A Quorum-based Framework for Establishing Control Channels in Dynamic Spectrum Access Networks*

Kaigui Bian, Jung-Min "Jerry" Park, and Ruiliang Chen
Department of Electrical and Computer Engineering
Virginia Tech, Blacksburg, VA, USA
{kgbian, jungmin, rlchen}@vt.edu

ABSTRACT

Establishing a control channel for medium access control is a challenging problem in multi-channel and dynamic spectrum access (DSA) networks. In the design of multi-channel MAC protocols, the use of channel (or frequency) hopping techniques (a.k.a. parallel rendezvous) have been proposed to avoid the bottleneck of a single control channel. In DSA networks, the dynamic and opportunistic use of the available spectrum requires that the radios are able to "rendezvous"—i.e., find each other to establish a link. The use of a dedicated global control channel simplifies the rendezvous process but may not be feasible in many opportunistic spectrum sharing scenarios due to the dynamically changing availability of all the channels, including the control channel. To address this problem, researchers have proposed the use of channel hopping protocols for enabling rendezvous in DSA networks. This paper presents a systematic approach, based on *quorum systems*, for designing and analyzing channel hopping protocols for the purpose of control channel establishment. The proposed approach, called *Quorum-based Channel Hopping* (QCH) system, can be used for implementing rendezvous protocols in DSA networks that are robust against link breakage caused by the appearance of incumbent user signals. We describe two optimal QCH systems under the assumption of global clock synchronization: the first system is optimal in the sense that it minimizes the time-to-rendezvous between any two channel hopping sequences; the second system is optimal in the sense that it guarantees the even distribution of the rendezvous points in terms of both time and channel, thus solving the *rendezvous convergence* problem. We also propose an asynchronous QCH system that does not require global clock synchronization. Our analytical and simulation results show that the channel hopping schemes designed using our framework outperform existing schemes under various network conditions.

*This work was partially sponsored by NSF through grants CNS-0627436, CNS-0716208, and CNS-0746925.

MobiCom'09, September 20–25, 2009, Beijing, China.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Algorithms, Performance

Keywords

Control channel, dynamic spectrum access, channel hopping, quorum system, medium access control, cognitive radio

1. INTRODUCTION

Dynamic spectrum access (DSA) networks [1] need to utilize available spectrum in a dynamic and opportunistic fashion without causing interference to co-located incumbent networks. Because entities of an incumbent network have absolute priority in accessing their spectrum bands, they are often called *incumbent* or *primary* users whereas entities of a DSA network are often called *secondary* users. In order to enable dynamic and opportunistic utilization of spectrum, radios must have the ability to locate each other in a multi-channel environment via a "rendezvous" process. A pair of nodes wishing to communicate with each other use one or more rendezvous to exchange control information that will enable the establishment of a link. When a central entity, such as a base station, is not available, the rendezvous process needs to be carried out in a distributed manner. To address this difficult problem, the vast majority of the existing MAC protocols for DSA networks rely on a dedicated global or group control channel [3, 10, 14, 23]. Assuming a common control channel certainly simplifies the rendezvous process as well as other medium access-related issues. However, relying on a common control channel has a number of important drawbacks. A common control channel may become a bottleneck (a la *control channel saturation problem*) or create a single point of failure. More importantly, the dynamically changing availability of spectrum may make it impossible to maintain a common control channel. In a DSA network, the availability of any channel cannot be guaranteed, thus making it impossible to guarantee the availability of the common control channel. Recall that secondary nodes must vacate any channel as soon as incumbent signals appear on that channel.

[1]DSA networks are also referred to as cognitive radio networks since the nodes utilize cognitive radio technology for opportunistic spectrum sharing (OSS).

In the design of multi-channel MAC protocols, the use of *channel hopping (CH)* (a.k.a. parallel rendezvous) techniques have been proposed to avoid the bottleneck of a single control channel [2, 19]. CH protocols are very useful in the context of medium access control in DSA networks because they provide an effective method of implementing rendezvous without relying on a common control channel.

To provide reliable performance in a DSA environment, a CH protocol needs to satisfy two critical requirements. The first requirement is to guarantee the periodic overlap between any pair of CH sequences so that a pair of nodes that wish to establish a link can rendezvous. To minimize channel access delay, the *time-to-rendezvous (TTR) value between two sequences needs to be bounded and small.* The second requirement is to *guarantee that any two CH sequences will rendezvous in more than one channel within a sequence period.* The inability to guarantee rendezvous in more than one channel can be a problem in DSA networks because the single rendezvous channel may become unavailable due to the appearance of incumbent signals. The proposed quorum system-based methodology enables the design of CH schemes that satisfy the two requirements—i.e., the CH schemes guarantee rendezvous in multiple channels while ensuring that the TTR has an upper bound.

Most, if not all, of the existing work on CH schemes [2, 8, 17, 19, 21] only provide ad-hoc approaches for generating CH sequences and evaluating their properties. In this paper, we present a systematic approach, based on *quorum systems*, for designing and analyzing CH protocols for the purpose of control channel establishment. The proposed approach, called *Quorum-based Channel Hopping (QCH)* system, utilizes the intersection property of quorum systems to generate CH sequences that enable rendezvous on multiple channels between any two CH sequences. Under the assumption of global clock synchronization, we describe two optimal QCH systems. The first system minimizes the upperbound of the TTR value between any two CH sequences. The second system is optimal in the sense that it evenly distributes the rendezvous points over different timeslots during a CH period, thereby alleviating the *rendezvous convergence* problem and increasing network capacity. We also propose an asynchronous QCH system that does not require global clock synchronization. This system has a bounded TTR value between any two CH sequences.

The rest of this paper is organized as follows: we provide background knowledge of the quorum system in Section 2. In Section 3, we describe the QCH system. We present two synchronous QCH systems and an asynchronous QCH system in Sections 4 and 5, respectively. In Section 6, we compare our proposed QCH systems and existing CH schemes and discuss the details of implementing the QCH system in MAC protocols. We discuss related work in Section 8 and conclude the paper in Section 9.

2. THE QUORUM SYSTEM

In this section, we provide a number of definitions that will facilitate the understanding of the various nomenclature and concepts that will be used throughout the paper.

2.1 Basic Definitions

Definition 1. *Given a finite universal set $U = \{0, ..., n-1\}$ of n elements, a quorum system S under U is a collection of non-empty subsets of U, which satisfies the intersection property:*

$$p \cap q \neq \emptyset, \forall p, q \in S.$$

Each $p \in S$ (which is a subset of U) is called a quorum.

2.2 Cyclic Quorum Systems

The *cyclic quorum system*, first introduced in [12], can be constructed using cyclic difference sets in combinatorial theory [20]. Here, we provide some definitions related to cyclic quorum systems since those systems are utilized to design channel hopping schemes in Sections 4 and 5.

Definition 2. *A set $D = \{a_1, a_2, ..., a_\kappa\} \subset \mathbf{Z}_n$ is called a relaxed cyclic (n, κ)-difference set if for every $d \not\equiv 0 \pmod n$ there exists at least one ordered pair (a_i, a_j), where $a_i, a_j \in D$, such that $a_i - a_j \equiv d \pmod n$. Here, $\mathbf{Z}_n$ denotes the set of nonnegative integers less than n.*

Definition 3. *A group of sets $B_i = \{a_1+i, a_2+i, ..., a_\kappa+i\} \mod n, i \in \{0, 1, ..., n-1\}$ is a cyclic quorum system if and only if $D = \{a_1, a_2, ..., a_\kappa\}$ is a relaxed cyclic (n, κ)-difference set.*

For example, $D = \{0, 1, 3\}$ is a relaxed cyclic $(7, 3)$-difference set under $\mathbf{Z}_7$ since each $d \in \{1, .., 6\}$ is congruent to the difference of two elements in D. Given D, $S = \{B_0, B_1, ..., B_6\}$ is a cyclic quorum system under $\mathbf{Z}_7$, where $B_i = \{0 + i, 1 + i, 3 + i\} \mod 7, i = \{0, 1, ..., 6\}$. It was proven in [11] that any quorum q in a cyclic quorum system under $U = \{0, ..., n-1\}$ must have a cardinality $|q| \geq \sqrt{n}$.

Given any n, a difference set as small as $\kappa \approx \sqrt{n}$ can be found when $\kappa^2 - \kappa + 1 = n$ and $\kappa - 1$ is a prime power. Such a difference set is called the *Singer* difference set [5], which is the *minimal* difference set whose size κ approximates the lower bound $\sqrt{n}$. Hence, cyclic quorum systems defined by the Singer difference sets are *minimal* cyclic quorum systems in the sense that their quorum sizes are close to the theoretical lower bound. For example, the set $\{1, 2, 4\}$ under $\mathbf{Z}_7$ is a Singer difference set when $\kappa = 3$.

Any set D that contains $\lceil \frac{n+1}{2} \rceil$ elements of $\mathbf{Z}_n$ is a relaxed cyclic $(n, \lceil \frac{n+1}{2} \rceil)$-difference set and a cyclic quorum system $S = \{B_0, B_1, ..., B_{n-1}\}$ can be constructed based on D according to Definition 3. Since D contains more than half of the elements in $\mathbf{Z}_n$, we refer to such a cyclic quorum system, S, as a *majority* cyclic quorum system. For example, $S = \{\{0, 1, 2\}, \{1, 2, 3\}, \{2, 3, 0\}, \{3, 0, 1\}\}$ is a majority cyclic quorum system under $\mathbf{Z}_4$.

2.3 Load of Quorum Systems

Here, we provide some definitions regarding the load of quorum systems. We will utilize these definitions to describe one of the optimal QCH systems introduced in Section 4. In the context of quorum systems, a *strategy* is a rule giving each quorum an access frequency so that the frequencies sum up to one. In other words, a strategy gives the frequency of picking each quorum. A strategy induces a *load* on each element, which represents the fraction of the time the element is used. Specifically, an element's load is the summation of the frequencies of all quorums that the element belongs to. Below, we provide more precise definitions.

Definition 4. *Let a quorum system $S = \{q_0, q_1, ..., q_{\kappa-1}\}$ be given over a universal set U. Then $W \in [0, 1]^\kappa$ is a strategy for S if it is a probability distribution over the quorums $q_j \in S$, i.e., $\sum_{j=0}^{\kappa-1} W_j = 1$.*

The *system load*, $\mathcal{L}(S)$, is the minimal load on the busiest element, minimizing over the strategies. A more precise definition follows.

DEFINITION 5. *Let a strategy W be given for a quorum system $S = \{q_0, q_1, ..., q_{\kappa-1}\}$ over a universal set U. For an element $i \in U$, the load induced by W on i is*

$$l_W(i) = \sum_{q_j \in S: i \in q_j} W_j.$$

The load *induced by a strategy W on a quorum system S is*

$$\mathcal{L}_W(S) = \max_{i \in U} l_W(i).$$

The system load *on a quorum system S is*

$$\mathcal{L}(S) = \min_{W} \{\mathcal{L}_W(S)\},$$

where the minimum is taken as the system load over all strategies W.

3. THE QUORUM-BASED CHANNEL HOPPING SYSTEM

3.1 Problem Formulation

Suppose there are N licensed channels in a DSA network, labeled as $0, 1, ..., N-1$. For formulating the channel hopping system, we assume that time is divided into CH periods, where each CH period is composed of T timeslots. For the sake of discussions, we assume that each timeslot is of unit duration so that each CH period is also T. Moreover, we assume that all nodes in the DSA network are synchronized (i.e., global clock synchronization) unless specified otherwise. In Section 5, we will discuss the design of CH systems that do not require global clock synchronization.

A CH sequence determines the order with which nodes visit all of the channels. We represent a CH sequence $\mathbf{u}$ of period T as a set of *pairs (2-tuples)*:

$$\mathbf{u} = \{(0, u_0), (1, u_1), ..., (i, u_i), ..., (T-1, u_{(T-1)})\},$$

where $u_i \in [0, N-1]$ represents the *channel index* of sequence $\mathbf{u}$ in the i^{th} timeslot of a CH period (i is the *slot index*).

Given two CH sequences $\mathbf{u}$ and $\mathbf{v}$, if $(i, j) \in \mathbf{u} \cap \mathbf{v}$, the pair (i, j) is called an *overlap* between $\mathbf{u}$ and $\mathbf{v}$. In this case, the i^{th} timeslot is called a *rendezvous slot* and channel j is called a *rendezvous channel* between $\mathbf{u}$ and $\mathbf{v}$. If a pair of neighboring nodes, say A and B, select $\mathbf{u}$ and $\mathbf{v}$ respectively as their CH sequences, then the resulting rendezvous channel can be used as a *pair-wise control channel*—i.e., the two nodes can exchange control information in channel j at the i^{th} timeslot of every CH period.

Let $I_j(\mathbf{u}, \mathbf{v})$ denote a function that indicates whether channel j is a rendezvous channel between two sequences $\mathbf{u}$ and $\mathbf{v}$, i.e.,

$$I_j(\mathbf{u}, \mathbf{v}) = \begin{cases} 1, & \text{if } \exists\, i \in [0, T-1],\ s.t.\ (i, j) \in \mathbf{u} \cap \mathbf{v}, \\ 0, & \text{otherwise.} \end{cases}$$

Now let us use $C(\mathbf{u}, \mathbf{v})$ to denote *the number of rendezvous channels* between two sequences $\mathbf{u}$ and $\mathbf{v}$, i.e.,

$$C(\mathbf{u}, \mathbf{v}) = \sum_{j=0}^{N-1} I_j(\mathbf{u}, \mathbf{v}).$$

In the opportunistic spectrum sharing paradigm, the value of $C(\mathbf{u}, \mathbf{v})$ directly impacts the *robustness* of the pair-wise control channel established using sequences $\mathbf{u}$ and $\mathbf{v}$. Recall that secondary users share spectrum opportunistically with incumbent users who have priority access rights. In such a scenario, secondary users are required to vacate the currently occupied channels when incumbent signals are detected in them. This requirement poses a difficult challenge in the design of MAC protocols for DSA networks—in particular, in terms of how to establish control channels in such a way that enables the reliable exchange of control information despite the unpredictable appearance of incumbent signals. The robustness of the control channels established using sequences $\mathbf{u}$ and $\mathbf{v}$ is proportional to the value of $C(\mathbf{u}, \mathbf{v})$, since this value determines the number of distinct channels in which the rendezvous occur within a sequence period. If the rendezvous are spread out over a greater number of distinct channels, then the probability of link breakage caused by the inability to exchange control packets (which in turn is due to the appearance of incumbent signals) decreases. Thus, we have the following *channel hopping system design problem.*

PROBLEM 1. *Given T, the CH system design problem is to devise a set of CH sequences of period T, denoted as H, which satisfies the following two properties:*

1. *$\forall \mathbf{u} \in H, |\mathbf{u}| = T$;*
2. *$m \geq 1$, where $m = \min_{\forall \mathbf{u}, \mathbf{v} \in H}\{C(\mathbf{u}, \mathbf{v})\}$.*

The set H is called a CH system *of period T, and m is* the degree of overlapping *of the CH system H.*

It is readily apparent that a CH system H is a quorum system under the universal set $U = \{(i, j) | i \in [0, T-1], j \in [0, N-1]\}$, since it satisfies the intersection property: any two sequences in H have at least one overlap. Each CH sequence in H is a quorum.

3.2 The Quorum-based Channel Hopping System

In this subsection, we introduce an algorithm that uses a quorum system to construct a CH system for any value of $m \in [1, N]$. We refer to this algorithm as Algorithm 1.

Without loss of generality, suppose we want to construct a CH system where every pair of CH sequences rendezvous in m different channels. We randomly select m channels from $\{0, ..., N-1\}$ to construct a *set of rendezvous channels*, such as $R = \{h_0, h_1, ..., h_{m-1}\}$. In our construction algorithm, every CH sequence is composed of m frames and each frame is composed of k slots (k is called the frame length). Hence, the period of each CH sequence is $T = m \cdot k$. We use the following example to explain the construction algorithm.

Suppose the set of rendezvous channels is $R = \{0, 1, 2\}$, each CH sequence is composed of $m = 3$ frames, and each frame has $k = 3$ slots.

1. First construct a universal set, $U = \mathbf{Z}_k = \{0, 1, 2\}$;
2. Construct a quorum system S under U, $S = \{\{0, 1\}, \{0, 2\}, \{1, 2\}\}$; [2]

[2]The desired properties of the CH system determines the particular quorum system that is constructed. In Section 4, we discuss a number of quorum systems that can be used to construct optimal CH systems.

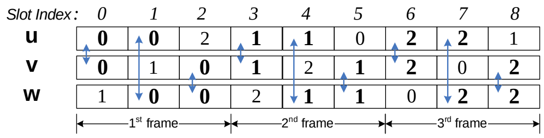


Figure 1: An illustration of QCH system Q with $m = 3$ and $k = 3$. Any two sequences overlap on three channels. We use the quorum system $S = \{\{0,1\},\{0,2\},\{1,2\}\}$ over $U = \{0,1,2\}$ to construct Q. The numbers inside the slots denote channel index values: bold-font values denote channel indexes from R and the non-bold font values denote channel indexes randomly chosen from $\{0,...,N-1\}$.

3. Using the quorum $q_0 = \{0,1\} \in S$, we construct a CH sequence $\mathbf{u}$ using the following procedure.

   - We make k channel assignments for the first frame in $\mathbf{u}$ using the following equation:

     $$u_i = \begin{cases} h_0, & \text{if } i \in q_0, \\ h\ , & \text{if } i \notin q_0. \end{cases}$$

     where h is a randomly selected channel from $\{0,..., N-1\}$. The (timeslot, channel) assignments for the first frame is obtained using a channel in R, $h_0 = 0$—i.e., $u_0 = 0, u_1 = 0, u_2 = h$.

   - Repeat the above procedure to make (timeslot, channel) assignments for each of the other frames using the remaining channels in R (i.e., channels 1 and 2 in this example). The resulting CH sequence is $\mathbf{u} = \{(0,0),(1,0),(2,h),(3,1),(4,1),(5,h),(6,2),(7,2),(8,h)\}$;

4. Repeat Step (3) for each of the other quorums in S (i.e., $q_1 = \{0,2\}$ and $q_2 = \{1,2\}$) to construct two other sequences, $\mathbf{v}$ and $\mathbf{w}$. The three CH sequences—$\mathbf{u}$, $\mathbf{v}$, and $\mathbf{w}$—are the elements of the set Q, which contains $|S| = 3$ CH sequences.

The sequences in Q are illustrated in Figure 1. Algorithm 1 constructs each sequence in Q by making k (timeslot, channel) assignments for each of the m rendezvous channels. One quorum in S is needed to generate each CH sequence in Q. Thus, $|Q| = |S|$.

Note that $\forall \mathbf{u}, \mathbf{v} \in Q$, there are two corresponding quorums $p, q \in S$ used for constructing $\mathbf{u}$ and $\mathbf{v}$, respectively. Because of the intersection property of S, $\mathbf{u}$ and $\mathbf{v}$ overlap in exactly m distinct channels—viz, the channels $h_d \in R, d \in [0, m-1]$ (see lines 3 and 6 of Algorithm 1). Also note that all of the sequences in Q have the same period, viz, $T = m \cdot k$ slots. Therefore, Q is a CH system that satisfies the requirements of Problem 1. We refer to the CH system constructed using Algorithm 1 as a *quorum-based channel hopping (QCH)* system. In Section 4, we will show how to minimize TTR between any two CH sequences. We will also describe a scheme that addresses the rendezvous convergence problem of CH systems by selecting a particular type of quorum system used in Algorithm 1. In Section 5, we show that this algorithm can be readily extended to generate CH systems that do not require global clock synchronization.

Algorithm 1 QCH System Construction Algorithm

Input: N, k, $R = \{h_0, h_1, ..., h_{m-1}\}$, $U = \mathbf{Z}_k$, and a quorum system S under U.
Output: Q.

```
1:  Q = ∅.
2:  for j = 0 to (|S| − 1) do
3:      for d = 0 to (m − 1) do
4:          for i = 0 to (k − 1) do
5:              if i ∈ q_j then
6:                  u_(i+d·m) = h_d.
7:              end if
8:              if i ∉ q_j then
9:                  u_(i+d·m) = h, randomly chosen from {0, ..., N − 1}.
10:             end if
11:         end for
12:     end for
13:     Q = Q ∪ u.
14: end for
```

3.3 Metrics for Evaluating CH Systems

We introduce two metrics—*maximum time-to-rendezvous* (MTTR) and *load*—that are used to evaluate CH systems. Note that both metrics can be used to evaluate all CH systems, not just quorum-based CH systems.

Maximum Time-to-Rendezvous. The first metric we introduce is the *maximum time-to-rendezvous* (MTTR) for a CH system, which is defined as the maximum time for any pair of sequences in a CH system to rendezvous. Let $M(H)$ denote the MTTR of a CH system H. It is obvious that the MTTR value impacts the medium access delay of MAC protocols that utilize channel hopping since the exchange of control information is not possible without rendezvous. Networks that require stringent delay requirements will require a CH system with a small MTTR value. For example, in a mobile DSA network, neighboring nodes have to exchange time-sensitive control information frequently—information such as spectrum sensing related control information, node location, link connectivity, etc.

In a QCH system Q constructed using Algorithm 1, the MTTR value is equal to the frame length k. In the QCH system Q given in Figure 1, the MTTR is $M(Q) = 3$. In Section 4.1, we describe a methodology for designing a QCH system that is optimal in terms of minimizing the MTTR.

Load of CH Systems. In CH MAC protocols, spreading out the rendezvous in time and frequency (i.e., channels) is important in order to take full advantage of the frequency diversity of multi-channel medium access. If a large proportion of neighboring nodes rendezvous on the same channel, then channel congestion can occur and lead to a control channel bottleneck problem—we use the term *rendezvous convergence* to refer to such a problem. Some CH MAC protocols (e.g., SSCH [2]) implement "customized" mechanisms to prevent rendezvous convergence. Ideally, a CH protocol should spread out the rendezvous over all channels evenly.

One advantage of using the proposed approach to devise CH schemes is that it can formally characterize the rendezvous convergence problem using the measure of *load* which is used in the study of quorum systems. In quorum systems, a *strategy* is a probabilistic rule that gives the frequency of accessing each quorum so that the frequencies sum up to one. Since a CH system is in essence a quorum system, we can use the definition of load given above to create an analogous definition for the load of a CH system. Let W_0 denote the following strategy: each radio randomly selects a sequence from a CH system with equal probability. Given a CH system, H, the load of H induced by W_0, $\mathcal{L}_{W_0}(H)$, is the load of the busiest element induced by W_0; the busiest element, in this context, refers to the (timeslot, channel)-pair included in the largest number of CH sequences. We define the *load of a CH system* as the load of the CH system induced by the particular strategy W_0.

In the QCH system Q shown in Figure 1, the load is $\mathcal{L}_{W_0}(Q) = 2/3$. In Section 4.2, we will discuss a QCH design that is optimal in the sense that it minimizes the load of the QCH system.

4. SYNCHRONOUS QCH SYSTEMS

In this section, we describe two optimal QCH systems, both of which require global clock synchronization.

4.1 Minimizing the MTTR in QCH Systems

Minimizing the MTTR of a QCH system is equivalent to minimizing its frame length k. To design an optimal QCH system that minimizes the MTTR, we first need to solve the following problem:

PROBLEM 2. *Given a QCH system Q,*

$$\begin{array}{ll} \text{minimize} & k, \\ \text{subject to} & \mathcal{L}_{W_0}(Q) < 1. \end{array}$$

The constraint $\mathcal{L}_{W_0}(Q) < 1$ equates to $\bigcap_{\mathbf{u}\in Q} \mathbf{u} = \emptyset$, which is needed to avoid the scenario in which the load of the QCH system is equal to one (i.e., there is at least one (timeslot, channel)-pair that is included in all of the sequences in Q).

The lower bound for k. To solve Problem 2, we find the lower bound for k when the load of the QCH system is less than one in the following theorem.

THEOREM 1. *Given a QCH system Q, a necessary condition for $\mathcal{L}_{W_0}(Q) < 1$ is $k \geq 3$.*

PROOF. We prove this theorem by contradiction. Let $k \leq 2$ and suppose we have a QCH system Q, where $T = k \cdot m$ and $\mathcal{L}_{W_0}(Q) < 1$.

If $k = 1$, then $T = m$. Since $C(\mathbf{u}, \mathbf{v}) \geq m \geq 1, \forall \mathbf{u}, \mathbf{v} \in Q$, all sequences in Q must be identical. In this case, the load of Q is 1, which contradicts the constraint $\mathcal{L}_{W_0}(Q) < 1$.

If $k = 2$, the universal set is $U = \{0, 1\}$ according to Algorithm 1. Any quorum system S over $U = \{0, 1\}$ has a system load of one, i.e., $\mathcal{L}(S) = 1$. Since the QCH system Q is constructed using S, $\mathcal{L}_{W_0}(Q) \geq \mathcal{L}(S) = 1$, and this contradicts the constraint $\mathcal{L}_{W_0}(Q) < 1$.

From Figure 1, we can see that there exists a QCH system in which $k = 3$ and its load is less than one.

From the above arguments, it is clear that $k \geq 3$ is a necessary condition for $\mathcal{L}_{W_0}(Q) < 1$. □

Construction of the M-QCH system. The QCH system that achieves the lower bound for k (i.e., $k = 3$) is an optimal QCH design in the sense that it minimizes the MTTR while keeping the load less than one. We refer to such a system as an *M-QCH System*, and it can be constructed using Algorithm 1 with a *majority* cyclic quorum system over a universal set $U = \mathbf{Z}_3$. The example QCH system shown in Figure 1 is an M-QCH system. An M-QCH system can support m rendezvous channels ($m \in [1, N]$) and it has the lowest MTTR value (i.e., 3) among all QCH systems. Hence, M-QCH systems are advantageous in establishing control channels with minimal medium access delay.

4.2 Minimizing the Load

In this subsection, we study an optimal QCH system, Q, that has the minimal load under the constraint $M(Q) \leq \tau$, for a given value of τ. To construct such a QCH system, we need to solve the following problem:

PROBLEM 3. *Given a QCH system Q,*

$$\begin{array}{ll} \text{minimize} & \mathcal{L}_{W_0}(Q), \\ \text{subject to} & M(Q) \leq \tau, \end{array}$$

where τ is the maximum allowed MTTR of Q.

The lower bound for load. We solve Problem 3 by finding the lower bound for $\mathcal{L}_{W_0}(Q)$ under the constraint $M(Q) \leq \tau$.

THEOREM 2. *Given a QCH system Q where $M(Q) \leq \tau$, the minimum load induced by W_0 on Q is $\frac{1}{\sqrt{\tau}}$, i.e.,*

$$\mathcal{L}_{W_0}(Q) \geq \frac{1}{\sqrt{\tau}}.$$

PROOF. In a QCH system Q where $M(Q) \leq \tau$, since $M(Q) = k$, we have $k \leq \tau$ (k is the frame length).

According to Algorithm 1, such a QCH system Q is constructed using a quorum system S over $U = \mathbf{Z}_k$. Thus, we have $\mathcal{L}_{W_0}(Q) \geq \mathcal{L}(S)$.

The propositions 4.1 and 4.2 in [15] state that the following relation is true:

$$\mathcal{L}(S) \geq \max\left\{\frac{1}{\varphi(S)}, \frac{\varphi(S)}{k}\right\},$$

where $\varphi(S)$ is the size of the smallest quorum in the quorum system S. Using the inequality of arithmetic and geometric means, it can be shown that

$$\mathcal{L}(S) \geq \frac{1}{\sqrt{k}}.$$

Since $k \leq \tau$, we have $\mathcal{L}_{W_0}(Q) \geq \mathcal{L}(S) \geq \frac{1}{\sqrt{k}} \geq \frac{1}{\sqrt{\tau}}$. □

Construction of the L-QCH system. Using Algorithm 1, we can construct an optimal QCH system that minimizes the value of $\mathcal{L}_{W_0}(Q)$ by using a *minimal* cyclic quorum system over a universal set $U = \mathbf{Z}_\tau$. We refer to such an optimal QCH system as an *L-QCH System*. An L-QCH system includes τ unique CH sequences. The L-QCH system Q shown in Figure 2 is constructed using a minimal cyclic quorum system S over $U = \mathbf{Z}_7$, which has a degree of overlapping of $m = N$ and $\tau = 7$. The load $\mathcal{L}_{W_0}(Q) = \frac{3}{7} \approx \frac{1}{\sqrt{\tau}}$.

4.3 Tradeoff Relationship between MTTR and Load

When devising a QCH scheme, one needs to consider the tradeoff relationship between MTTR and load. In general, reducing the frame length k of a QCH system will lead to higher load and hence aggravate the rendezvous convergence

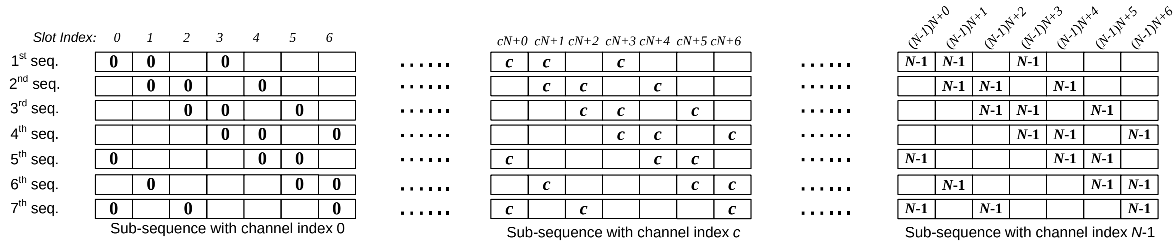


Figure 2: An L-QCH system, Q, with $m = N$ rendezvous channels and $\tau = 7$. To construct Q, we use a minimal cyclic quorum system $S = \{\{0,1,3\},\{1,2,4\},\{2,3,5\},\{3,4,6\},\{4,5,0\},\{5,6,1\},\{6,0,2\}\}$ under $U = \mathbf{Z}_7$. The channel indexes for "blank" slots are randomly selected from $[0, N-1]$. Any two sequences in this system overlap on all N channels.

problem. However, increasing k will increase the MTTR and increase the expected TTR, in turn increasing the channel access delay.

Assuming a very simple channel access strategy, we illustrate an example of how one may find an appropriate value for k by making an appropriate tradeoff between MTTR and load. Suppose there is a network with X nodes, all within transmission range of each other. Assuming strategy W_0 and an L-QCH system, Q, with a frame length of k, the expected number of nodes that are assigned the same channel for a given timeslot (i.e., the channel index h_d in line 6 of Algorithm 1) is $Y = \frac{X}{\sqrt{k}}$. For simplicity of calculations, suppose the following simple channel access rule is used by all nodes:

- In every timeslot, a node decides to transmit on its assigned channel with a probability ρ;
- A packet collision occurs when two nodes transmit on the same channel during the same time slot. We assume that time slot boundaries are aligned.

Thus, the probability that a transmitter successfully transmits a message to its receiver can be simply estimated as

$$P_s = \frac{m}{T} \cdot \rho(1-\rho)^{Y-1} = \frac{1}{k} \cdot \rho(1-\rho)^{Y-1}.$$

Using the relation given above, one can readily find the value of k that maximizes P_s. As the previous example illustrates, the tradeoff between MTTR and load needs to be considered in the context of the particular network performance metric that is deemed important.

5. ASYNCHRONOUS CH SYSTEMS

In this section, we describe an *asynchronous* CH system that does *not* require global clock synchronization. The objective is to devise a CH system, H, that enables any pair of CH sequences to overlap by at least half of a timeslot for every sequence period (i.e., for every T consecutive timeslots) even under the assumption that slot boundaries are misaligned by an arbitrary amount.

5.1 Rotation Closure Property in CH Systems

We extend the concept of the *rotation closure property* of quorum systems [11] so that it is applicable to CH systems. We will show that a CH system with the rotation closure property is an asynchronous CH system that does not require global clock synchronization.

DEFINITION 6. *Given a non-negative integer i and a CH sequence $\mathbf{u}$ in a CH system H of period T, we define*

$$rotate(\mathbf{u}, i) = \left\{(j, v_j) | v_j = u_{(j+i) \bmod T}, j \in [0, T-1]\right\}.$$

For example, given $\mathbf{u} = \{(0,0),(1,1),(2,2)\}$ and $T = 3$, $rotate(\mathbf{u}, 2) = \{(0,2),(1,0),(2,1)\}$.

DEFINITION 7. *A CH system H of period T and a degree of overlapping m is said to have the rotation closure property if $\forall \mathbf{u}, \mathbf{v} \in H, i \in [0, T-1], C(rotate(\mathbf{u}, i), \mathbf{v}) \geq m$.*

Building on the above definitions, the following theorem states that a CH system with the rotation closure property ensures rendezvous even when the slot boundaries are not aligned.

THEOREM 3. *If a CH system H of period T and a degree of overlapping m satisfies the rotation closure property, any pair of CH sequences in H must overlap by at least $m/2$ timeslots for every T consecutive timeslots even when the timeslot boundaries are misaligned by an arbitrary amount.*

PROOF. Suppose that a CH system H satisfies the rotation closure property and two nodes, A and B, each picks a CH sequence from H randomly—viz, $\mathbf{u}$ and $\mathbf{v}$, respectively. For the sake of our discussions, suppose the length of a timeslot is 1. We consider two cases.

1) When slot boundaries are aligned: Without loss of generality, let us suppose node A's clock is i slots ahead of node B's clock. With respect to node B's clock, node A's sequence $\mathbf{u}$ is equivalent to $rotate(\mathbf{u}, i)$. Since H has the rotation closure property, $C(rotate(\mathbf{u}, i), v) \geq m$. Hence, the two sequences must have at least m rendezvous channels between them (i.e., overlap by at least m timeslots). It is obvious that the same result is obtained when we assume that A's clock is i slots behind B's clock.

2) When slot boundaries are misaligned: Suppose node A's clock is ahead of node B's clock by an arbitrary amount of time, say $i + \delta$, where $i \in \mathbf{Z}_T, 0 < \delta < 1$.

- If $\delta \leq 1/2$, let us shift left node B's sequence by δ and designate this sequence as $\mathbf{v}'$.[3] It is obvious that the slot boundaries of $\mathbf{u}$ and $\mathbf{v}'$ are aligned and the former is ahead of the latter by i slots in terms of their respective nodes' clocks. Since H has the rotation closure property, $C(rotate(\mathbf{u}, i), \mathbf{v}') \geq m$, and thus $\mathbf{u}$ must overlap with $\mathbf{v}$ by $m(1-\delta)$ timeslots. This means

[3]Shifting a node's CH sequence *left/right* by δ is equivalent to *advancing/retreating* the node's clock by δ.

that the two sequences overlap with each other by at least $m/2$ timeslots for every T consecutive timeslots.

- If $\delta > 1/2$, let us shift right node B's sequence by $1-\delta$ and designate this sequence as $\mathbf{v}'$. It is obvious that the slot boundaries of $\mathbf{u}$ and $\mathbf{v}'$ are aligned and the former is ahead of the latter by $i+1$ slots in terms of their respective nodes' clocks. Since H has the rotation closure property, $C(rotate(\mathbf{u}, i+1), \mathbf{v}') \geq m$, and thus $\mathbf{u}$ must overlap with $\mathbf{v}$ by $m\delta$ timeslots. This means that the two sequences overlap with each other by at least $m/2$ timeslots for every T consecutive timeslots.

□

From Theorem 3, we can conclude that any two nodes that select CH sequences from a system with the rotation closure property can rendezvous with each other during the overlap of their sequences even if they are asynchronous (i.e., slot boundaries are not aligned). If multiple pairs of nodes happen to rendezvous at the same slot on the same channel, they can follow a channel contention procedure (e.g., 802.11 RTS/CTS protocol) to carry out the pair-wise rendezvous.

Henceforth we refer to a quorum-based CH system that satisfies the rotation closure property as an *asynchronous quorum-based CH (A-QCH)* system. Next, we describe an algorithm, Algorithm 2, for constructing an A-QCH system that uses two different types of cyclic quorum systems.

Algorithm 2 A-QCH System Construction Algorithm

Input: N, k, $R = \{h_0, h_1\}$, $U = \mathbf{Z}_k$, and two cyclic quorum systems S and S' over U.
Output: Q.

1: $Q = \emptyset$.
2: **for** $j = 0$ to $(|S| - 1)$ **do**
3:     **for** $i = 0$ to $(k-1)$ **do**
4:         **if** $i \in B_j$ **then**
5:             $u_i = h_0$.
6:         **else if** $i \in B'_j$ **then**
7:             $u_i = h_1$.
8:         **else**
9:             $u_i = h$ randomly chosen from $\{0, ..., N-1\} \setminus \{h_0, h_1\}$.
10:         **end if**
11:     **end for**
12:     $Q = Q \cup \mathbf{u}$.
13: **end for**

5.2 Construction of A-QCH Systems

Algorithm 2 uses two types of cyclic quorums systems to construct an A-QCH system that guarantees at least two rendezvous channels between any two sequences (i.e., $C(\mathbf{u}, \mathbf{v}) \geq 2, \forall \mathbf{u}, \mathbf{v} \in H$). This A-QCH system is composed of CH sequences that have only one frame per sequence period (i.e., $T = k$). In each constructed CH sequence, a subsequence constructed by a minimal cyclic quorum S is interleaved with a subsequence constructed by a majority cyclic quorum system S'. Refer to [12] for methods to construct minimal cyclic quorums and majority cyclic quorums. A pseudo-code of Algorithm 2 is given above and its description is given below.

1. First construct a universal set $U = \mathbf{Z}_k$;
2. Find a minimal (k, κ)-difference set $D = \{a_1, a_2, ..., a_\kappa\}$ such that $\kappa < \frac{k}{2}$ and construct a minimal cyclic quorum system based on D, such as $S = \{B_i | B_i = \{a_1 + i, a_2 + i, ..., a_\kappa + i\} \mod k, i \in [0, k-1]\}$;
3. Construct a relaxed cyclic $(k, \lceil \frac{k+1}{2} \rceil)$-difference set $D' = \{a'_1, a'_2, ..., a'_{\lceil \frac{k+1}{2} \rceil}\}$ such that $D' \cap D = \emptyset$. Then, construct a majority cyclic quorum system based on D', such as $S' = \{B'_i | B'_i = \{a'_1 + i, a'_2 + i, ..., a'_{\lceil \frac{k+1}{2} \rceil} + i\} \mod k, i \in [0, k-1]\}$. Note that $|S| = |S'| = k$, and $|D'| = \lceil \frac{k+1}{2} \rceil$;
4. Use the minimal cyclic quorum system S for assigning the first rendezvous channel h_0 to appropriate slots in a CH sequence $\mathbf{u}$ (see lines 4 and 5 in the algorithm);
5. Use the majority cyclic quorum system S' to assign the second rendezvous channel h_1 to appropriate slots in a CH sequence $\mathbf{u}$ (see lines 6 and 7 in the algorithm).
6. The remaining slots in $\mathbf{u}$ are assigned a channel index randomly chosen from $\{0, ..., N-1\} \setminus \{h_0, h_1\}$ (see line 9 in the algorithm).

An example A-QCH system is shown in Figure 3. One can readily show that an A-QCH system constructed using Algorithm 2 satisfies the rotation closure property and that the TTR value between any two sequences in an A-QCH system is bounded by the length of its sequence period $T = k$.

Given that $D' \cap D = \emptyset$, k must be no less than $|D| + |D'|$ so that a CH sequence can accommodate two subsequences constructed using S and S'. In [12], Luk and Wong conducted an exhaustive search to find the minimal difference sets under $\mathbf{Z}_k$ for $k = 4, ..., 111$. Based on their results, we can infer that: when $k = 9$, $|D| = 4$ and $|D'| = 5$; when $k > 9$, $k > |D| + |D'|$. Thus, to satisfy $k \geq |D| + |D'|$, the minimum possible value for k is 9—this implies that the MTTR of an A-QCH system is no less than 9. The load of an A-QCH system is approximately $\frac{1}{2}$, which is also the load value of a majority cyclic quorum system.

In our description of A-QCH systems given above, we used relaxed cyclic difference sets D and D' for generating cyclic quorum systems that facilitate the construction of a CH system with the rotation closure property. The specific choices of D and D' and the resulting cyclic quorum systems have no significance—i.e., the quorum systems that we have chosen are merely our design choices for constructing an A-QCH system; it is likely that there are other quorum systems that can be used to construct A-QCH systems of similar or different structure.

6. DISCUSSIONS

6.1 Comparisons

In this subsection, we compare the proposed QCH systems with three existing CH schemes using four metrics: degree of overlapping, MTTR, load, and robustness to clock skew.

Blind rendezvous (BR) channel hopping [17]. In this scheme, each node hops from one channel to another randomly. At a particular instant, a node occupies one of these channels with probability $1/N$, where N is the total number of channels. When two nodes occupy the same channel at the same time, rendezvous occurs. The BR scheme does not guarantee a bounded TTR between any two sequences.

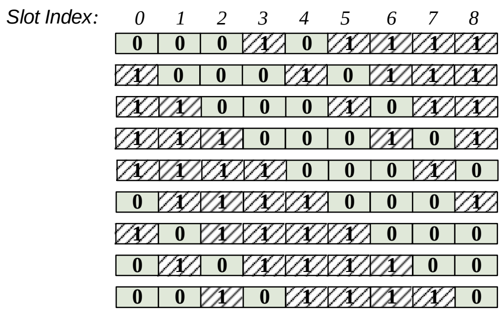


Figure 3: An A-QCH system Q with $m = 2$ and $T = k = 9$. The universal set, U, is $\mathbf{Z}_9$, S is constructed using $D = \{0, 1, 2, 4\}$, and S' is constructed using $D' = \{3, 5, 6, 7, 8\}$. Note that $D' \cap D = \emptyset$. The numbers inside the slots represent the channel index values.

Slotted Seeded Channel Hopping (SSCH) [2]. Each node is allowed to have one or multiple (channel, seed)-pairs to determine its CH sequences. SSCH allows $(N - 1)$ seeds. Each sequence period includes a parity slot at which time instant all nodes with the same seed are guaranteed to rendezvous on a channel indicated by the seed value. Thus, the load of the SSCH system is $\frac{1}{N-1}$. When each node selects one (channel, seed)-pair, the resulting sequence period is $(N + 1)$ timeslots, and each pair of sequences rendezvous exactly once within a period. Thus, the MTTR of SSCH is $(N + 1)$. By design, SSCH is a synchronous CH system, although results in [2] show that it can tolerate moderate clock skew. The amount of clock skew used in [2] to evaluate SSCH is very small relative to one slot duration.

Sequence-based rendezvous (SeqR) [8]. Each sequence generated by the SeqR scheme has a period of $N(N+1)$ slots. This scheme builds the initial sequence, $\mathbf{u}$, by first selecting a permutation of elements in $\mathbf{Z}_N$. Then it repeats the selected permutation $(N+1)$ times in the sequence $\mathbf{u}$ using the following method: the permutation is used contiguously N times, and once the permutation is interspersed with the other N permutations. For example, when $N = 3$, one can select a permutation such as $\{0, 2, 1\}$. Then the channel indexes of the initial sequence $\mathbf{u}$ would be { ***0***, 0,2,1, ***2***, 0,2,1, ***1***, 0,2,1 }. Note that the elements in the permutation $\{0, 2, 1\}$ is interspersed with the three replications of the same permutation. By applying the operation $rotate(\mathbf{u}, i), \forall i \in [1, N(N+1)-1]$ to the initial sequence, $\mathbf{u}$, a number of new sequences can be generated, thereby creating a total of $N(N + 1)$ sequences. Collectively, this set of sequences forms an asynchronous CH system that satisfies the rotation closure property. The sequence period is $N(N + 1)$ and $C(\mathbf{u}, \mathbf{v}) \geq 1, \forall \mathbf{u}, \mathbf{v} \in H$. Its MTTR is $N(N + 1)$ and its load is $\frac{1}{N}$.

SSCH, M-QCH, and L-QCH are synchronous CH systems that require the slot and period boundaries to be aligned. In contrast, SeqR and A-QCH are asynchronous CH systems that have no such requirements. A comparison of all the CH schemes discussed in this paper are summarized in Table 1. Note that the metrics MTTR and load are not applicable to the BR scheme because it does not guarantee a bounded TTR between two sequences. In terms of degree of overlapping, M-QCH and L-QCH are superior to others since the two schemes can maximize the degree of overlapping to N channels.

Table 1: A comparison of CH schemes.

	Degree of overlapping	MTTR	Load	Asynchronous operation
BR	0	N/A	N/A	N/A
SSCH	1	$N+1$	$\frac{1}{N-1}$	No
M-QCH	$[1, N]$	3	$\frac{2}{3}$	No
L-QCH	$[1, N]$	k	$\frac{1}{\sqrt{\tau}}$	No
SeqR	1	$N(N+1)$	$\frac{1}{N}$	Yes
A-QCH	2	≥ 9	$\approx \frac{1}{2}$	Yes

6.2 Implementing QCH in DSA Networks

In this subsection, we discuss some of the important issues that may arise when implementing a QCH system in DSA networks. Dynamic and opportunistic utilization of fallow spectrum requires that radios be capable of locating each other to establish a link via a rendezvous process. As mentioned previously, the use of a common control channel simplifies the rendezvous process but this approach may not be feasible in many DSA network deployment scenarios. For instance, in an ad hoc DSA network that opportunistically uses available spectrum, there is no central entity that can designate a common control channel. Furthermore, this approach does not provide an adequate method of switching the control channel to another channel when incumbent signals are detected on the current control channel. In a DSA network, channel availability cannot be guaranteed for any channel, including the control channel. It is important to note that the proposed quorum-based CH methodology is a systematic approach for facilitating the exchange of control information in a distributed fashion, specifically tailored for DSA networks.

Sequence adjustment for opportunistic spectrum utilization. After randomly selecting a CH sequence (from a QCH system), each node performs channel hopping as specified in its sequence in order to rendezvous with a neighbor that it wants to establish a link with. In an opportunistic spectrum sharing environment, a secondary node may need to alter its sequence due to the appearance of incumbent signals. A node should avoid hopping to a channel if incumbent signals are detected in that channel in order to prevent interfering with incumbent communications. If incumbent signals are detected in one or more of the channels in its sequence, then the node simply replaces those channels with other channels. The replacement channels are randomly selected from the set of channels that are free of incumbent signals. When none of the incumbent-occupied channels is included in the set of rendezvous channels, the degree of overlapping and the MTTR of the QCH system is not affected by the sequence adjustment. However, if incumbent signals are detected in some of the rendezvous channels, then the ensuing sequence adjustment will affect the degree of overlapping and MTTR—specifically, the degree of overlapping will decrease and the MTTR will increase. Thus, in order to ensure maximum availability of the control channels, the QCH system should have a degree of overlapping close or equal to N. In this case, most or all of the available channels can be used as rendezvous channels which enables pairs of nodes to rendezvous within a reasonable amount of time even if some of the rendezvous channels are occupied by incumbent users.

Data exchange after rendezvous. The proposed QCH scheme facilitates the exchange of control information via parallel rendezvous that enable multiple radio pairs to establish links simultaneously on distinct channels. However, the QCH scheme does not dictate how the radios coordinate the exchange of data information once the control information has been exchanged (via rendezvous). There are a number of known techniques for coordinating the exchange of data packets in a multi-channel environment. In a scheme known as *(temporary) common hopping* [2,19], a transmitting node alters its hopping sequence so that it matches that of the receiving node while it is transmitting data packets, and then returns back to its original sequence once the transmission has finished.

Hidden terminal problem. Like most multi-channel MAC protocols [2,18,19], the QCH system adopts the technique of exchanging RTS/CTS packets to avoid the *hidden terminal* problem. When multiple nodes hop onto a common channel at the same time, each node has to send an RTS to reserve the channel in the current slot before transmitting a control or data packet.

Hidden incumbent problem. In addition to the hidden terminal problem, DSA networks face another type of problem, viz, the *hidden incumbent* problem [4,7]. Although the hidden incumbent problem was originally defined in the context of IEEE 802.22 networks, it can be generalized to other types of DSA networks. The hidden incumbent problem refers to a situation in which a consumer premise equipment (CPE) is within the protection region of an operating incumbent but fails to report the existence of the incumbent to its base station (BS). Suppose that the BS started service in a certain band unaware of the fact that an incumbent is using the same band. In such a scenario, CPEs within the incumbent's transmission range may not be able to decode the BS signal because of the strong interference from the incumbent signal. Moreover, the CPEs cannot report the existence of the incumbent as their transmission will cause interference to the incumbent. Therefore, these CPEs are unable to report the existence of the incumbent to the BS, and hence the BS fails to detect the presence of the incumbent.

The proposed QCH system alleviates the hidden incumbent problem because it enables a pair of secondary nodes to rendezvous in more than one channel. As can be seen in Table 1, all variations of the QCH system can *guarantee* rendezvous in more than one distinct channel (as evidenced by the fact that their degree of overlapping is greater than one). The same cannot be said of the existing channel hopping schemes. The advantage of guaranteeing rendezvous in multiple channels is obvious: if a node detects an incumbent signal in the current rendezvous channel, one of the other rendezvous channels can be used to report the incumbent appearance to the neighboring nodes. Note that QCH's ability to rendezvous in multiple distinct channels emulates the technique of *out-of-band signaling* without requiring multiple radios per node. Out-of-band signaling is proposed in the IEEE 802.22 standard to address the hidden incumbent problem.

7. PERFORMANCE EVALUATION

We simulate the QCH scheme in ns-2 (version 2.31) [22] and use three MAC-layer reference protocols for comparison: IEEE 802.11b, SSCH, and the SeqR protocol. The data rate is 11 Mbps by default. Note that IEEE 802.11b and SSCH were not designed for use in DSA networks. However, they serve as good benchmarks in evaluating the performance of QCH. Furthermore, the design criteria of CH schemes for conventional multi-channel networks are almost identical to those of CH schemes for DSA networks, and SSCH is one of the most well-known schemes of the former type. In the simulations, secondary nodes can opportunistically access three channels (i.e., $N = 3$). The channel switching delay is chosen as $80\mu s$, which is well supported by existing technology [9]. The duration of a time slot is 200 ms. Every node uses Ad hoc On-Demand Distance Vector Routing (AODV) [16] as the routing protocol. At the transport layer, UDP is used in the simulations by default. The traffic generator uses Constant Bit Rate (CBR) flows with a flow rate of 11 Mbps and a packet size of 512 bytes. The transmission range of every node is 250 m. We simulated two networks: a static network with ten single-hop flows in a $100m \times 100m$ square area and a random network with five multi-hop flows in a $1000m \times 1000m$ square area. In the simulations, we study the time-to-rendezvous (TTR) value and the throughput in each CH protocol under varying conditions, including random incumbent traffic, node mobility, and multi-flow complex networks.

The following protocols were simulated.

- SSCH: Each node randomly chooses one (channel, seed)-pair to construct its CH sequence. For example, if a node selects the pair $(0, 1)$, then its CH sequence has a period of $(N + 1)$ slots, and the channel indexes in its sequence are $\{0, 1, 2, 1\}$. The last slot of a period is the parity slot, and the channel index of this slot is equal to the value of the node's seed.
- SeqR: This is the protocol proposed in [8]; it was briefly described in Section 6.1.
- QCH: We simulate two synchronous QCH systems (M-QCH, and L-QCH) and an synchronous one (A-QCH).

We assume that every node randomly picks one sequence from a CH system and performs channel hopping in accordance with the sequence. Once the sending-receiving node pair rendezvous on a channel, the pair performs common hopping to exchange data packets. The sender follows the receiver's sequence.

Incumbent traffic generation. In the simulations, we generated incumbent traffic as follows. In every time slot, the incumbent transmitter decides whether to transmit or not by flipping a coin. If the incumbent transmitter decides to transmit, it randomly selects one or two channels and transmits packets in the current time slot. All of the secondary nodes are within the transmission range of the incumbent transmitter. A single incumbent transmitter was simulated. A channel is tagged as "unavailable" while incumbent traffic is present on it. All secondary nodes should refrain from transmitting on unavailable channels during the period of incumbent transmission. Note that all nodes that perform channel hopping are secondary nodes.

7.1 Impact of Time-to-Rendezvous

We first simulated a single-hop flow to show the effect of TTR on channel access delay and the effect of channel switching overhead on throughput. The results are shown in Figure 4. We can see that the starting times of the traffic delivery for the simulated protocols are different, which coincides with the discrepancy of the protocols' channel access delays due to the variation in TTR values. Note that the throughput of each CH protocol is lower than that of 802.11b, which we can attribute to the channel switching overhead.

Next, we simulated a network with ten single-hop *disjoint* flows in a $100m \times 100m$ square area. Two flows are considered disjoint if they do not share either endpoint. The average TTR for three CH schemes (when there is no incumbent traffic) is shown using the leftmost group of bars in Figure 5. As can be seen, M-QCH has the lowest average TTR compared to SSCH and SeqR—this is expected since M-QCH has the lowest MTTR value among the three CH protocols.

7.2 Impact of Degree of Overlapping

As expected, our simulation results indicate that a CH scheme's degree of overlapping has a clear impact on its TTR value when the incumbent transmitter is active. The average TTR for three CH schemes in the presence of incumbent traffic is shown using the center and rightmost groups of bars in Figure 5. M-QCH has a clear advantage over SSCH and SeqR in terms of TTR, because M-QCH's degree of overlapping is greater than that of the other two schemes in this simulation. This advantage becomes more evident in the presence of incumbent traffic since a pair of nodes using M-QCH can rendezvous on other channels if the current rendezvous channel is occupied by incumbent signals. In contrast, a pair of nodes using either SSCH or SeqR can rendezvous only on one channel (here, we are referring to the initial rendezvous). This implies that the nodes may not be able to achieve the initial rendezvous until the incumbent vacates the rendezvous channel. Note that in SSCH, initial rendezvous is needed to exchange data, such as each other's sequence, that is required to rendezvous in multiple channels.

Next, we set up ten *non-disjoint* flows in a $100m \times 100m$ square area, where every node serves as both a transmitter and a receiver in multiple flows. In other words, this scenario includes multiple simultaneous flows with common endpoints. We assume temporary common hopping, i.e., each transmitter node has to change its hopping sequence and follow the receiver's sequence after a rendezvous has occurred to bootstrap communications. If the receiver node also acts as a transmitter in another flow, it must also follow the sequence of its intended receiver after a rendezvous. Thus, some nodes in this network have to switch between CH sequences continuously, and this scenario puts stress on a CH protocol's ability to establish links. Temporary common hopping prescribes that a transmitter should return back to its original sequence once the transmission has finished—this avoids the global synchronization of the CH sequences over the entire network (i.e., a scenario in which every node uses the same sequence). We compare the per-flow throughput of M-QCH, SSCH, and SeqR in Figure 6. When an incumbent signal is detected, M-QCH replaces the incumbent-occupied channel in its sequence with any incumbent-free channel. The results in the figure show that M-QCH outperforms the other two protocols, since M-QCH is faster in re-establishing links—this, of course, is due to the fact that M-QCH enables rendezvous in a greater number of distinct channels per sequence period.

7.3 Impact of the Load

In this set of simulation experiments, we investigated the effect of load (as defined in Section 2.3) on network performance. In general, the load of a CH system determines the number of concurrent co-channel transmissions in each time slot. If the load is low, the number of concurrent co-channel transmissions in each slot is small, which means that the traffic is more evenly distributed among different channels in every time slot. In general, a more even distribution of traffic among channels implies higher network throughput. In the simulations, we varied the number of disjoint flows in a $100m \times 100m$ square area, and the results are shown in Figure 7. In the figures, we can see that L-QCH and SeqR outperform the other schemes since the two schemes have the lowest load (viz $\frac{1}{3}$) compared to the other schemes (M-QCH has a load of $\frac{2}{3}$ and SSCH incurs a load of $\frac{1}{2}$ as indicated in Table 1). It is interesting to note that M-QCH's performance is inferior to that of the other schemes when the number of flows is small (because M-QCH has the highest load); however, when the number of flows is large, the system throughput for SSCH is lower than that of the other schemes. This phenomenon can be attributed to the limiting effect of the parity slot prescribed by SSCH when the network is close to saturation: nodes using SSCH can only utilize $(N-1)$ channels specified by $(N-1)$ seed values in the parity slot. In contrast, nodes using the other CH protocols can fully utilize all N channels in any time slot. From Figure 7, we can conclude that CH schemes that have lower load values are generally advantageous in terms of being able to support higher throughput; when the network is nearly saturated, the system throughput is closely related to the number of channels that can be fully utilized by each CH scheme.

7.4 Impact of Clock Skew

In this simulation experiment, we investigated the effect of clock skew (i.e., misalignment of the slot boundaries) on the TTR of asynchronous CH schemes. Synchronous CH schemes, such as SSCH, can only tolerate a minimal amount of clock skew. In [2], the authors showed that SSCH can perform well as long as the clock skew is very small relative to the timeslot length. However, if the clock skew is non-trivially large, synchronous CH schemes cannot guarantee rendezvous between any pair of sequences. In contrast, asynchronous CH schemes can make such a guarantee irrelevant of the amount of clock skew. We simulated a network with ten single-hop disjoint flows with two asynchronous CH systems—A-QCH and SeqR—in a $100m \times 100m$ square area. The sequence period of A-QCH was set to 9. We introduced a clock skew of up to one time slot length between each sender and receiver pair such that the sender is always ahead of the receiver by the clock skew amount. The average TTR for both schemes is shown in Figure 8. Both A-QCH and SeqR have a bounded TTR regardless of the amount of clock drift, because the set of sequences generated by both schemes satisfy the rotation closure property. A-QCH's average TTR is slightly lower than that of SeqR. This can be explained by the fact that the simulated A-QCH system's MTTR value is 9 whereas the SeqR's MTTR value is 12.

7.5 Impact of Node Mobility

In this simulation experiment, we investigated the impact of node mobility on the performance of a QCH scheme.

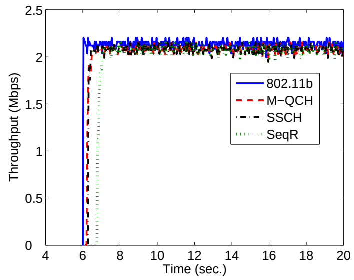


Figure 4: Effect of time-to-rendezvous and channel switching.

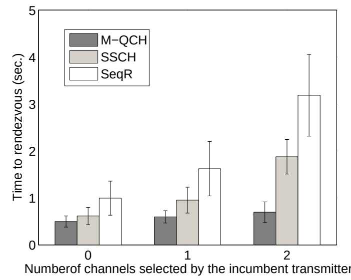


Figure 5: Time-to-rendezvous with incumbent traffic.

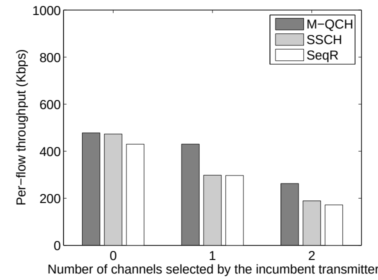
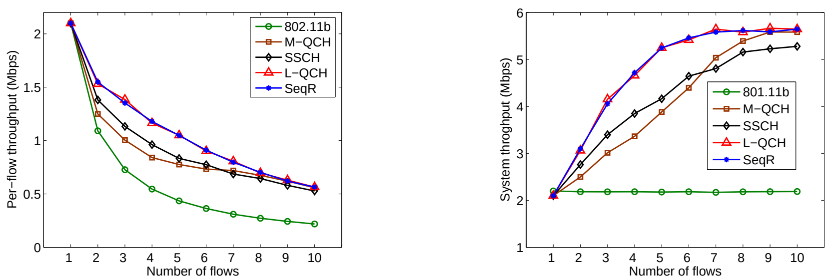


Figure 6: Throughput of non-disjoint flows with incumbent traffic.



(a) Per-flow throughput;

(b) System throughput.

Figure 7: Effect of load on throughput.

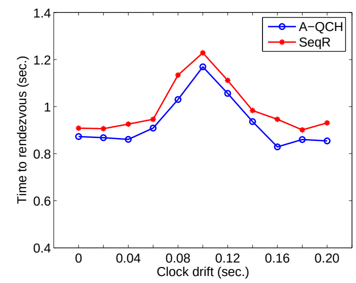


Figure 8: Time-to-rendezvous vs. clock skew.

Specifically, we studied M-QCH's performance in a multi-flow random network. A random network was set up by placing 500 nodes randomly in a $1000m \times 1000m$ square area. We simulated two cases: when the nodes are static and when they are mobile. In the case of mobile nodes, each node's movement follows the random way point mobility model: a node's maximum speed is 10 m/s, minimum speed is 5 m/s, and a node's maximum pausing time is 10 s. We randomly chose ten nodes from the network and set up five UDP flows among them. Ten independent simulation runs were conducted for each result. The results are shown in Figure 9. As expected, the figure shows that the throughput gap between M-QCH and 802.11b decrease when nodes are mobile. M-QCH's throughput loss can be attributed to: (1) the overhead of re-establishing links and routes when a node moves out of communication range of its neighbors in the same flow, and (2) the control overhead incurred when a node changes its CH sequence to synchronize with one of its neighbor's sequence for data transmission.

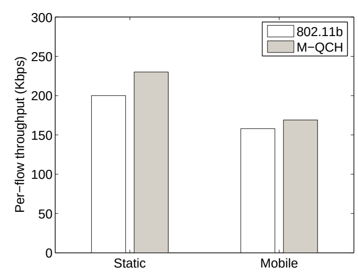


Figure 9: Effect of node mobility.

8. RELATED WORK

DSA related research has received great attention recently. A major thrust in this research area is the development of spectrum sensing techniques capable of accurately detecting the existence of incumbent users or spectrum opportunities [1]. Once secondary users learn the available spectrum using spectrum sensing, they need to coordinate with each other to allocate the spectrum resources and dynamically change the allocation when primary users reclaim any spectrum. A MAC protocol for a DSA network—a.k.a. a cognitive MAC protocol—needs to make provisions to support spectrum sharing. Existing cognitive MAC protocols can be divided into two categories.

The first category takes a centralized approach. That is, a centralized entity in a DSA network controls the spectrum allocation and access rules for the network. The centralized entity can be physically centralized, such as a base station in an 802.22 network [7]. The advantage of this approach is its design simplicity and ease in achieving optimal spectrum access efficiency or fairness. However, for certain applications, the centralized approach may not be appropriate.

In the distributed approach, secondary users build up peer-to-peer ad hoc communications with each other based on DSA. Most cognitive MAC protocols are derived from conventional multi-channel MAC protocols. Here, the term "conventional" MAC is used to describe a MAC designed for non-DSA networks. See [13] for a comprehensive survey on conventional multi-channel MAC protocols. The schemes proposed in [3, 10, 14, 23] are all derived from conventional multichannel MAC protocols that rely on some form of a *dedicated* control channel. The HC-MAC [10] protocol considers the hardware limitations of a secondary user with a single transceiver. It focuses on the problem of how to optimize the proportion of time that each node allocates between spectrum sensing and spectrum access. The HD-MAC protocol [23] utilizes distributed coordination to elect a control channel for each group of secondary users that are in the same vicinity. Therefore, HD-MAC does not rely on a *global* common control channel. A similar idea is proposed in [3] for cognitive radio-based mesh networks. In [6], the scheme proposed features a dynamic control channel that can switch among channels depending on spectrum availability.

9. CONCLUSION

In this paper, we presented a systematic approach, based on *quorum systems*, for designing and analyzing channel hopping (CH) protocols that enable control channel establishment in DSA networks. A noteworthy feature of the proposed *Quorum-based Channel Hopping* (QCH) system is that it can establish control channels in multiple frequency channels so that the secondary network is less vulnerable to the unpredictable appearance of incumbent signals. We proposed two synchronous optimal designs of the QCH system: the first optimal design minimizes the MTTR of the CH system and the second optimal design guarantees the even distribution of the rendezvous points in terms of both time and frequency. Minimizing the MTTR ensures short expected TTR which decreases channel access delay. An even distribution of rendezvous points alleviates the rendezvous convergence problem and increases the network capacity. We also proposed an asynchronous QCH system that has a bounded TTR without requiring global clock synchronization. We have shown, using analytical and simulation results, that the CH schemes designed using the quorum-based framework outperform existing schemes under various network conditions.

10. 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 Journal (Elsevier)*, 50(13):2127–2159, September 2006.

[2] 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 MobiCom*, pages 216–230, September 2004.

[3] T. Chen, H. Zhang, G. M. Maggio, and I. Chlamtac. CogMesh: A Cluster-based Cognitive Radio Network. In *Proc. of IEEE DySpan*, pages 168–178, April 2007.

[4] R. Chen, J.-M. Park, Y. T. Hou, and J. H. Reed. Toward Secure Distributed Spectrum Sensing in Cognitive Radio Networks. *IEEE Communications Magazine Special Issue on Cognitive Radio Communications*, 46(4):50–55, April 2008.

[5] C. J. Colbourn and E. J. H. Dinitz. *The CRC Handbook of Combinatorial Designs*. CRC Press, 1996.

[6] C. Cordeiro and K. Challapali. C-MAC: A Cognitive MAC Protocol for Multi-Channel Wireless Networks. In *Proc. of IEEE DySpan*, pages 147–157, April 2007.

[7] IEEE 802.22 Working Group. `http://www.ieee802.org/22/`.

[8] L.A. DaSilva and I. Guerreiro. Sequence-Based Rendezvous for Dynamic Spectrum Access. In *Proc. of IEEE DySpan*, pages 1–7, October 2008.

[9] F. Fitzek, D. Angelini, G. Mazzini, and M. Zorzi. Design and Performance of An Enhanced IEEE 802.11 MAC Protocol for Multihop Coverage Extension. *IEEE Wireless Communications*, 10(6):30–39, December 2003.

[10] J. Jia, Q. Zhang, and X. S. Shen. HC-MAC: A Hardware-constrained Cognitive MAC for Efficient Spectrum Management. *IEEE Journal on Selected Areas in Communications Special Issue on Cognitive Radio Theory and Applications*, 26(1):106–117, January 2008.

[11] J. R. Jiang, Y. C. Tseng and T. Lai. Quorum-based Asynchronous Power-saving Protocols for IEEE 802.11 Ad Hoc Networks. *ACM Journal on Mobile Networks and Applications*, 10(1-2):169–181, February 2005.

[12] W.-S. Luk and T.-T. Wong. Two New Quorum Based Algorithms for Distributed Mutual Exclusion. In *Proc. of IEEE ICDCS*, pages 100–106, May 1997.

[13] J. Mo, H.-S.W. So, and J. Walrand. Comparison of Multichannel MAC Protocols. *IEEE Transactions on Mobile Computing*, 7(1):50–65, January 2008.

[14] H. Nan, T.-I. Hyon, and S.-J. Yoo. Distributed Coordinated Spectrum Sharing MAC Protocol for Cognitive Radio In *Proc. of IEEE DySpan*, pages 240–249, April 2007.

[15] M. Naor and A. Wool. The Load, Capacity, and Availability of Quorum Systems. *SIAM Journal on Computing*, 27(2):214–225, 1998.

[16] C. Perkins and E. Royer. Ad Hoc On-Demand Distance Vector Routing. In *Proc. of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pages 90–100, February 1999.

[17] M. D. Silvius, F. Ge, A. Young, A. B. MacKenzie, and C. W. Bostian. Smart Radio: Spectrum Access for First Responders. In *Proc. of SPIE*, Vol. 6980, Wireless Sensing and Processing III, April 2008.

[18] J. So and N. Vaidya. Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using a Single Transceiver. In *Proc. of ACM MobiHoc*, pages 222–233, May 2004.

[19] H. W. So, J. Walrand and J. Mo. McMAC: A Multi-Channel MAC Proposal for Ad Hoc Wireless Networks. In *Proc. of IEEE WCNC*, pages 334–339, March 2007.

[20] D. R. Stinson. *Combinatorial Designs: Constructions and Analysis*. Springer-Verlag, 2003.

[21] A. Tzamaloukas and J. J. Garcia-Luna-Aceves. Channel-Hopping Multiple Access. In *Proc. of IEEE ICC*, pages 415–419, June 2000.

[22] The Network Simulator (ns-2). `http://www.isi.edu/nsnam/ns/`.

[23] J. Zhao, H. Zheng, and G.-H. Yang. Distributed Coordination in Dynamic Spectrum Allocation Networks. In *Proc. of IEEE DySpan*, pages 259–268, November 2005.