Asynchronous Quorum-Based Blind Rendezvous Schemes for Cognitive Radio Networks

Jang-Ping Sheu, *Fellow, IEEE*, Chih-Wei Su, and Guey-Yun Chang

***Abstract*—In cognitive radio networks, unlicensed users [secondary users (SU)] need to rendezvous on licensed channels before establishing communication links. Dedicated common control channel is the simplest way to achieve rendezvous. However, due to the absolute priority of licensed users [primary users (PU)] on accessing licensed channels, a dedicated common control channel may cause the PU long-time blocking problem, and the control channel saturation problem in a high SU density environment. Channel hopping schemes have been proposed to avoid the problems mentioned above. In this paper, we introduce two quorum-based channel hopping schemes. Our schemes outperform in terms of the four metrics: maximum time to rendezvous, channel loading, degree of rendezvous, and maximum conditional time to rendezvous.**

***Index Terms*—Channel hopping, cognitive radio networks, quorum system.**

I. Introduction

OWING TO THE increasing demand for bandwidth in unlicensed spectrum band (e.g., ISM band) and the underutilization of licensed spectrum bands (e.g., 400–700 MHz) [1], cognitive radio networks (CRNs) have become an important technology for addressing unlicensed users to access licensed spectrum bands. In CRNs, unlicensed users called secondary users (SUs), can dynamically and opportunistically access the licensed spectrum bands which are allocated to licensed users, called primary users (PUs). Since PUs have absolute priority to access licensed spectrum bands, licensed spectrum access of SUs should not interfere PUs' signals. Once a PU's signal appears, SUs should vacate the spectrum (i.e., channel) immediately and find another vacant channel to proceed the transmission. For this purpose, each SU is equipped with one or more cognitive radio transceivers which can switch their operation channels and sense/detect vacant ones. After completing the sensing process, each SU has a set of vacant channels (or *available channel*s). When two SUs want to communicate with each other, they should be able to rendezvous on the same available channel for control message/data exchange.

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Implementing rendezvous on available channels is challenging. The availability of a channel is position-varying (depends on the position of the SU relative to PUs) and time-varying (depends on the appearance time of PU signals). More precisely, two SUs who want to rendezvous may have distinct sets of available channels and cannot be aware of each other available channel set. Most of existing rendezvous schemes adopt dedicated common control channel (DCCC) [8]–[11], [14], [17], [22]. In DCCC-based approaches, a globally available channel is chosen to exchange the control messages/data. Although these strategies simplify the rendezvous process, they have the following drawbacks: (1) Maintaining globally available channels is usually infeasible for CRNs since SUs may not have globally/commonly available channels; (2) DCCC may be continuously blocked/occupied by PUs for a long time, called *the PU long-time blocking problem* [18]; (3) A single DCCC will be a bottleneck and cause *the control channel saturation problem* [18] in a high node density or high traffic environments.

Channel hopping (CH) techniques have been proposed to solve the dedicated rendezvous channel problem. In CH-based schemes, each SU generates its CH sequence and hops on licensed channels according to the generated sequence. A pair of SUs could have multiple rendezvous on distinct channels. CH-based schemes can be classified according to two criteria, asymmetric-role versus symmetric-role, and time synchronous versus time asynchronous. Asymmetric-role approaches [5], [6] assume that each SU has a pre-assigned role, a sender or a receiver, before starting rendezvous. Different roles of SUs use different ways to generate CH sequences. In asymmetric-role approaches, the rendezvous between the sender-receiver pairs is guaranteed, while the rendezvous between sender-sender pairs is not (i.e., rendezvous is not guaranteed when each node may become a sender and a receiver simultaneously). Symmetric-role approaches [3]–[7], [12], [15], [16], [18], [19], [21] have no pre-assigned role and thus each SU uses the same way to generate CH sequences. Synchronous CH systems [3], [4], [18], [19] require a synchronous global clock, while asynchronous CH systems [4]–[7], [12], [15], [16], [21] do not. Clearly, without global clock synchronization, guaranteeing rendezvous in asynchronous CH systems is more challenging.

In general, CH systems in CRNs are evaluated by the following four metrics [5].

1) Maximum Time-to-Rendezvous (MTTR): The maximum time between any pair of sequences in a CH system to rendezvous on a channel (no matter the channel is available or not) is called the maximum-time-to-rendezvous. Since the control message exchange is not possible without

rendezvous, minimizing the MTTR can also reduce the medium access delay.

2) Channel Loading: In CH systems, it is important to spread out the rendezvous in time and channel. Given a CH scheme which has M different CH sequences, the maximum proportion of the M CH sequences rendezvous on the same channel at the same timeslot is its *channel loading*. For a CH scheme with channel loading α and M CH sequences, there are at most $M\alpha$ CH sequences rendezvous on the same channel at the same timeslot. A large channel loading leads to the control channel bottleneck problem and high probability of channel congestion.

3) Degree of Rendezvous: The minimum number of distinct rendezvous channels for any two CH sequences is called the *degree of rendezvous* of the CH system. If two sequences rendezvous on an unavailable channel, they would not exchange the control message. Maximizing the degree of rendezvous can maximize the probability of rendezvous on commonly available channels and reduce the impact of PU long time blocking problem.

4) Maximum Conditional Time-to-Rendezvous (MCTTR): The maximum time between any two CH sequences to rendezvous on an available channel is called the *maximum conditional time to rendezvous*. In an N-degree-of-rendezvous CH system, any pair of sequences can rendezvous on all of N channels. If there exists at least one commonly available channel for any two SUs, then any pair of sequences can exchange control message successfully within a guaranteed time.

In this paper, we study asynchronous CH approaches. Existing asynchronous CH approaches usually have one or more of the following drawbacks: unbounded/long MTTR and MCTTR [4], [12], [20], [21], high/unbalanced channel loading [4], and low degree of rendezvous [4], [12], [20], [21]. In this paper, we proposed two quorum-based CH protocols for asynchronous environments: one asymmetric-role approach, D-QCH, and one symmetric-role approach, S-QCH. To reduce MCTTR, each D-QCH/S-QCH sequence is determined according to the detected available channels. D-QCH has smaller $\text{MCTTR} = (\alpha - k + 1)N$, where α is the number of channels available to the receiver and k is the number of channels commonly available to sender and receiver. S-QCH has $\text{MCTTR} = (\alpha - k + 1)N(2N + 1)$, where α is the number of channels available to a SU.

The rest of this paper is organized as follows. Section II describes the system model and quorum systems. Section III provides the detail of our two asynchronous CH protocols, and theoretical analysis is presented in Section IV. We compare the performance of our proposed scheme with previous work in Section V. Section VI presents the simulation results. Finally, Section VII concludes this paper.

II. PRELIMINARY

A. System Model

Throughout this paper, we consider asynchronous environments without global system clock. We assume that time is divided into multiple slots. The local clock of each SU may have different slot shifts with the global clock and the slot boundary is aligned [5], [23]. Let Δ be the minimal desired time to exchange information (i.e., control message/data) between SUs. To cope with slot boundary misalignment, the slot time is set to be 2Δ to ensure that the information exchange can be completed in a time slot (because for each local time slot t of a sender, there exists a local time slot t' of the receiver such that t and t' are overlapped not smaller than Δ) [23]. Hence, slot boundary can be regarded as aligned.

We also assume that there are N orthogonal licensed channels, which are labeled as $0, 1, \ldots,$ and $N - 1$. Each SU is equipped with a single half-duplex cognitive radio transceiver, so they can only either transmit or receive over one channel at a certain time. SUs are able to perform perfect spectrum sensing on their operating channels. Note that, any two SUs may have different sets of available channels. In this paper, "available channel set" of a SU is obtained by performing spectrum sensing before the SU develops its channel hopping sequence. Then SUs use their "available channel sets" to determine their hopping sequences. Obviously, channel availability may change over time, i.e., a channel c in the determined "available channel set" may become unavailable when an SU sender wants to transmit packets at channel c. To protect PU transmission, in each slot, each SU sender performs spectrum sensing to acquire the availability of the operating channel before it starts a transmission. When an SU sender detects PU signals at the operating channel in slot t, the SU sender vacates the operating channel and does not transmit any packet in slot t.

A CH sequence determines the order with which an SU visits all of the N licensed channels. We represent a CH sequence u with CH period $= T$ slots as $u = \{u_0, u_1, \ldots, u_i, \ldots, u_{T-1}\}$, where $u_i \in [0, N-1]$ represents the channel visited by sequence u in the i^{th} timeslot of a CH period. Each SU repeats its CH sequence once per CH period, i.e., $u_j = u_{(j \bmod T)}$. Let $G(u, i)$ be the global time of sequence u's local i^{th} timeslot. We say that two CH sequences u and v can *rendezvous* if $\exists\, i$ and j. such that $u_i = v_j = h$ and $G(u, i) = G(v, j)$, where $h \in [0, N-1]$. In this case, the channel h is called a *rendezvous channel*. Once two sequences rendezvous, they can exchange the control message on the rendezvous channel every CH period as long as the rendezvous channel is available.

B. The Quorum System

Below we provide a brief introduction of quorum systems and a property of quorums [5].

Definition 1: Given an n-element universal set $U = \{0, 1, \ldots, n-1\}$, a quorum system Q under U is a collection of non-empty subsets of U, which satisfies the rotation closure property. Each $q \in Q$ (i.e., a subset of U) is called a *quorum*.

Rotation Closure Property: Let Q be a collection of non-empty subsets of a universal set U. Then we say that Q satisfies the rotation closure property if $\forall p, q \in Q$, $p \neq q$ and $\forall k \in [0, n-1]$, $Qrotate(p, k) \cap q \neq \emptyset$, where $Qrotate(p, k) = \{(i + k) \bmod n \,|\forall i \in p\}$ is a cyclic rotation of quorum p by k shifts. For example, assume $n = 5$, $Q = \{\{0, 1, 2\}, \{1, 2, 3\}, \{2, 3, 4\}\}$, $p = \{2, 3, 4\}$ and $q = \{1, 2, 3\}$, we have that $Qrotate(p, 2) = \{4, 0, 1\}$ and $Qrotate(p, 2) \cap q = \{1\}$.

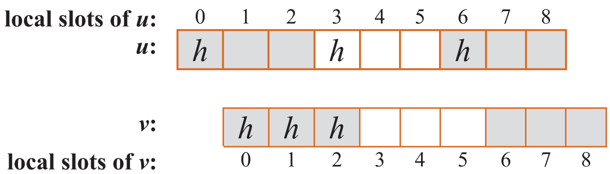


Fig. 1. Sequences associated with quorums $q_1 = \{0, 3, 6\}$ and $q_2 = \{0, 1, 2\}$.

III. Asynchronous Quorum-Based Channel Hopping System

In this section, we proposed two quorum-based asynchronous CH schemes for CRNs. Intuitively, a quorum-based asynchronous CH system H with CH period T and degree of rendezvous $= 1$ can be designed as follows.

1. Each SU chooses a quorum q_i in the default quorum system $Q = \{q_1, q_2\}$ under universal set $U = \{0, 1, \ldots, T-1\}$, where $q_1 = \{0, t, 2t, \ldots, (n-1)t\}$ and $q_2 = \{0, 1, 2, \ldots, t-1\}$, $T = nt$, n and t are integers.
2. Element e of the SU's sequence is assigned to be the default channel h if $e \in q_i$, and the other channels otherwise.

For example, $n = 3$, $t = 3$, $Q = \{\{0, 3, 6\}, \{0, 1, 2\}\}$ and $U = \{0, 1, 2, 3, 4, 5, 6, 7, 8\}$. Two SUs choose distinct quorums q_1 and q_2, respectively, to construct their sequences u and v, respectively (see Fig. 1). That is, sequences u and v visit default channel h at their SUs' local time slots 0, 3, 6, and 0, 1, 2, respectively. By the rotation property of quorums, sequences u and v are guaranteed to rendezvous on default channel h within $T = 9$ slots in synchronous/asynchronous environments.

To design an asynchronous CH system with the degree of rendezvous $= \alpha^*$, we need to construct α^* distinct quorum systems under U. These α^* quorum systems are mapped to α^* licensed channels in a one-to-one manner. Each sequence includes α^* disjoint quorums (which all come from distinct quorum systems), and each quorum denotes the set of slots to visit the mapped channel. Below, we develop two quorum-based asynchronous CH systems, D-QCH and S-QCH.

A. Asymmetric-Role Asynchronous Approach D-QCH

In this subsection, we propose an asynchronous asymmetric-role CH scheme, Dynamic asymmetric-role Quorum-based Channel Hopping (D-QCH). In [6], an N-degree-of-rendezvous asynchronous system needs at least N^2 timeslots to rendezvous on all the N channels, i.e., MCTTR $= N^2$. In fact, rendezvous on uncommonly available channels is of no use, since SUs cannot communicate on unavailable channels (for the purpose of protecting PUs' signals). To reduce MCTTR, our D-QCH sequences include available channels only. Without loss of generality, assume that receiver and sender have α and β available channels, respectively, and k commonly available channels, where $\alpha, \beta \in [1, N]$ and $k \in [1, \min(\alpha, \beta)]$. The CH sequences for sender and receiver are described below.

1) Receiver Sequence in D-QCH: When SUs have nothing to send, they serve as receivers and build D-receiver sequences.

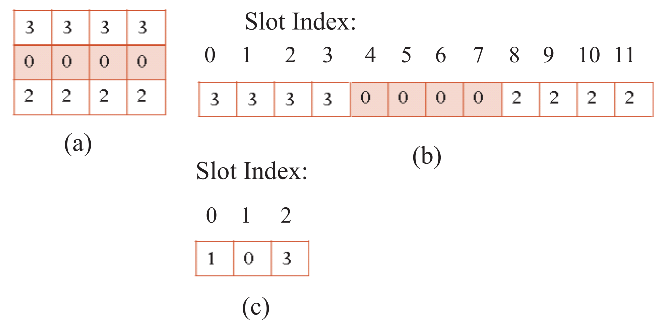


Fig. 2. A D-QCH system with $N = 4$. (a) The D-receiver matrix corresponds to available channels $\{0, 2, 3\}$. (b) The D-receiver sequence corresponds to the D-receiver matrix in (a). (c) The D-sender sequence corresponds to available channels $\{0, 1, 3\}$.

The process of building a D-receiver sequence is as follows. First, randomly select a permutation of α available channels, denoted as $r = \{r_0, r_1, \ldots, r_{\alpha-1}\}$. Second, construct an $\alpha \times N$ matrix (called D-*receiver matrix*), where row i of the matrix is filled with the element r_i. Third, generate a D-receiver CH sequence with CH period $= \alpha \times N$ by concatenating rows of the D-receiver matrix. Consider the case that $N = 4$, the SU serving the receiver role has available channels $\{0, 2, 3\}$ and the permutation $r = \{3, 0, 2\}$. Then it has a $3 \times 4 (= \alpha \times N)$ D-receiver matrix as shown in Fig. 2(a) and a D-receiver CH sequence with CH period 3×4 as shown in Fig. 2(b).

2) Sender Sequence in D-QCH: If SUs have data to transmit, they serve as senders and generate the D-sender CH sequences as follows. First, randomly select a permutation of β available channels, denoted as $s = \left\{s_0, s_1, \ldots, s_{\beta-1}\right\}$. Second, construct the D-sender sequence with CH period $= \beta$ as follows: the i-th element of the D-sender sequence is s_{i-1}. Consider the case that $N = 4$, an SU serving the sender role has available channels $\{0, 1, 3\}$, and the permutation $s = \{1, 0, 3\}$. Then the D-sender sequence has CH period $= 3$ as shown in Fig. 2(c).

In Section IV-A, it is proved that in D-QCH, a D-sender sequence and a D-receiver sequence can rendezvous on all their k common available channels. Besides, D-QCH has been shown to have MTTR $=$ MCTTR $= (\alpha - k + 1)N$. Clearly, when both receiver and sender have few available channels, D-QCH can reduce the MTTR and MCTTR.

B. Symmetric-Role Asynchronous Approach S-QCH

In this subsection, we propose a Symmetric-role Quorum-based Channel Hopping algorithm (S-QCH) for symmetric-role asynchronous environments. Recall that in symmetric-role environments, SUs are not pre-assigned as sender or receiver. Thus, all SUs use the same way to generate their CH sequences in S-QCH.

Without loss of generality, assume that SU x has α available channels. For ease of discussion, let an *h'-sub-column* of SU x be filled with a permutation of all N licensed channels (see Fig. 3(a)) and let an *h-sub-column* of SU x be a sub-column generated by replacing each unavailable channel

(a)

2
0
1

(b)

1
0
1

(c)

0	1
0	1
0	1

Fig. 3. An *h-sub-column* and α *w-sub-columns*, for $N = 3$, $\alpha = 2$, and available set $= \{0, 1\}$. (a) The chosen h'-sub-column. (b) An *h-sub-column*. (c) α distinct *w-sub-columns*. Each *w-sub-column* can rendezvous with the *h-sub-column* in (b).

(a)

2
0
1

(b)

1
0
1

(c)

0	1	0	1	1	1	0
0	0	0	0	1	0	0
0	1	0	1	1	1	0
1	1	0	1	1	1	0
1	0	0	0	1	0	0
1	1	0	1	1	1	0

Fig. 4. S-QCH when $N = 3$, $\alpha = 2$, and available channel set of the SU is $\{0, 1\}$. (a) The chosen h'-sub-column. (b) The developed *h-sub-column* (which is generated by replacing unavailable channel 2 in the h'-sub-column (in (a)) with available channel 1 (see gray elements)). (c) S-QCH matrix M. The gray numbers denote the available channels used to replace unavailable channels in the matrices.

in an h'-sub-column of SU x with a randomly selected available channel of SU x (see Fig. 3(b)). Let a *w-sub-column* of SU x be filled with N copies of the same available channel of SU x (see Fig. 3(c)). The S-QCH sequence of SU x includes one kind of *h-sub-column* and α distinct kinds of *w-sub-columns*. Clearly, the *h-sub-column* (in Fig. 3(b)) can rendezvous with each *w-sub-column* on different channels (in Fig. 3(c)).

In S-QCH, each SU can develop its sequence as described below.

CH sequence in S-QCH: The CH sequence is constructed by the aid of a matrix M which has αN rows (labeled as $0, 1, \ldots, \alpha N - 1$) and $2N + 1$ columns (labeled as $0, 1, \ldots, 2N$). An example of matrix M is shown in Fig. 4(c). Concatenate rows in M into a CH sequence with CH period $\alpha N(2N + 1)$. In other words, in S-QCH, SU executes the CH matrix along rows. The detail of matrix M is described below.

1) Column 0 of matrix M is filled with α distinct *w-sub-columns* sequentially.
2) Choose an h'-sub-column H' and develop *h-sub-column* H by H', see Fig. 4(a) and (b).
3) Each odd-index column of M is filled with α copies of the chosen *h-sub-column* H, see Fig. 4(c).
4) Label the N licensed channels as $0, 1, \ldots, N - 1$. Map even-index column $2(i + 1)$ to the *w-sub-column* which is filled with licensed channel i if the licensed channel i is available to the SU, and an arbitrary *w-sub-column* otherwise, for $0 \le i \le N - 1$. More precisely, each even-index column of M is filled with α copies of the mapped *w-sub-column*, see Fig. 4(c). Clearly, each even-index column in M is filled with exactly the same channel.

In Section VI, S-QCH is proved to have MCTTR $=$ MTTR $= (\alpha - k + 1)N(2N + 1)$, where k is the number of channels commonly available to a given communication pair. When all channels are available (to the communication pair), S-QCH has the optimal degree of rendezvous $= N$ and optimal channel loading $= 1/N$.

IV. Performance Analysis

In this section, we evaluate our two CH systems in terms of the four metrics: degree of rendezvous, channel loading, MTTR, and MCTTR. For ease of the following discussion, let $C(u, v)$ be the number of rendezvous channels between two sequences u and v in a CH period. Clearly, we have $C(u, v) \in [0, N]$. For a CH sequence $u = \{u_0, u_1, \ldots, u_i, \ldots, u_{T-1}\}$, denote $Srotate(u, l)$ as a cyclic rotation of u by l timeslots, i.e.,

$$Srotate(u, l) = \{u_{((0+l) \bmod T)}, u_{((1+l) \bmod T)}, \ldots, u_{((i+l) \bmod T)}, \ldots, u_{((T-1+l) \bmod T)}\},$$

where l is a non-negative integer. For example, given $u = \{0, 1, 2\}$ and $T = 3$, $Srotate(u, 1) = \{1, 2, 0\}$.

Lemma 1: H is an asynchronous CH system with degree of rendezvous $= m$ if and only if for arbitrary two CH sequences u and v in H, the following statement holds.

$$\forall l \in [0, T - 1], C(u, Srotate(v, l)) \ge m, \text{ where } m \in [0, N].$$

Proof: According to the definition of degree of rendezvous in Section I, the correctness is obvious and the proof is omitted. ■

A. Performance of D-QCH

The performance of D-QCH (in terms of the four metrics) depends on the number of available channels since the CH sequences are determined according to the channels available to the sender and receiver.

Lemma 2: Suppose that a receiver x has α available channels. In D-QCH, the sequences of a sender and its receiver can rendezvous on all of their commonly available channels within αN slots, where α denotes the number of channels available to the receiver.

Proof: Suppose that a sender has β available channels. Without loss of generality, assume that the D-sender sequence v (of the sender) is l slots ahead of the D-receiver sequence u (of its receiver). In this case, the rendezvous of u and v is the same as that of u and $Srotate(v, l)$ in synchronous environments. Note that, sequence u visits the same available channel every N timeslots (see Fig. 2(b)) and sequence $Srotate(v, l)$ contains all of its available channels every β timeslots, where $\beta \le N$. In synchronous environments, it is not difficult to see that u and $Srotate(v, l)$ can rendezvous on all channels commonly available to the sender and the receiver within the CH period of the D-receiver sequence, i.e., αN timeslots. ■

Theorem 3: D-QCH has degree of rendezvous $= k$ and MCTTR $=$ MTTR $= (\alpha - k + 1)N$, where α and k denote the number of channels available to the receiver and the number of channels commonly available to both the sender and the receiver, respectively.

0	1	2	3	4	5	6
0	2	0	2	0	2	2
0	0	0	0	0	0	2
0	0	0	0	0	0	2
2	2	0	2	0	2	2
2	0	0	0	0	0	2
2	0	0	0	0	0	2

(a)

0	1	2	3	4	5	6
1	2	1	2	1	2	2
1	1	1	1	1	1	2
1	1	1	1	1	1	2
2	2	1	2	1	2	2
2	1	1	1	1	1	2
2	1	1	1	1	1	2

(b)

0	1	2	3	4	5	6
2	2	1	2	1	2	2
2	1	1	1	1	1	2
2	1	1	1	1	1	2
1	2	1	2	1	2	2
1	1	1	1	1	1	2
1	1	1	1	1	1	2

(c)

Fig. 5. Rendezvous of matrices M and M^*_{21}. (a) Matrix M when available set $= \{0, 2\}$. (b) Matrix M^* when available set $= \{1, 2\}$. (c) Matrix M^*_{21} when available set $= \{1, 2\}$. M and M^*_{21} rendezvous on the entire N channels at column 6 of M.

Proof: According to Lemma 2, any pair of D-sender sequence and D-receiver sequence are guaranteed to rendezvous on all their common available channels. Thus, D-QCH has degree of rendezvous $= k$. Note that there are $\alpha - k$ channels unavailable to the sender, but available to the receiver. By definition, the D-receiver sequence can be divided into several N-length segments, where each segment is filled with the same channel indices. Note that every segment (in the D-receiver sequence) can rendezvous with the sender sequence, if the segment (in the D-receiver sequence) visits a commonly available channel. So, the D-sender sequence and D-receiver sequence can rendezvous within $(\alpha - k)N + N = (\alpha - k + 1)N$ timeslots. That is, D-QCH has MCTTR $=$ MTTR $= (\alpha - k + 1)N$. ■

On the other hand, since D-QCH only considers available channels and each SU may have distinct available channels, the original definition of channel loading in Section I is not applicable to D-QCH. When all channels are available, D-QCH has optimal channel loading $1/N$. Furthermore, D-QCH has optimal degree of rendezvous N, optimal MTTR $= N$ and optimal MCTTR $= N$. When not all channels are available to SUs, D-QCH rendezvous over all commonly available channels, and improves MTTR and MCTTR especially when only few channels are available.

B. Performance of S-QCH

For ease of discussion, let a *parity column* be a column which contains α different *w-sub-column*s (see column 0 in Fig. 5(a)), and a *periodic column* to be a column which contains α *copies of an h-sub-column*s (see odd columns in Fig. 5(a)), where α is the number of channels available to the SU.

Theorem 4: S-QCH has MCTTR $= (\alpha - k + 1)N(2N + 1)$ and degree of rendezvous $= k$, where α and k denote the number of channels available to the receiver and the number of channels commonly available to both the sender and the receiver, respectively.

0	2	0	2	0	2	2
0	0	0	0	0	0	2
0	0	0	0	0	0	2
2	2	0	2	0	2	2
2	0	0	0	0	0	2
2	0	0	0	0	0	2

(a)

2	1	2	1	2	2	2
1	1	1	1	1	2	2
1	1	1	1	1	2	1
2	1	2	1	2	2	1
1	1	1	1	1	2	1
1	1	1	1	1	2	2

(b)

Fig. 6. Matrices M and M_{22} rendezvous on commonly available channel 2 at column 0 of M.

Proof: It is sufficient to show that in S-QCH, any two SUs, x and y, are guaranteed to rendezvous on all their k commonly available channels and rendezvous on a commonly available channel within CH period $(\alpha - k + 1)N\,(2N + 1)$. Without loss of generality, assume that SU y starts its sequence l slots ahead from that SU x starts. Let X be the sequence of SU x and let Y be the sequence of SU y. In each CH period of SU x, the sequence of SU y is $Srotate(Y, l)$. The rendezvous of these two SUs is the same as that of X and $Srotate(Y, l)$ in a synchronous environment. Let the matrix corresponding to Y and $Srotate(Y, l)$ be M^* and M^*_l (i.e., Y and $Srotate(Y, l)$ are generated by concatenating rows in M^* and M^*_l, respectively). For example, Fig. 5(b) and (c) show M^* and M^*_{21}, respectively. Clearly, the rendezvous of these two SUs is the same as the rendezvous of M and M^*_l. Let a rendezvous of two matrices (or a rendezvous of two columns) be a matrix entry (or column entry) whose values in these two matrices (or two columns) are the same. A rendezvous of M and M^*_l is a matrix entry whose values in M and M^*_l are the same. Without loss of generality, assume that the slot shift $l = (2N + 1) \times r + c$, where $r \in [0, \alpha N - 1]$ is the shift of row and $c \in [0, 2N]$ is the shift of column. Then, we consider the following three different cases.

Case 1: $c = 0$. When $c = 0$, there is no column shift. For any value of r, M and M^*_l are guaranteed to rendezvous on even columns $2(i + 1)$, when channel i is a commonly available channel. Suppose that there are k channels commonly available to these two SUs. Fig. 5 shows when slots shift $l = 21 = (2N + 1) \times r + 0$ and $N = 3$, M and M^*_{21} can rendezvous on all their commonly available channel (i.e., channel 2) at column 6.

Case 2: c is odd. When c is odd, M and M^*_l have odd column shifts. Fig. 6 shows when slot shift $l = 22 = (2N + 1) \times r + 1$ and $N = 3$, M and M^*_{22} has one column shift. For any value of r, the column 0 in M must be a parity column, and the column 0 in M^*_l must be a periodic column. Clearly, a parity column and a periodic column are guaranteed to rendezvous on all their commonly available channels. Besides, these two columns can rendezvous on a commonly available channel at row 0 to row $(\alpha - k + 1)N - 1$. Fig. 6 shows that M and M^*_{22} rendezvous on commonly available channel 2 at column 0.

Case 3: c is even and $c \neq 0$. When c is even, M and M^*_l have even column shifts. Fig. 7 shows when slots shift

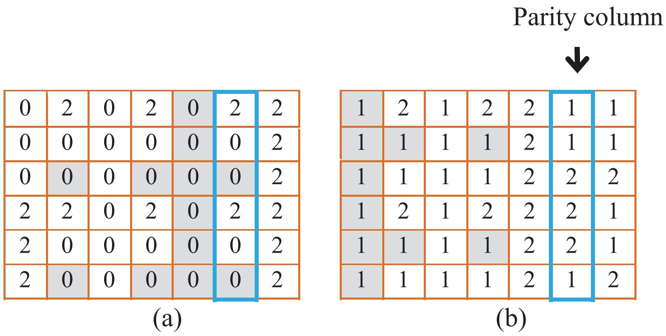


Fig. 7. Matrices M and M_{23} rendezvous on commonly available channel 2 at column 5 of M.

$l = 23 = (2N + 1) \times r + 2$ and $N = 3$, M^*_{23} has two column shifts. For any value of r, one odd column of M^*_l should be a parity column. Fig. 7 shows column 5 of M^*_{23} is a parity column. Note that all odd columns in M are periodic columns. As the discussion in case 2, the parity column in M^*_l and the periodic columns in M are guaranteed to rendezvous on all commonly available channels. Besides, these two columns can rendezvous on a commonly available channel at row 0 to row $(\alpha - k + 1)N - 1$. ■

Summarizing the discussion above, we have that any two SUs in S-QCH are guaranteed to rendezvous on all k commonly available channels within CH period $(\alpha - k + 1)N\,(2N + 1)$.

Theorem 5: S-QCH has MTTR $= (\alpha - k + 1)N(2N + 1)$.

Proof: The result could be obtained by Theorem 4. ■

Similarly, the original definition of channel loading in Section I is not applicable to S-QCH. When all channels are available (to the communication pair), S-QCH has optimal channel loading $1/N$. Furthermore, S-QCH has optimal degree of rendezvous N, optimal MTTR $= N(2N + 1)$ and optimal MCTTR $= N(2N + 1)$.

V. Comparison

In this section, we compare the proposed CH systems with existing CH schemes using four metrics: degree of rendezvous, channel loading, MTTR and MCTTR.

A. Asymmetric-Role Asynchronous CH Protocols

Below we briefly investigate the current asymmetric-role asynchronous CH algorithms with heterogeneous available channel set [5], [6], [24], [25].

In [5], asynchronous maximum overlapping CH (A-MOCH) scheme use quorum systems to construct CH sequences. In A-MOCH, the sender sequences are constructed by an $N \times N$ Latin square and the receiver sequences are constructed by an $N \times N$ identical-row square. Each row i of a Latin square is filled with $Srotate(x, i)$, where x is a permutation of $\{0, 1, \ldots, N - 1\}$. All rows of an identical-row square are the same, and each row is filled with a permutation of $\{0, 1, \ldots, N - 1\}$. A-MOCH has MTTR $= N^2 - N + 1$, channel loading $= 1/N$, degree of rendezvous $= N$, and MCTTR $= N^2$.

In [6], asynchronous CH (ACH) scheme also uses quorum systems to construct CH sequences. A receiver sequence and a sender sequence is generated by concatenating rows in an $N \times N$ receiver matrix and an $N \times N$ sender matrix, respectively. In a sender matrix, all array elements in the same column are assigned the same channel index and N columns are assigned to distinct N channel indices. In a receiver matrix, each column and each row is a permutation of $\{0, 1, \ldots, N - 1\}$. ACH has MTTR $= N^2 - N + 1$, channel loading $= 1/N$, degree of rendezvous $= N$, and MCTTR $= N^2$.

In [24], [25], a sender randomly selects a subset of its available channel set. Then, it hops and broadcasts periodically on the selected available set. Each receiver listens for two time slots on each of its available channels periodically. To guarantee rendezvous, the sender's selected available subset should include a channel available to its receiver. A detail discussion on the probability of the selected available subset including an available channel was derived in [25].

Compared with asymmetric-role-asynchronous CH schemes above, our D-QCH reduces the MCTTR from N^2 to $(\alpha - k + 1)N$, where α is the number of channels available to receiver and k is the number of channels available to both sender and receiver (see Table I).

B. Symmetric-Role Asynchronous CH Protocols

Below we briefly investigate the current symmetric-role asynchronous CH algorithms. Four schemes, A-QCH [4], SeqR [12], ASYNC-ETCH [21], and DRSEQ [20], are applicable to homogeneous available channel sets, and the remaining schemes (i.e., JS [15], [16], Sym-ACH [7], DRDS [27], EJS [26], E-AHW [13], and CRSEQ [2]) are applicable to heterogeneous available channel sets. Recall that in symmetric-role approaches, SUs do not have pre-assigned roles. Existing approaches usually suffer from low degree of rendezvous (≤ 2) and unbounded MCTTR [4], [12], [20], [21]. In [4], asynchronous quorum-based CH (A-QCH) scheme determine two cyclic quorums systems Q and Q'. Choose quorums p and p' from quorum systems Q and Q', respectively. Use p and p' for assigning the rendezvous channels h_0 and h_1 to appropriate elements in a CH sequence. Each remaining unassigned element of the CH sequence is randomly assigned a channel h, where $h \neq h_0$ and $h \neq h_1$. A-QCH has MTTR ≥ 9, channel loading $\approx 1/2$, and degree of rendezvous $= 2$.

In [12], sequence-based rendezvous scheme (SeqR) selects a permutation of the N channels first and build the sequence by repeating the permutation $N + 1$ times. SeqR has MTTR $= N(N + 1)$, channel loading $= 1/N$, and degree of rendezvous $= 1$. In [20], deterministic rendezvous scheme (DRSEQ) has CH period $2N + 1$. In a CH period, the sequence hops from channels 0 to channel $N - 1$ sequentially in the first N slots and hops from channels $N - 1$ to channel 0 sequentially in the succeed N slots, and the sequence is idle in the last slot. DRSEQ has MTTR $= 2N + 1$, channel loading $= 2/(2N + 1)$, and degree of rendezvous $= 1$.

In [21], asynchronous efficient channel hopping (ASYNC-ETCH) scheme has MTTR $= N(2N + 1)$, channel loading $= 1/N$, and degree of rendezvous $= 1$. Each sequence u in ASYNC-ETCH is constructed from N subsequences, where each subsequence consists of a pilot slot and two strings xs,

TABLE I
A COMPARISON OF CH SCHEMES

Model	Protocol	Deg. of rendezvous	Channel load	MTTR	MCTTR
Asymmetric-role Asynchronous	A-MOCH [5]	N	$1/N$	N^2-N+1	N^2
	ACH [6]	N	$1/N$	N^2-N+1	N^2
	D-QCH	N*	$1/N$*	$(\alpha-k+1)N$	$(\alpha-k+1)N$
Symmetric-role Asynchronous	A-QCH [4]	2	≈1/2	≥ 9	-
	SeqR [12]	1	$1/N$	$N(N+1)$	-
	ASYNC-ETCH[21]	1	$1/N$	$N(2N+1)$	-
	DRSEQ [20]	1	$2/(2N+1)$	$2N+1$	-
	JS [15, 16]	N	$(4N+P)/3NP$	$3P$	$3NP(P-1)+3P$
	Sym-ACH [7]	N	$1/N$	$6nN^2$	$6nN^2$
	DRDS [27]	N	$1/N$	$3P$	$3P^2+2P$
	EJS [26]	N	$1/N$	$4P$	$4P(P+1-k)$
	E-AHW [13]	N	$1/N$	$3nP$	$3P(n+1)(\alpha-k+1)$
	CRSEQ [2]	N	$1/N$	$3P^2-3P$	$3P^2-3P$
	S-QCH	N*	$1/N$*	$(\alpha-k+1)N(2N+1)$	$(\alpha-k+1)N(2N+1)$

-: Unknown.
*: When all channels are available.
N: Number of licensed channels.
α: Number of channels available to receiver.
β: Number of channels available to sender.
k: Number of channels available to both sender and receiver.
P: A smallest prime which is larger than N.
n: Unique n-bit ID which is suggested using 48-bit MAC address.

where x is a clockwise sequence with initial channel 0 and a selected CH seed k. The pilot slots in each subsequence combined in order are exactly a sequence x.

In [15], [16], jump-stay scheme (JS) is proposed to have bounded MCTTR. The sequence of JS can be divided into $2N$ inner-rounds, each round has $3P$ slots, where P is the smallest prime larger than N. Each round consists of a jump-pattern and a stay-pattern. SUs jump on all the N channels in the jump-pattern and stay on a specific channel in the stay-pattern. A jump-pattern lasts for $2P$ slots while a stay-pattern lasts for P slots. JS has MTTR $= 3P$, maximum degree of rendezvous $= N$, and MCTTR $= 3NP(P-1) + 3P$.

In [7], Sym-ACH assumes that each SU has a unique n-bit ID which is suggested using 48-bit MAC address. The CH sequences are constructed by the aid of $3n$ bits. These $3n$ bits consist of n-bit ID, n bits zero, and n bits one. Each bit is mapped to two N^2-slot sub-sequences, where bit one is mapped to two column-based sub-sequences and bit zero is mapped to two span-based sub-sequences. Sym-ACH has MTTR $= 6nN^2$, channel loading $= 1/N$, degree of rendezvous $= N$, and MCTTR $= 6nN^2$.

In [27], the CH sequence is generated by a disjoint relaxed difference set (DRDS), $S = \{D_1, D_2, \ldots, D_N\}$. For each $i \in D_j$, at the i-th slot of a CH period, a DRDS-based sequence visits channel j if channel j is available, and the sequence visits an available channel randomly otherwise. DRDS has MTTR $= 3P$, channel loading $= 1/N$, degree of rendezvous $= N$, and MCTTR $= 3P^2 + 2P$.

In EJS [26], each round has $4P$ timeslots: $3P$ timeslots for Jump pattern and P timeslots for Stay pattern. The starting-index of round n is $((i_0 + n - 1) \bmod P) + 1$. EJS has MTTR $= 4P$, channel loading $= 1/N$, degree of rendezvous $= N$, and MCTTR $= 4P(P + 1 - k)$, where k is the number of channels commonly available to the two users. If channel i (in the EJS sequence) is unavailable, it is replaced by the $((i - 1) \bmod \alpha) + 1$-th channel in the available channel set.

In E-AHW [13], each SU is assumed to have a unique n-bit ID which is suggested using 48-bit MAC address. The CH sequence of an SU is constructed by the aid of the string z which is composed of "2" and its ID. For each bit i of string z, it is mapped to a $3P$-length string. The $3P$-length string consists of Stay-Jump-Jump pattern if bit $i = 0$; Jump-Jump-Jump pattern if bit $i = 1$; Stay-Stay-Jump pattern, if bit $i = 2$. An inner alternate CH sequence is the sequence generated by concatenating $3P$-length strings mentioned above. A CH sequence is generated by concatenating α inner alternate CH sequence, where α is the number of available channels. Note that stay patterns in the same inner alternate CH sequence but corresponds to distinct bit do not stay at the same channel. To reduce rendezvous time, random replacement (unavailable channels in a CH sequence are randomly replaced with available channels) is adopted.

In [2], a CRSEQ sequence is divided into N sub-sequences. The i-th subsequence consists two parts: the first part approximately consists of two Jump patterns, $(a_i, (a_i + 1) \bmod N, \ldots, (a_i + N - 1) \bmod N, a_i, (a_i + 1) \bmod N, \ldots, (a_i + N - 2) \bmod N)$ and the second part is a stay pattern which consists of N copies of i s, where a_i is a triangular number, $i(i + 1)/2$ and $i \in [1, N]$.

Compared with existing symmetric-role-asynchronous CH schemes in Table I, S-QCH has the optimal degree of rendezvous and optimal channel loading. Although EJS and DRDS have MCTTR and MTTR shorter than our S-QCH when sender and receiver have distinct available channel sets, our S-QCH has average TTR shorter than EJS's and close to DRDS's, see simulation results in Section VI.

VI. Performance Evaluation

In this section, we evaluate the performance of the proposed CH schemes. We compare them with seven representative N-degree asynchronous protocols, A-MOCH [5], ACH [6] for asymmetric-role environments, CRSEQ [2], Sym-ACH [7], DRDS [27], and EJS [26] for symmetric-role environments. We have presented the theoretical performance of these algorithms in Table I. In this section, we focus on the experimental results of the algorithms.

All simulations below are executed in time asynchronous environments (i.e., SU sequences may start at distinct global slots). PUs and SUs are randomly deployed in a 1000 m × 1000 m square area, and have the same transmission radius 250 m. Each PU transmits packets on a randomly selected operating channel. Note that, multiple PUs may choose the same operating channel. PUs generate traffic on its operating channel with probability $P_\alpha = 0.1$ and each transmission lasts for $\beta = [50, 100]$ slots, whereas SUs can opportunistically access licensed channels. For each SU, its available channel set is obtained by performing spectrum sensing before determining its CH sequence. By "the determined available (or unavailable) channels", SUs determine their sequences. Each SU hops between channels according to its sequence. At the very beginning of a slot, each SU sender performs sensing before transmission. An SU sender starts transmission if no PU/SU signal is detected. That is, if channel availability changes during a CH period, SUs in D-QCH/S-QCH (and other CH schemes) do not change their sequences. SUs generate traffic (control messages only) with probability $S_\alpha = 0.1$. Each slot is assumed to be sufficient for one pair of SUs to exchange control messages, but not sufficient for two. More precisely, when more than one sender-receiver pair rendezvous on the same available channel, by the aid of waiting a random back-off time, only one pair can successfully exchange control messages. Since we only focus on the performance of rendezvous, we do not use any MAC protocol to handle the SU transmission after rendezvous (and exchange control messages).

In S-QCH and D-QCH, each unavailable channel is replaced with a randomly chosen available channel. Since the available channels used for replacement are randomly selected, we can balance the loading of the available channels.

In this section, the average time-to-successful-rendezvous (TTSR) is the average time for a sender-receiver pair to successfully exchange control messages.

A. Asymmetric-Role and Asynchronous Environment

In the first set of simulations, CRNs are assumed to have disjoint single-hop data flows only (i.e., when an SU u servers as a sender, no other SU would regard u as its receiver) and the number of licensed channels N is set to be 10. We also assume that when more than one pair of SUs rendezvous on the same available channel, only one pair can successfully exchange control messages. We compare the TTSR of D-QCH, ACH and A-MOCH under various conditions, including the number of PUs, the number of SUs, and the number of licensed channels, in Section VI-A-1, Section VI-A-2, and Section VI-A-3, respectively. In the second set of simulations (in Section VI-A-4), we remove the assumption of disjoint single-hop data flows, which implies that when an SU u serves as a sender, there may exist some SU that regards u as its receiver.

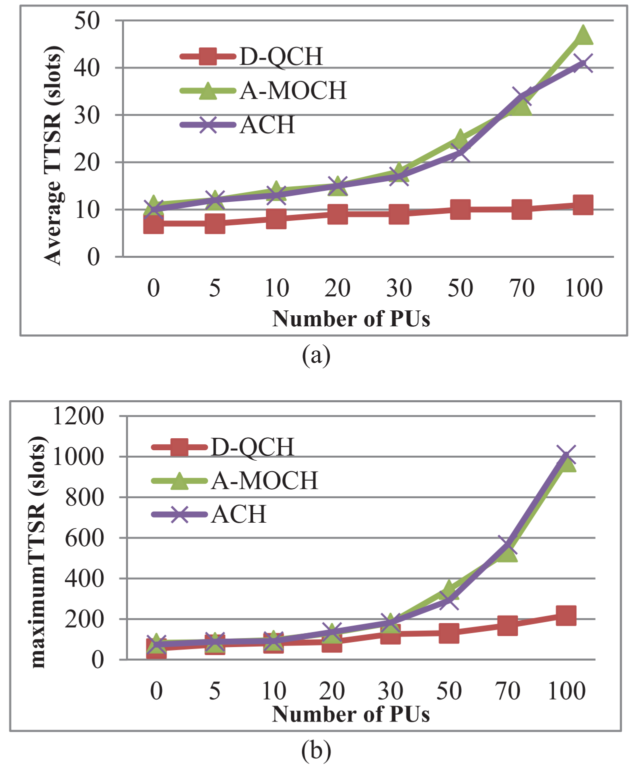


Fig. 8. TTSR vs. the number of PUs in asymmetric-role environments.

1) Impact of the Number of Pus: In the following simulations, the number of SUs is fixed at 50 and the number of PUs varies from 0 to 100. Since high PU density leads to fewer available channels, SUs usually need more time to rendezvous on an available channel, i.e., the TTSR increases as the number of PUs increases. Fig. 8(a) shows the average TTSR of D-QCH, ACH, and A-MOCH. When PU density is low, D-QCH has TTSR shorter than that of ACH and A-MOCH since D-QCH has small MTTR. The number of PUs has a rather less negative impact on D-QCH. This is because D-QCH would skip unavailable channels (i.e., the probability of an SU staying at an available channel increases) and thus the probability of two neighboring SUs staying at the same available channel increases, especially when PU density is high. Fig. 8(b) shows the maximum TTSR. ACH and A-MOCH have nearly the same maximum TTSR because they have the same MCTTR.

2) Impact of the Number of SUs: To evaluate the impact of the number of SUs, in the following simulations, the number of PUs is fixed at 20 and the number of SUs varies from 10

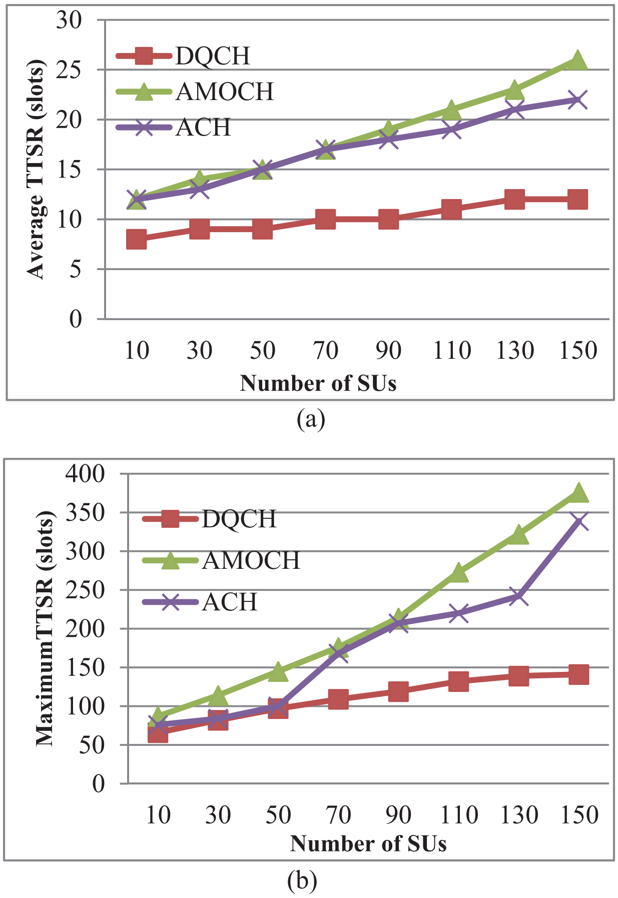


Fig. 9. TTSR vs. the number of SUs in asymmetric-role environments.

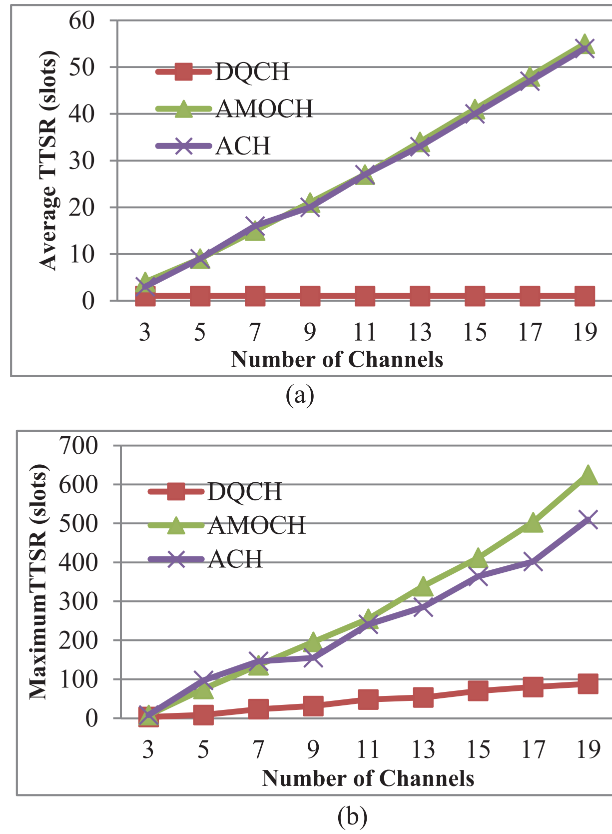


Fig. 10. TTSR vs. the number of channels in asymmetric-role environments.

to 150. Since high SU density leads to serious congestion, the TTSR increases as the number of SUs increases. Fig. 9(a) and (b) show the average and maximum TTSR of D-QCH, ACH and A-MOCH. When congestion occurs, a rendezvous pair which fails to exchange control message on the currently available rendezvous channel needs next rendezvous. Recall that D-QCH has MCTTR smaller than that of ACH and A-MOCH. Once the rendezvous pair fails to contend for rendezvous channel, D-QCH takes less time for next rendezvous. According to the discussion above, D-QCH has better performance, especially in high SU density environments.

3) Impact of Number of Licensed Channels: In this simulation, the number of licensed channels N varies from 3 to 19, and each SU has $0.3N$ available channels on average. Fig. 10(a) and (b) show the average and maximum TTSR of D-QCH, ACH and A-MOCH. Since the MCTTR of D-QCH is smaller than that of ACH and A-MOCH, D-QCH has the shortest TTSR.

4) Rendezvous Rate: In this simulation, we consider the impact of a number of PUs on the success rate. The success rate is the proportion of sender-receiver pairs which can success on an available channel (i.e., congestion is not taken into account). Here, we remove the assumption of disjoint single-hop data flows, which implies that when an SU u serves as a sender, there may exist some SU that regards u as its receiver. For any pair of sender and receiver, it is guaranteed to rendezvous on a common available channel within MCTTR if the common available channel exists. However, the rendezvous between any pair of senders are not guaranteed. If a sender cannot rendezvous its destination within MCTTR, we regard it as timeout and fail to rendezvous. The number of SUs is fixed at 50 and the number of PUs varies from 10 to 150. Fig. 11 shows the success rate of D-QCH, ACH, and A-MOCH. When the number of PUs is zero (i.e., all channels are available), the success rate of D-QCH is better than ACH and A-MOCH since D-QCH has lower MTTR. As the number of PUs increases, the average TTSR of ACH and A-MOCH increases (refer to Fig. 8) and thus the success rate decreases. For D-QCH, all SUs visit available channels only. When the number of PUs increases, the number of available channels decreases and hence increases the number of successes, i.e., success rate increases, even if some destinations of senders serve as senders.

B. Symmetric-Role and Asynchronous Environment

In this subsection, CRNs are assumed to have multiple non-disjoint single-hop data flows and $N = 8$ licensed channels. We compare the TTSR of S-QCH, CRSEQ [2], Sym-ACH [7], DRDS [27], and EJS [26] under various conditions, including the number of PUs, the number of SUs, and the number of licensed channels. In DRDS, CRSEQ and EJS, the smallest prime P which is larger than N is 11. In Sym-ACH, node ID is 48-bit MAC address (which is suggested in [7]).

For fair comparison, in the following simulations, random channel replacement scheme (i.e., unavailable channel is randomly replaced with an available channel) is applied to all

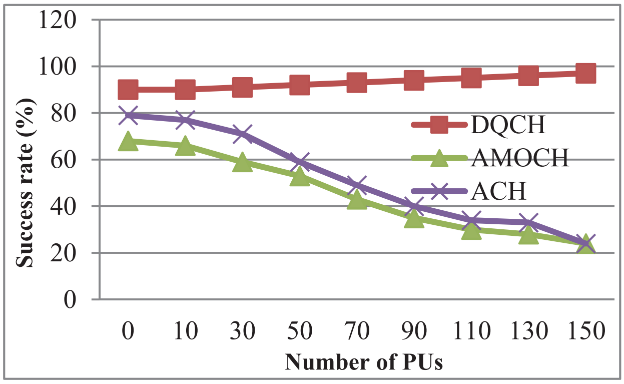
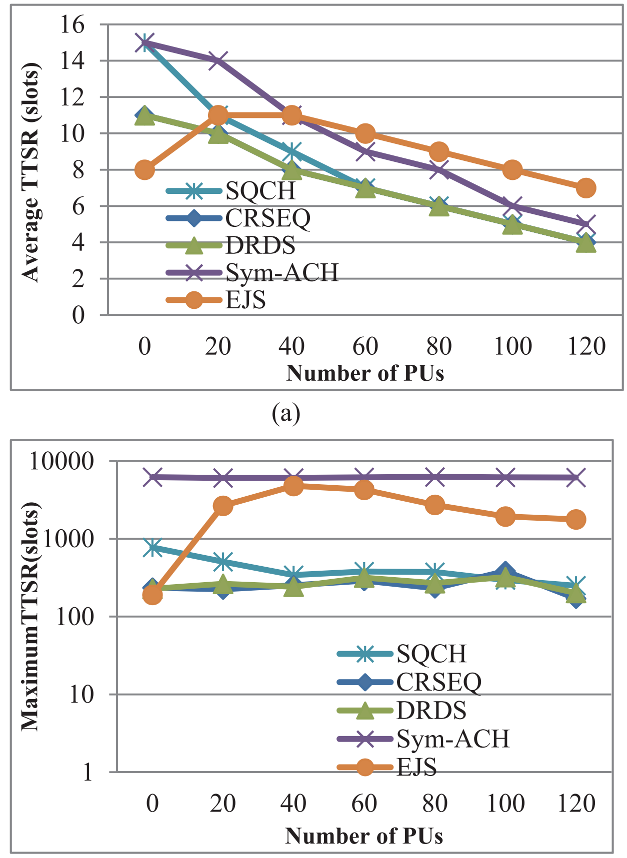


Fig. 11. Success rate vs. the number of PUs in asymmetric-role environments.



(a)

(b)

Fig. 12. TTSR vs. the number of PUs in symmetric-role environments.

CH algorithms except the algorithm has its own replacement method.

1) Impact of the Number of PUs: In these simulations, the number of SUs is fixed at 50 and the number of PUs varies from 0 to 120. Fig. 12(a) and (b) show the impact of the number of PUs in symmetric-role environments. The TTSR decreases as the number of PUs increases in asymmetric-role environments. This is because channel replacement is applied to all these schemes. When the number of PUs increases, the probability of a communication pair staying at the same channel increases. Note that EJS has large TTSR. This is because EJS has high collision rate. In EJS's replacement method, most of the unavailable channels may be replaced with the same available channel, which results in the high collision rate. Sym-ACH has large maximum TTSR because of its large MCTTR.

2) Impact of the Number of SUs: To evaluate the impact of the number of SUs, in the following simulations, the number of PUs is fixed at 70 and the number of SUs varies from 30 to 150. Fig. 13(a) and (b) show that the average and maximum TTSR of S-QCH, CRSEQ, Sym-ACH, DRDS, and EJS increase as the number of SUs increases. This is because more SUs results in more packet collision. Owing to large MCTTR, Sym-ACH takes much more time for next rendezvous (once packet collision occurs). Note that EJS has large TTSR. This is because EJS's replacement method results in the high collision rate.

3) Impact of the Number of Licensed Channels: In the following simulations, the number of licensed channels N varies from 30 to 150, and there are $5N$ SUs and $5N$ PUs. Each SU has $0.3N$ available channels on average. Fig. 14(a) and (b) show the impact of the number of licensed channels. These schemes have similar average TTSR, when there are few license channels, but many PUs and SUs. Owing to shorter MCTTR, S-QCH, CRSEQ, and DRDS have shorter maximum TTSR. Similarly, EJS's replacement method results in the high collision rate.

VII. Discussion and Conclusion

Cognitive radio network is a promising technology to fully exploit the under-utilized (or low-utilization) spectrum. The rendezvous protocols cannot guarantee whether two SUs can rendezvous or not even there are commonly available channels if channel availability changes before the rendezvous. When the availability of a channel frequently changes (during a CH period), current CH algorithms in cognitive radio networks either have low rendezvous rate or high collision rate (although every SU can change its hopping sequence anytime according to channel availability, collision between SU signals increases a lot, which results in many useless rendezvous). The main idea of mitigating the problem above is to reduce time to rendezvous (i.e., TTR). Obviously, short TTR implies a small probability of encountering availability change (before rendezvous). Compared to existing CH algorithms, our algorithms outperform in terms of TTR (i.e., TTSR in Section VI) even when channel availability changes during a CH period. Therefore, the performance of the rendezvous algorithms are focus on reducing the ATTR, MTTR, and MCTTR which can increase the rendezvous probability.

Recall that k denotes the number of channels commonly available to the sender and the receiver, N denotes the number of licensed channels, and α denotes the number of channels available to the receiver. Our D-QCH outperforms in terms of MTTR/MCTTR in all cases. Our S-QCH has short MCTTR ($\approx 2N^2 + N$ when $\alpha \approx k$) and short average TTR (see simulation results in Section VI-B), compared to DRDS (with MCTTR $= 3P^2 + 2P$) and CRSEQ (with MCTTR $= 3P^2 - P$), in symmetric available channel set environments (i.e., nodes of a communication pair have the same available channel set). As mentioned in above, in real communication scenarios, α is close to k. In asymmetric available channel set environments

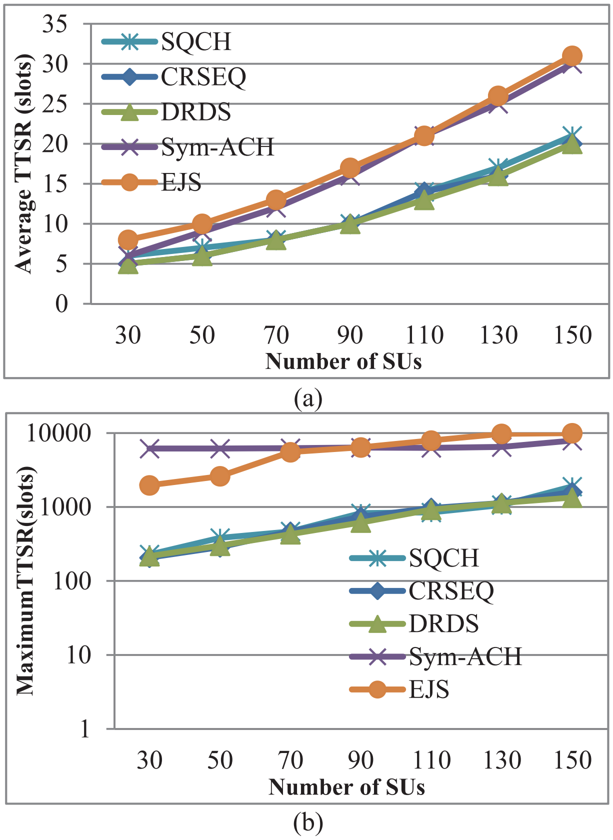


Fig. 13. TTSR vs. the number of SUs in symmetric-role environments.

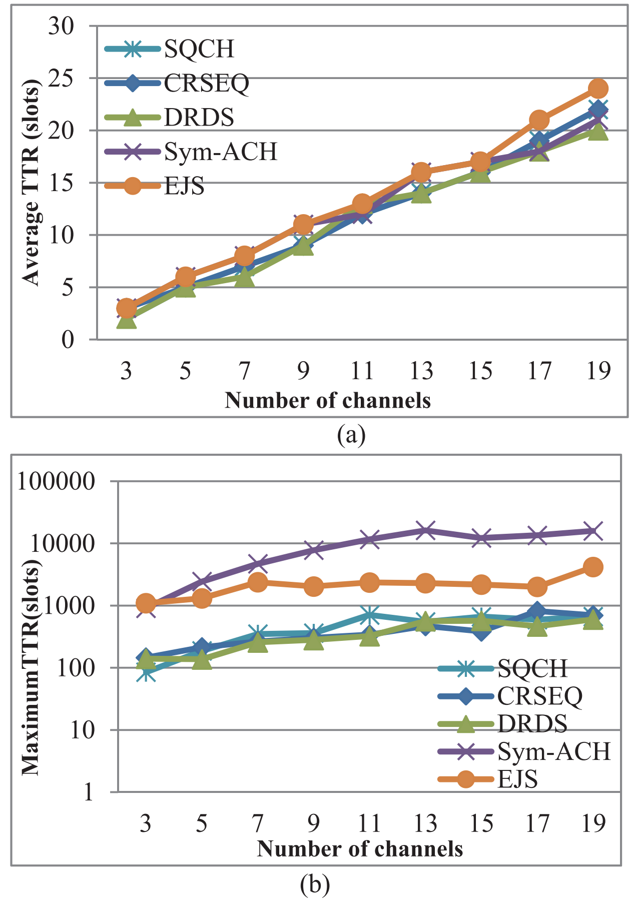


Fig. 14. TTSR vs. the number of channels for symmetric-role environment.

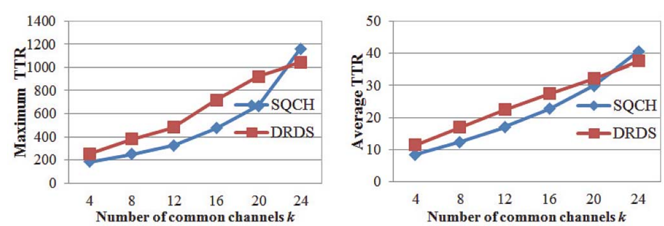


Fig. 15. Effect of the number of commonly available channels (i.e., k) when $\alpha - k = 2$ and $N = 32$.

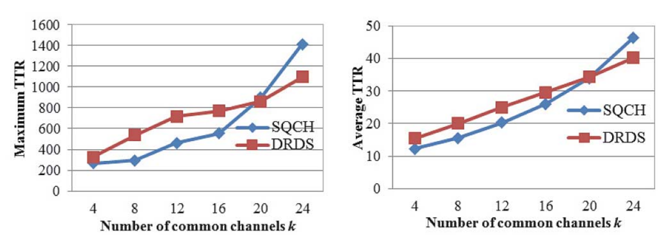


Fig. 16. Effect of the number of commonly available channels (i.e., k) when $\alpha - k = 3$ and $N = 32$.

(i.e., nodes of a communication pair may have distinct available channel sets), S-QCH has average TTR similar to that of DRDS and CRSEQ. DRDS has been proved to be nearly optimal in terms of MCTTR. For environments with uniformly distributed clock drifts and commonly available channel sets, it is not difficult to see that DRDS has nearly optimal average TTR (our simulation results also confirm the fact). Since our S-QCH and DRDS has nearly the same average TTR, our S-QCH is nearly optimal in terms of average TTR. When PU communication radius is much larger than SU', in high node density CR networks, many SUs may have the same or nearly the same commonly available channel set ($\alpha \approx k$). In the environments mentioned above, if the number of commonly available channels (i.e., k) is smaller than N, S-QCH has better performance. Refer to Figs. 15–17 below. S-QCH outperforms when $\alpha - k \leq 4, k \leq 24,$ and $N = 32$. This is because in many existing channel hopping schemes, sender and receiver may meet many times on unavailable channels (even if no available channel changes its availability during rendezvous process). In our S-QCH, to reduce rendezvous time, no meet on unavailable channels occurs if no available channel changes its availability during rendezvous process.

Indeed, channel availability change reduces the throughputs of CR channel hopping systems. According to our simulation results, the impact of channel availability change has rather little impact on average TTR of S-QCH (and other channel hopping schemes in CR networks), if the channel availability does not frequently changes (which is a reasonable assumption in CR networks), see Figs. 18 and 19 below. Fig. 18 shows the average TTR of different schemes when available channels do not change before rendezvous. Fig. 19 shows the average TTR of different schemes when each available channel may become unavailable with probability 10% every 100 time slots. We can see that the average TTR of all schemes in Figs. 18 and 19

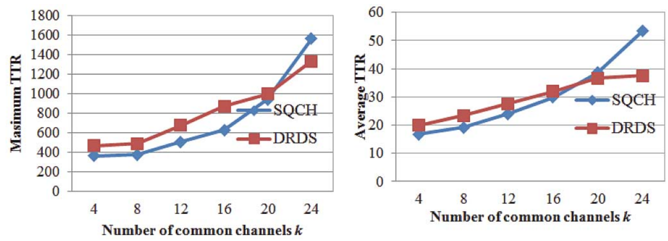


Fig. 17. Effect of the number of commonly available channels (i.e., k) when $\alpha - k = 4$ and $N = 32$.

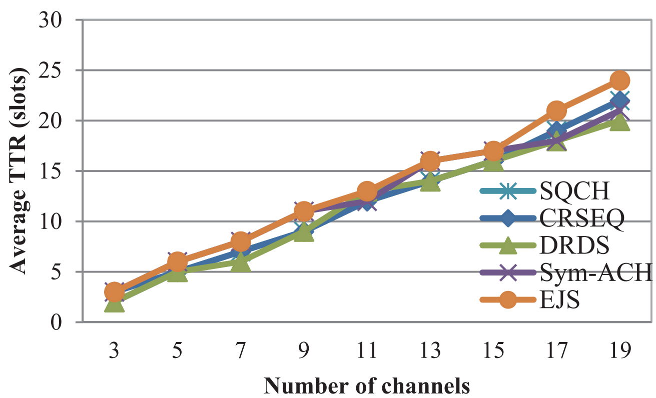


Fig. 18. ATTR when channel availability does not change before rendezvous.

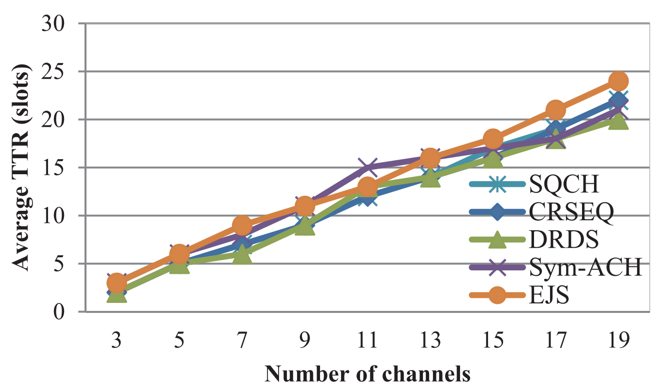


Fig. 19. ATTR when each available channel may become unavailable with probability 10% every 100 time slots.

are similar. This is because S-QCH (and other channel hopping schemes) has short average TTR and high degree of rendezvous (i.e., sender and receiver can rendezvous on many commonly available channels).

Our S-QCH is a blind rendezvous scheme. Due to the nature of blind rendezvous, the information of commonly available channels is not necessary for achieving rendezvous. In our scheme, each SU is aware of its own available channels, but unaware of other SU's available channels. That is, a sender does not know which channel is commonly available to both it and its target receiver. A blind rendezvous scheme guarantees the rendezvous of a communication pair, if there exists a channel c commonly available to the communication pair which does not change its availability during the rendezvous process of the communication pair.

In this paper, we have introduced two asynchronous quorum-based CH protocols for CRNs. For asymmetric-role environments, D-QCH has the maximum degree of rendezvous among commonly available channels, and excellent MTTR and MCTTR. By dynamically changing the CH period, D-QCH reduces the time-to-rendezvous, especially when available channels are few. For symmetric-role environments, S-QCH has the maximum degree of rendezvous, balanced channel loading, and excellent MCTTR. According to our simulations, D-QCH has performance better than previous work, while S-QCH outperforms in environments with high PU density or high SU traffic volume.

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