lceil\frac{P}{min\{m,n\}-1}\right\rceil}$	$\geq \frac{5P-4}{3}+(2P+1+\frac{1}{P})\times\frac{1}{3Q^{m+n-1}}$

Remarks: i) m, n are the numbers of radios of two users; Q is the number of channels; P is the smallest prime number which is not smaller than Q. ii) In the existing algorithms, we select the Jump-Stay algorithm for comparison since it is shown to have the best overall performance [2]. MTTR and E(TTR) of the existing algorithms are derived by independently applying the Jump-Stay algorithm in each of the radios. iii) In a heterogeneous CRN, different SUs may be equipped with different numbers of radios.

II. FORMULATION

We consider a CRN consisting of K ($K\geq 2$) users. We assume that the network is time-slotted and all timeslots are with the same and fixed length. The licensed spectrum is divided into Q ($Q\geq 1$) non-overlapping channels $C=\{c_1,c_2,\ldots,c_Q\}$, where c_i denotes the i-th channel and usually is called channel i for convenience. We assume that all users in the networks know indices of channels. Let $C_i\in C$ denote the set of available channels of user i (i=1, 2, ···, K), where a channel is said to be available to a user if the user can communicate on the channel without causing interference to any PUs. C_i can be identified by a spectrum sensing method (e.g., [8]) before the rendezvous process. Without loss of generality, we consider the rendezvous of a pair of users, say user i and user j, $i\neq j$ and i, j=1, 2, ···, K. User i is equipped with m ($m>1$) radios and user j is equipped with n ($n>1$) radios. Note that m may not be equal to n in heterogeneous CRNs. Let G denote the number of commonly-available channels of user i and user j. The CH sequence of user i is denoted by $\{\overrightarrow{S_1^i},\overrightarrow{S_2^i},\overrightarrow{S_3^i},\cdots\}$, where vector $\overrightarrow{S_t^i}=\{S_{t1}^i,S_{t2}^i,S_{t3}^i,\cdots,S_{tm}^i\}$ represents that user i hops on channels $\{S_{t1}^i,S_{t2}^i,S_{t3}^i,\cdots,S_{tm}^i\}(S_{t*}^i\epsilon C_i)$ on m radios in timeslot t. In Figure 1, we assume that user i is equipped with 3 radios and user j is equipped with 2 radios. It gives a view of the sequences of users i and user j. R_i represents the *i-th* radio of user.

We consider the following two models [2-3, 8-10].

i) Symmetric model. All users have the same available channels. In other words, $C_i=C_j$.

ii) Asymmetric model. The available channels of user i are different with user j. But, there is at least one commonly available channel for them. That is, $C_i\neq C_j$ and $G\neq 0$.

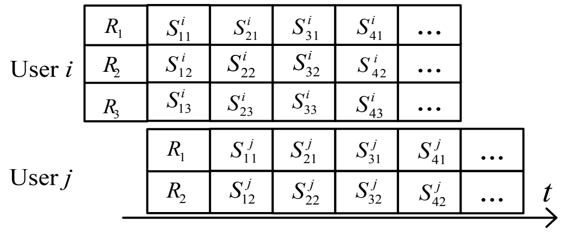


Figure 1. Structure of sequence when users have multiple radios

We assume that time-synchronization is not available in the networks. In each timeslot, user i hops on m channels and user j hops on n channels to attempt rendezvous. We say that a rendezvous is achieved if user i and user j hop on a same channel in any of the radios in the same timeslot. Since time-synchronization is not available, "the same timeslot" of CH sequences means that the overlap of two timeslots is sufficient to complete all necessary steps for rendezvous. In this sense, we can assume the CH sequences of all users are slot-aligned even without time-synchronization [2]. We define the rendezvous problem as follows.

Rendezvous problem: Given a multi-hop CRN consisting of K ($K\geq 2$) users, C_i denotes the set of available channels of user i. The problem is to design a rendezvous algorithm to generate the CH sequence on the multiple radios of the users, such that any pair of users are guaranteed to hop on a commonly-available channel in one of the radios in the same timeslot, regardless of different time when the users start their CH sequences.

III. SOLUTIONS

We generalize the random algorithm and the existing algorithms to use multiple radios for faster rendezvous in sections III.A and III.B respectively. In section III.C, we design a new rendezvous algorithm which specifically exploits multiple radios for more efficient rendezvous.

A. Generalized Random Algorithm

When there is a single radio, the random algorithm randomly selects an available channel in each time slot and attempts to achieve rendezvous on this channel in this slot. When there are multiple radios, this random algorithm can be generalized as follows: each radio randomly and independently selects an available channel in each time slot and attempts to achieve rendezvous on this channel in this slot. When two or more radios happen to select the same channel, these radios will randomly select again until they select different channels. The following theorem gives the performance properties of the generalized random algorithm.

Theorem 1. The E(TTR) of the generalized random rendezvous algorithm is equal to $\frac{Q^{m+n}}{Q^{m+n}-A_Q^{m+n}}$ under the symmetric model. Its MTTR is equal to infinity.

Proof: The proof is given in [16].

B. Generalized Existing Rendezvous Algorithms

In the literature, several rendezvous algorithms have been proposed for CRNs with one radio per user. We consider two strategies to generalize these algorithms to use multiple radios:

a. *Independent Sequence*: Apply an existing algorithm in each radio which generates CH sequence independently.

b. *Parallel Sequence*: Apply an existing algorithm to generate a CH sequence. The CH sequence is in parallel performed in all radios.

We first consider the Independent Sequence strategy. With the Independent Sequence, each radio of a user is treated as a virtual user which independently attempts rendezvous by performing existing algorithm *A*. This strategy is formally presented as follows.

Independent Sequence

1: **Input**: Q, m, A, C_i *//existing algorithm A and user i*
2: t=1; $\overrightarrow{S_t^i} = \{S_{t1}^i, S_{t2}^i, S_{t3}^i, \ldots, S_{tm}^i\}$;
3: S_{Ak}, $k \in (1, m)$*//the k-th sequence generated by A*
4: **while** (*not rendezvous*)
5: **for** $k \leftarrow 1$ to m
6: $S_{tk}^i = S_{Akt}$;
7: **end**
8: t=t+1;
9: Attempt rendezvous on $\overrightarrow{S_t^i}$;
10: **end**

In line 3, since the user has *m* radios, it generates *m* independent CH sequences by algorithm *A*. In line 6, the *k-th* sequence is performed in the *k-th* radio. Let $\mathrm{MTTR_A}$denote the MTTR of *A* in CRNs with single radio. The following theorem states that applying existing algorithm *A* in multiple radios independently does not decrease the MTTR, compared with $\mathrm{MTTR_A}$. That is, advantage of multiple radios is not properly utilized in this strategy.

Theorem 2. If two users perform existing algorithm *A* in multiple radios with Independent Sequence, the maximum time-to-rendezvous (MTTR) is equal to $MTTR_A$.

Proof: The proof is given in [16].

Among the existing rendezvous algorithms, the Jump-Stay algorithm performs well [2]. We apply it to multiple radios.

Corollary 1. Under the symmetric model, any two users performing Jump-Stay in multiple radios with Independent Sequences achieve rendezvous in at most $3P$ timeslots which is an upper-bound of MTTR. E(TTR) is not greater than $\frac{5P-4}{3} + \frac{1}{3Q^{m+n-1}} \times (2P + 1 + \frac{1}{P})$, where *P* is the smallest prime number which is not smaller than *Q*.

Proof: The proof is given in [16].

We now consider the Parallel Sequence strategy. Each user applies an existing algorithm to generate a CH sequence. Then, this CH sequence is in parallel performed in all radios of the user. For instance, algorithm *A* generates CH sequence $\{s_1, s_2, s_3, s_4, \cdots\}$. Suppose that a user is equipped with three radios. In the first timeslot, the three radios hop on s_1, s_2 and s_3, respectively. In the second timeslot, the three radios hop on s_4, s_5 and s_6, respectively, and so on. The strategy of Parallel Sequence is formally presented as the following, where user *i* is equipped with *m* radios.

Parallel Sequence

1: **Input**: Q, m, A, C_i *//existing algorithm A and user i*
2: t=1; $\overrightarrow{S_t^i} = \{S_{t1}^i, S_{t2}^i, S_{t3}^i, \ldots, S_{tm}^i\}$;
3: S_A; *//the sequence generated by A*
4: **while** (*not rendezvous*)
5: **for** $k \leftarrow 1$ to m
6: $S_{tk}^i = S_{A((t-1)\times m+k)}$;
7: **end**
8: t=t+1;
9: Attempt rendezvous on $\overrightarrow{S_t^i}$;
10: **end**

Line 3 reveals one key point. That is, each user has only one sequence which is generated by *A*. In line 6, *m* channels in S_A will be copied to *m* radios in each timeslot.

Theorem 3. Suppose that all users are equipped with *m* radios. Under the symmetric and the asymmetric models, any two users performing existing algorithm *A* in multiple radios with Parallel Sequence achieve rendezvous in at most $\left\lceil \frac{MTTR_A}{m} \right\rceil$ timeslots.

Proof: The proof is given in [15].

Corollary 2. Suppose that all users are equipped with *m* radios. Under the symmetric model, any two users performing Jump-Stay in multiple radios with Parallel Sequences achieve rendezvous in at most $\left\lceil \frac{3P}{m} \right\rceil$ timeslots. E(TTR) is not greater than $(\frac{5P}{3} + \frac{11}{3} + \frac{1}{Q})/m$, where *P* is the smallest prime number which is not smaller than *Q*.

Proof: The proof is given in [16].

C. New Algorithm

The analysis in Section B reveals that the Parallel Sequence strategy can better exploit multiple radios to achieve smaller MTTR. Hence we adopt this strategy in our algorithm. Our basic idea is to assign multiple radios with two roles: *general radio* and *dedicated radio*. There is only one dedicated radio and the remaining radios are general radios. Users hop on available channels in the general radios while stay on a specific channel in the dedicated radio. The rendezvous is expected to be achieved between the general radios of one user and the dedicated radio of the other. Suppose that a user is equiped with *m* radios. Our algorithm, *Role-based Parallel Sequence* (*RPS*), is described as follows.

i). All radios are divided into two groups, (m−1) *general radios* and one *dedicated radio*.

ii). A starting index *i* is randomly selected from [1, P−1]. A step-length *r* is randomly selected from [1, P−1]. *P* is the smallest prime number which is not smaller than *Q*.

iii). The (m−1) general radios in parallel hop on *P* channels with step-length *r* in the round-robin fashion.

iv). The dedicated radio stays on one channel for $\left\lceil \frac{P}{m-1} \right\rceil$ timeslots and switches to next channel for the same duration. The stay channel is taken from [1, Q] in the round-robin fashion.

v). If the channel is not available to the user, a random available channel will be selected to replace it.

The algorithm is formally presented as follows.

RPS Algorithm

1: **Input**: Q, m, C_i
2: t=1; $\overrightarrow{S_t^i} = \{S_{t1}^i, S_{t2}^i, S_{t3}^i, \ldots, S_{tm}^i\}$;
3: P=the smallest prime number not smaller than Q;
4: i=RandomSelect(1,P); r= RandomSelect(1,Q);
5: **while** (*not rendezvous*)
6: **for** $k \leftarrow 1$ to (m-1)
7: S_{tk}^i=(i+((t-1)×(m-1)+k-1)×r-1)%P+1;
8: **if** $S_{tk}^i > Q$
9: $S_{tk}^i = S_{tk}^i \% Q$;
10: **if** $S_{tk}^i \notin C_i$
11: S_{tk}^i=RandomSelect(C_i);
12: **end**
13: $S_{tm}^i = \left(\left\lceil \frac{t}{\lceil P/_{m-1} \rceil} \right\rceil - 1\right) \% Q + 1$;
14: **if** $S_{tm}^i \notin C_i$
15: S_{tm}^i=RandomSelect(C_i);
16: t=t+1;
17: Attempt rendezvous on $\overrightarrow{S_t^i}$;
18: **end**

In line 4, starting index i and step-length r are preselected randomly. In lines 6-9, the (m−1) general radios will hop on continuous (m−1) channels with i and r. In line 13, the dedicated radio will switch to the next channel after $\left\lceil \frac{P}{m-1} \right\rceil$ timeslots. It can guarantee a rendezvous under the asymmetric model. Lines 10-11 and 14-15 ensure that the channels are available to the user.

Theorem 4. Under the symmetric model, let m and n denote the number of radios of two users, respectively. If $m \neq n$, MTTR of *RPS* is not greater than $\left(2 \times \left\lceil \frac{P}{\max\{m,n\}} \right\rceil - 1\right)$ and E(TTR) of *RPS* is not greater than $\left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil + \frac{\left(\left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil - 1\right)^2}{2\times\left\lceil \frac{P}{\min\{m,n\}-1} \right\rceil}$; if m=n, MTTR of *RPS* is not greater than $\left(\left\lceil \frac{P}{\max(m,n)-1} \right\rceil\right)$ and E(TTR) of *RPS* is not greater than $\left(\left\lceil \frac{P}{\max(m,n)-1} \right\rceil\right)$.

Proof. We assume that user i is equipped with m radios while user j is equipped with n radios. Figure 2 lists the four subcases of rendezvous under symmetric model. Figures 2(a), 2(b), and 2(c) happen when $m \neq n$. Since the results depend on which user starts hopping first, we assume m<n, i.e., $\left\lceil \frac{P}{m-1} \right\rceil > \left\lceil \frac{P}{n-1} \right\rceil$. Figure 2(d) happens when $m = n$. A remarkable distinguishment between them is whether the length of each round of the two users is same.

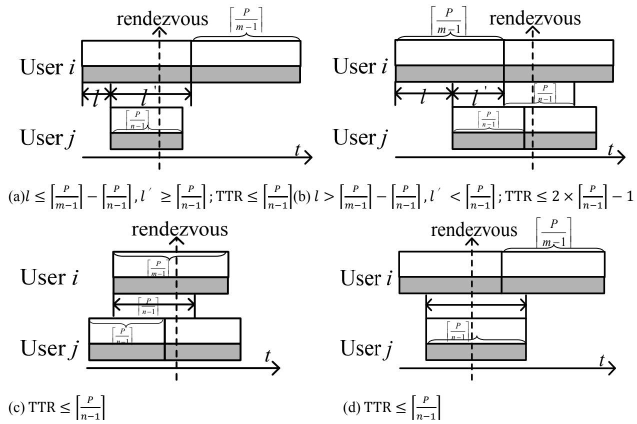


Figure 2. Four cases of *RPS* under the symmetric model

Case 1: Figure 2(a). $l' \geq \left\lceil \frac{P}{n-1} \right\rceil$ implies that there is a permutation of all channels before the *dedicated radio* of user i transfer to next channel. The rendezvous is achieved between *general radios* of user j and *dedicated radio* of user i during the first $\left\lceil \frac{P}{n-1} \right\rceil$ timeslots. That is, $TTR \leq \left\lceil \frac{P}{n-1} \right\rceil$.

Case 2: Figure 2(b). In this subcase, $l' < \left\lceil \frac{P}{n-1} \right\rceil$ implies that there is no enough timeslots for user j to have permutation of all channels before the *dedicated radio* of user i transfer to next channel. The rendezvous can only be guaranteed between *general radios* of user i and *dedicated radio* of user j during the first $2\left\lceil \frac{P}{n-1} \right\rceil - 1$ timeslots. That is, $TTR \leq 2\left\lceil \frac{P}{n-1} \right\rceil - 1$.

Case 3: Figure 2(c). User j starts firstly. User j has a permutation of all channels in any continuous $\left\lceil \frac{P}{n-1} \right\rceil$ timeslots. When user i starts, it will stay on one channel for $\left\lceil \frac{P}{m-1} \right\rceil$ timeslots. $\left\lceil \frac{P}{m-1} \right\rceil > \left\lceil \frac{P}{n-1} \right\rceil$. So, a rendezvous is guaranteed before $\left\lceil \frac{P}{n-1} \right\rceil$ timeslots.

Case 4: Figure 2(d). m=n. the rendezvous is achieved before the first $\left\lceil \frac{P}{m-1} \right\rceil$(or $\left\lceil \frac{P}{n-1} \right\rceil$) timeslots.

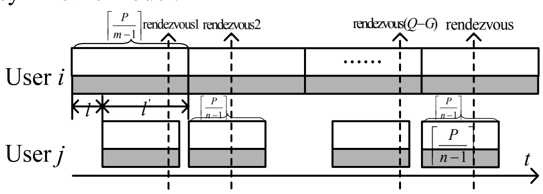
When $m \neq n$, in the above analysis, $\left\lceil \frac{P}{m-1} \right\rceil$is replaced by $\left\lceil \frac{P}{\min\{m,n\}-1} \right\rceil$ and $\left\lceil \frac{P}{n-1} \right\rceil$ by $\left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil$. According to analysis of these cases, we prove that MTTR is$\left(2 \times \left\lceil \frac{P}{\max\{m,n\}} \right\rceil - 1\right)$. Combining with the occurrence probabilities we derive an upper-bound of E(TTR) under the symmetric model.

$$\mathrm{E(TTR)} \leq \frac{1}{2} \times \left[\frac{\left\lceil \frac{P}{\min\{m,n\}-1} \right\rceil - \left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil + 1}{\left\lceil \frac{P}{\min\{m,n\}-1} \right\rceil} \times \left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil + \frac{\left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil - 1}{\left\lceil \frac{P}{\min\{m,n\}-1} \right\rceil} \times \left(2 \times \left\lceil \frac{P}{max\{m,n\}} \right\rceil - 1\right) \right] + \frac{1}{2}\left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil \leq \left\lceil \frac{P}{\max\{m,n\}-1} \right\rceil + \frac{\left(\left\lceil \frac{P}{max\{m,n\}-1} \right\rceil - 1\right)^2}{2\times\left\lceil \frac{P}{\min\{m,n\}-1} \right\rceil}.$$

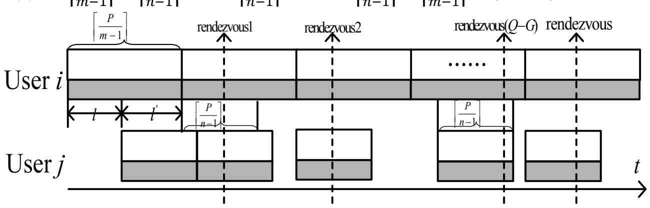
There is only one case when $m = n$. The MTTR and the upper-bound of E(TTR) are both $\left\lceil \frac{P}{m-1} \right\rceil$ or $\left\lceil \frac{P}{n-1} \right\rceil$. ∎

Theorem 5. Under the asymmetric model, let *m* and *n* denote the number of radios of two users, respectively. If $m \neq n$, MTTR of *RPS* is not greater than $\left(2\times\left\lceil\frac{P}{\max\{m,n\}}\right\rceil-1\right)+\left\lceil\frac{P}{\min\{m,n\}}\right\rceil\times(Q-G)$ and E(TTR) of *RPS* is not greater than $\left\lceil\frac{P}{\max\{m,n\}-1}\right\rceil+\frac{\left(\left\lceil\frac{P}{\max\{m,n\}-1}\right\rceil-1\right)^2}{2\times\left\lceil\frac{P}{\min\{m,n\}-1}\right\rceil}+\left\lceil\frac{P}{\min\{m,n\}}\right\rceil\times(Q-G)$; if *m*=*n*, MTTR of *RPS* is not greater than $\left(\left\lceil\frac{P}{m-1}\right\rceil\times(Q-G+1)\right)$ and E(TTR) of *RPS* is not greater than $\left(\left\lceil\frac{P}{m-1}\right\rceil\times(Q-G+1)\right)$.

Proof. Due to the limited space, we list case 1 and 2 under the asymmetric model. The assumption is same with the symmetric model.



(a)$l \le \left\lceil\frac{P}{m-1}\right\rceil-\left\lceil\frac{P}{n-1}\right\rceil, l' \ge \left\lceil\frac{P}{n-1}\right\rceil$; TTR $\le \left\lceil\frac{P}{n-1}\right\rceil+\left\lceil\frac{P}{m-1}\right\rceil\times(Q-G)$



(b)$l > \left\lceil\frac{P}{m-1}\right\rceil-\left\lceil\frac{P}{n-1}\right\rceil, l' < \left\lceil\frac{P}{n-1}\right\rceil$; TTR $\le 2\times\left\lceil\frac{P}{n-1}\right\rceil-1+\left\lceil\frac{P}{m-1}\right\rceil\times(Q-G)$

Figure 3. two cases of *RPS* under the asymmetric model

Under the asymmetric model, since the available channel sets of two users are different from each other, the users may achieve many potential rendezvous (rendezvous 1 to ($Q-G$) in Figure 3). In Figure 3(a), user j has a permutation of all channels before $\left\lceil\frac{P}{n-1}\right\rceil$ and the *dedicated radio* of user *i* stays on one channel during this period. There is a potential rendezvous before $\left\lceil\frac{P}{n-1}\right\rceil$, this channel may be not a commonly available channel to all users. The next potential rendezvous can be guaranteed in the next round of user i ($\left\lceil\frac{P}{m-1}\right\rceil$ to $2\times\left\lceil\frac{P}{m-1}\right\rceil$ in Figure 3) because only after these timeslots the *dedicated radio* of user *i* will transfer to the next channel. We can say, under asymmetric model, we expect a rendezvous between the *dedicated radio* of the user with less radios (user *i*) and the *general radios* of the user with more radios (user *j*). The worst case is repeating the rendezvous under symmetric model for $(Q-G)$ times. Above all, the new MTTR should be equal or smaller than $\left\lceil\frac{P}{min\{m,n\}-1}\right\rceil\times(Q-G)$. We assume the probability of event that a commonly available channel appears on the 1*st* to $(Q-G)$-*th* potential rendezvous is equal. The upper-bound of E(TTR) when $m \neq n$ extend for $\left\lceil\frac{P}{\min\{m,n\}-1}\right\rceil\times(Q-G)$ in all cases. In this way,

$$\text{E(TTR)} \le \left\lceil\frac{P}{\max\{m,n\}-1}\right\rceil+\frac{\left(\left\lceil\frac{P}{\max\{m,n\}-1}\right\rceil-1\right)^2}{2\times\left\lceil\frac{P}{\min\{m,n\}-1}\right\rceil}+\left\lceil\frac{P}{\min\{m,n\}-1}\right\rceil\times(Q-G)$$

And similarly, the MTTR and the upper-bound of E(TTR) when *m*=*n* is $\left(\left\lceil\frac{Q}{m-1}\right\rceil\times(Q-G+1)\right)$. ■

IV. SIMULATION

In simulation, TTR is counted as the number of timeslots that it takes for the two users to achieve rendezvous. For the Independent Sequences and the Parallel Sequences, the Jump-Stay algorithm [3] is applied. Under the symmetric model, all channels are available to all users. Under the asymmetric model, we introduce a parameter θ *(0<θ<1)* and randomly select channels from the channel set, such that the average size of commonly-available channels is equal to θQ. We let θ=0.5 and equally assign the rest channels to the two users (i.e., each user has $\left(\frac{\theta+1}{2}\right)Q$ channels and each pair users have θQ commonly-available channels). For each set of parameter values, we perform 1,000,000 independent runs under the symmetric model and 10,000,000 independent runs under the asymmetric model and then compute E(TTR) and MTTR accordingly.

We first study the merit of multiple radios over single radio. We adopt Jump-Stay [3] in the single-radio scenario and the generalized Jump-Stay algorithm (parallel Jump-Stay described in Section III.B) in the multi-radio scenario. Figure 4 shows the results for the symmetric model. It can be seen that using multiple radios can significantly reduce both E(TTR) and MTTR. For example, when there are 20 available channels and the number of radios is increased from 1 to 2, E(TTR) is decreased from 12.944 to 5.426 while MTTR is decreased from 65 to 35. For the asymmetric model, Figure 5 shows that multiple radios can give larger performance improvement. For example, when there are 20 available channels and the number of radios is increased from 1 to 2, E(TTR) is decreased from 19.463 to 6.898 while MTTR is decreased from 206 to 48.

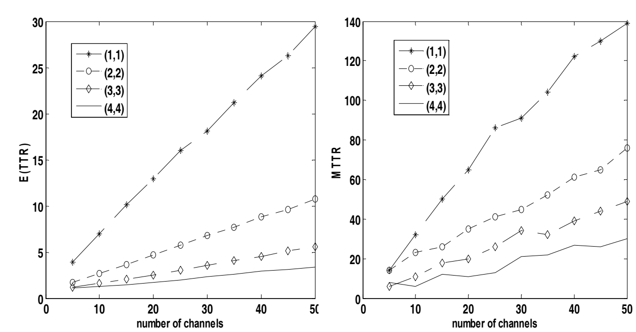


Figure 4. Performance of multi-radio and single-radio under the symmetric model

We now study the performance of the proposed rendezvous algorithm and the generalized versions of the existing algorithms. We let *m*=3 and *n*=4. Figure 6 and 7 show the results for the symmetric and asymmetric models respectively. We see that the proposed algorithm gives the best performance in terms of both E(TTR) and MTTR. For example, for 20 available channels under the symmetric model, the proposed algorithm gives an E(TTR) of 1.933 and a MTTR of 14, while the generalized version of the best existing algorithm (parallel Jump-Stay) gives an E(TTR) of 2.388 and a MTTR of 39. These results show that the proposed algorithm can better exploit the availability of multiple radios for more efficient rendezvous.

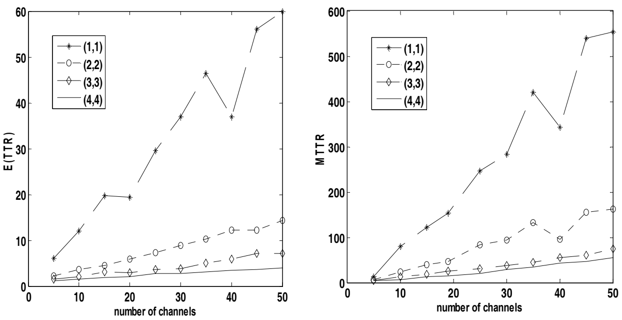


Figure 5. Performance of multi-radio and single-radio under the asymmetric model

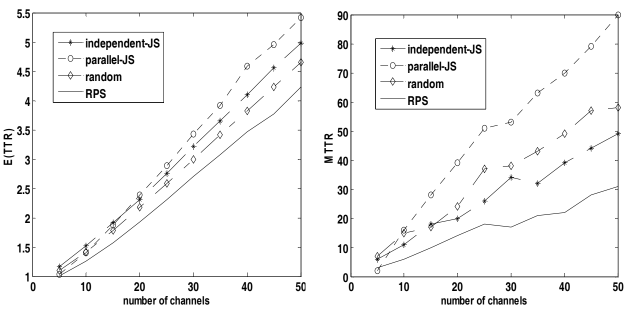


Figure 6. Performance of the proposed rendezvous algorithm and the existing rendezvous algorithms (generalized to multi-radio) under the symmetric model

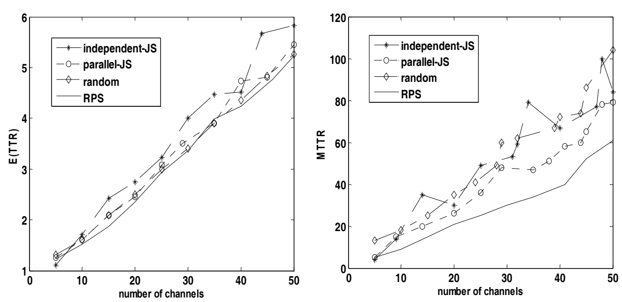


Figure 7. Performance of the proposed rendezvous algorithm and the existing rendezvous algorithms (generalized to multi-radio) under the asymmetric model

V. CONCLUSIONS

We studied a new approach to rendezvous in cognitive radio networks. In this approach, each user is equipped with multiple radios (wireless transceivers) so that the rendezvous performance could be significantly improved at low cost. Under this approach, we designed a rendezvous algorithm which specifically exploits multiple radios for efficient rendezvous. We derived the maximum TTR (MTTR) and the upper bounds on the expected TTR (E(TTR)) of this algorithm, and demonstrated via extensive simulation that its MTTR and E(TTR) could be significantly reduced. Therefore, the proposed approach and the proposed rendezvous algorithm could cost-effectively improve the rendezvous performance.

ACKNOWLEDGMENT

This work is supported in part by grants FRG2/11-12/160 and FRG2/12-13/055 of Hong Kong Baptist University. Zhiyong Lin is supported by the National Natural Science Foundation of China (Grant No. 61202453) and the Natural Science Foundation of Guangdong Province in China (Grant No. S2011040002890).

REFERENCES

[1] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, “NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey,” *Computer Networks*, vol. 50, no. 13, pp. 2127-2159, 2006.

[2] H. Liu, Z. Lin, X. Chu, and Y. W. Leung, “Taxonomy and Challenges of Rendezvous Algorithms in Cognitive Radio Networks,” invited position paper, *Proc. Int. Conf. Computing, Networking and Communication*, pp. 645-649, Hawaii, 2012.

[3] H. Liu, Z. Lin, X. Chu, and Y. W. Leung, “Jump-Stay Rendezvous Algorithm for Cognitive Radio Networks,” *IEEE Trans. Parallel and Distributed Systems,* vol. 23, no. 10, pp. 1867-1881, 2012.

[4] N. C. Theis, R. W. Tomas, L. A. DaSilva, “Rendezvous for Cognitive Radios,” *IEEE Trans. Mobile Comput.,* vol. 10, no. 2, 2011.

[5] J. Shin, D. Yang, and C. Kim, ”A Channel Rendezvous Scheme for Cognitive Radio Networks, ” *IEEE Communications Letters,* vol. 14, no. 10, pp. 954-956, 2010.

[6] C. Cormio and K. R. Chowdhury, “Common Control Channel Design for Cognitive Radio Wireless Ad Hoc Networks Using Adaptive Frequency Hopping,” *Ad Hoc Networks*, vol. 8, pp. 430-438, 2010.

[7] H. Liu, Z. Lin, X. Chu, and Y. W. Leung, “Ring-Walk Based Channel-Hopping Algorithm with Guaranteed Rendezvous for Cognitive Radio Networks,” *Proc. of IEEE/ACM International Conference on Green Computing and Communications,* 2010.

[8] M. M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, “DIMSUMnet: New Directions in Wireless Networking Using Coordinated Dynamic Spectrum,” *Proc. of IEEE WoWMoM 2005,* pp. 78-85, Jun. 2005.

[9] B. Horine and D. Turgut, “Performance Analysis of Link Rendezvous Protocol for Cognitive Radio Networks*,” Proc. of Second IEEE Int’l Conf. Cognitive Radio Oriented Wireless Nerworks and Comm. (CROWNCOM ’07),* pp. 503-507, Aug. 2007.

[10] P. Sutton, K. Nolan, and L. Doyle, “Cyclostationary Signatures in Practical Cognitive Radio Applications*,” IEEE J. Selected Areas inComm.,* vol. 26, no. 1, pp. 13-24, Jan. 2008.

[11] V. Brik, E. Rozner, S. Banerjee, and P. Bahl, “DSAP: A Protocol for Coordinated Spectrum Access,” *Proc. of IEEE DySPAN 2005,* pp. 611-614, Nov. 2005.

[12] J. Jia, Q. Zhang, and X. Shen, “HC-MAC: A Hardware-constrained Cognitive MAC for Efficient Spectrum Management,” *IEEE Journal on Selected Areas in Communications,* vol. 26, no. 1, pp.106-117, 2008.

[13] L. Ma, X. Han, and C.-C. Shen, “Dynamic Open Spectrum Sharing for Wireless Ad Hoc Networks,” *Proc. of IEEE DySPAN 2005, pp. 203-213,* Nov. 2005.

[14] Zhiyong Lin, Hai Liu, Xiaowen Chu, Yiu-Wing Leung, “Jump-Stay Based Channel-Hopping Algorithm with Guaranteed Rendezvous for Cognitive Radio Networks,” *in Proceedings of IEEE INFOCOM 2011, Shanghai, China,* 10-15 Apr. 2011

[15] K. Bian, J.-M. Park, and R. Chen, “A Quorum-based Framework for Establishing Control Channels in Dynamic Spectrum Access Networks,” *Proc. of MobiCom’09,* Sept. 2009.

[16] L. Yu, H. Liu, Y. W. Leung, X. Chu, and Z. Lin, “Multiple Radios for Effective Rendezvous in Cognitive Radio Networks: Proof of Theoretical Results” Internal Report, Department of Computer Science, Hong Kong Baptist University, Sept. 2012. [Online: http://www.comp.hkbu.edu.hk/~ywleung/paper/Multiradio_CRN.pdf].