A Quasi-random Algorithm for Anonymous Rendezvous in Heterogeneous Cognitive Radio Networks

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Abstract—The multichannel rendezvous problem that asks two secondary users to rendezvous on a common available channel in a cognitive radio network (CRN) has received a lot of attention lately. Most rendezvous algorithms in the literature focused on constructing channel hopping (CH) sequences that guarantee finite maximum time-to-rendezvous (MTTR). However, these algorithms perform rather poorly in terms of the expected time-to-rendezvous (ETTR) even when compared to the simple random algorithm. In this paper, we propose the quasi-random (QR) CH algorithm that has a comparable ETTR to the random algorithm and a comparable MTTR to the best bound in the literature. Our QR algorithm does not require the unique identifier (ID) assumption and it is very simple to implement in the symmetric, asynchronous, and heterogeneous setting with multiple radios. In a CRN with \(N\) commonly labelled channels, the MTTR of the QR algorithm is bounded above by \(9M [n_1/m_1] \cdot [n_2/m_2]\) time slots, where \(n_1\) (resp. \(n_2\)) is the number of available channels to user 1 (resp. 2), \(m_1\) (resp. \(m_2\)) is the number of radios for user 1 (resp. 2), and \(M = \left\lceil \frac{\log_2 N}{4} \right\rceil \ast 5 + 6\). Such a bound is only slightly larger than the best \(O((\log\log N) \cdot \frac{\log n}{\log \log n})\) bound in the literature. When each SU has a single radio, the ETTR is bounded above by \(\frac{2}{G^2} + 9M [n_1/n_2] \cdot (1 - \frac{G}{2}) \cdot M\), where \(G\) is the number of common channels between these two users. By conducting extensive simulations, we show that for both the MTTR and the ETTR, our algorithm is comparable to the simple random algorithm and it outperforms several existing algorithms in the literature.

Index Terms—rendezvous search, channel hopping, cognitive radio networks.

I. INTRODUCTION

In a cognitive radio network (CRN), there are a set of frequency channels that are shared by two types of spectrum users: primary users (PUs) and secondary users (SUs). PUs have dedicated channels assigned to them. On the other hand, SUs can only access channels that are not being used by PUs. As such, SUs need to sense a number of frequency channels that are not used by PUs. Such a set of channels is called the available channel set for an SU. In order for two SUs to communicate with each other, they need to find a common available channel. Such a problem is known as the multichannel rendezvous problem in a CRN and it is usually solved in a distributed manner by hopping over the available channels over time. For the multichannel rendezvous problem, it is thus important to design channel hopping (CH) sequences so as to minimize the time-to-rendezvous (TTR).

For the multichannel rendezvous problem, there are many CH schemes proposed in the literature (see e.g., [1]–[23]). As discussed in the tutorial [24] and the book [25], CH schemes can be classified into various categories depending on their assumptions.

1) Asymmetric vs. symmetric: In a symmetric CH scheme, users follow the same strategy to generate their CH sequences. On the other hand, asymmetric algorithms (see e.g., [17], [18], [8], [20]) can assign users different roles so that they can follow different strategies to generate their CH sequences. For instance, a user can be assigned the role of a sender or receiver. The receiver can stay on the same channel while the sender cycles through all the available channels. Since users follow different strategies, the time-to-rendezvous can be greatly reduced by using asymmetric algorithms.

2) Anonymous vs. anonymous: One simple way to assign different roles to users is by their identifiers (ID). In [17], [4], [13], [9], [6], [19], [20], it is assumed that each user is assigned with a unique ID, e.g., a MAC address. As such, users can map their IDs to play different roles to speed up the rendezvous process.

3) Synchronous vs. asynchronous: A CH scheme is synchronous if the clocks (i.e., the indices of time slots) of both SUs are the same. Synchronous CH schemes can achieve better performance than asynchronous CH schemes as both SUs can start their CH sequences simultaneously. However, in a distributed environment it might not be practical to assume that the clocks of two users are synchronized yet. Without clock synchronization, guaranteed rendezvous is much more difficult. In the literature, there are various asynchronous algorithms (see e.g., [17], [18], [8], [20], [13], [9], [6], [7], [15], [14]).

4) Homogeneous vs. heterogeneous: A CH scheme is called homogeneous if the available channel sets of the two SUs are the same. On the other hand, it is called heterogeneous if the available channel sets of the two SUs are different. Two SUs that are close to each other are likely to have the same available channel sets. Due to the limitation of the coverage area of a user, two SUs tend to have different available channel sets if they are far apart. Rendezvous in a homogeneous environment is in general much easier than that in a heterogeneous environment. There are various heterogeneous...
CH algorithms that have bounded TTR (see e.g., [17], [18], [3], [7], [14]). We note that in the literature some authors refer a homogenous (resp. heterogeneous) environment as a symmetric (resp. asymmetric) environment.

5) Oblivious vs. non-oblivious: In most previous works for the multichannel rendezvous problem, it is commonly assumed that there is a universal channel labelling. As such, it is possible for a user to learn from a failed attempt to rendezvous. On the other hand, oblivious rendezvous (see e.g., [10], [22], [13], [19]) is referred to as the setting where nothing can be learned from a failed attempt to rendezvous.

6) Single radio vs. multiple radios: Recently, several research works focus on the multi-radio CH schemes [10], [21], [22], [24]. SUs equipped with multiple radios can generate CH sequences that hop on more than one channel in a time slot. This improves the probability of rendezvous and thus shortens the time-to-rendezvous.

As pointed out in the recent paper [19], most works in the literature focused on deriving bounds for maximum time-to-rendezvous (MTTR), and they perform rather poorly in terms of expected time-to-rendezvous (ETTR) even when compared to the simple random algorithm. The rationale behind that is because there is usually a “stay” mode in these CH schemes. When an SU is in its “stay” mode, it stays on the same channel for a rather long period of time. As such, it is very likely that two SUs stay on two different channels for a long period of time. To address the large ETTR problem, a hybrid CH algorithm was proposed in [15] for a homogeneous CRN. The idea is to interleave the simple random algorithm with a periodic CH algorithm that has a bounded MTTR, such as CRSEQ [11] and JS [3]. However, the hybrid CH algorithm can only be used in a homogeneous CRN.

In [19], the authors considered the oblivious rendezvous problem in heterogeneous CRNs and proposed a CH algorithm such that its ETTR is comparable to that of the random algorithm while its MTTR is still upper bounded by a finite constant. This is done by assuming there is a unique ID assigned to each user. One of the problems of such an approach is that the length of an ID is usually very long, e.g., a MAC address contains 48 bits. As the MTTR bound in [19] is proportional to the length of an ID, the MTTR bound could also be large in practice. On the other hand, using the (mapped) ID to generate CH sequences makes it difficult for an SU to remain anonymous. In particular, if the ID of a user is known to an adversary, then it could be used by the adversary to construct the same CH sequence for jamming attack [16]. Thus, for security reason it is crucial to eliminate the need of the unique ID assumption for each SU in [19].

Without the unique ID assumption for each SU in [19], the question is then whether it is still possible to have a rendezvous algorithm that has a comparable ETTR to the random algorithm and a comparable MTTR to the best bound in the literature. Such a question is not only of theoretical interest but also of practical importance as the random algorithm outperforms most rendezvous algorithms in the literature regarding ETTR (despite its lack of theoretical guarantee for MTTR). To address such a question, we extend the construction in [19] by proposing a quasi-random CH algorithm in this paper. The main idea of our quasi-random algorithm is to select at random an arbitrary channel in the available channel set of an SU as its ID (channel). By doing so, we can leverage the construction in [19] that maps a binary ID to a CH sequence. The problem is that the unique ID assumption in [19] is no longer valid as the two SUs might select one of their common channels as their IDs. To deal with such a problem, our second idea is to extend a binary ID to a ternary ID with elements in \{0, 1, 2\}. When the symbol “2” appears, an SU simply stays on the channel that is used as its ID. By doing so, SUs with the same ID are still guaranteed to rendezvous.

Our setting for the multichannel rendezvous problem is the symmetric, anonymous, asynchronous, and heterogeneous setting with multiple radios. However, we do assume that there is a universal channel labelling. Specifically, we consider a CRN with \(N\) channels (with \(N\geq2\), indexed from 0 to \(N-1\). Time is slotted (the discrete-time setting) and indexed from \(t=0,1,2,\ldots\). There are two users who would like to rendezvous on a common available channel by hopping over these \(N\) channels with respect to time. The available channel set for user \(i\), \(i=1,2\), is

\[
\mathcal{C}_i = \{c_i(0), c_i(1), \ldots, c_i(n_i-1)\},
\]

where \(n_i = |c_i|\) is the number of available channels to user \(i\), \(i=1,2\). We assume that there is at least one channel that is commonly available to the two users, i.e.,

\[
\mathcal{C}_1 \cap \mathcal{C}_2 \neq \emptyset.
\]

Moreover, we assume that user \(i\) has \(m_i\) radios, where \(m_i \geq 1\), \(i=1\) and 2. Denote by \(X_i(t)\) (resp. \(X_2(t)\)) the set of channels selected by user 1 (resp. user 2) on its \(m_i\) radios at time \(t\) (of the global clock). Then the time-to-rendezvous (TTR), denoted by \(T\), is the number of time slots (steps) needed for these two users to select a common available channel, i.e.,

\[
T = \inf\{t \geq 0 : X_1(t) \cap X_2(t) \neq \emptyset\} + 1,
\]

where we add 1 in (2) as we start from \(t = 0\).

For the quasi-random algorithm, we have the following theoretical results:

(i) The MTTR is bounded above by \(9M[n_1/m_1] \cdot [n_2/m_2]\) time slots, where \(M = [\log_2 N]/4 \cdot 5 + 6\). Such a bound is only slightly larger than the best \(O((\log \log N)^{\alpha_{n_1m_1} / m_1m_2})\) bound in the literature (see e.g., [23] and references therein).

(ii) When each SU has a single radio, the ETTR is bounded above by \(\frac{n_1n_2}{G} + 9Mn_1n_2 \cdot (1 - \frac{G}{n_1n_2})^M\), where \(G\) is the number of common channels between these two users. Note that the first term is the ETTR of the random algorithm and the second term approaches 0 when \(M \to \infty\). Thus, the ETTR of the quasi-random algorithm is almost the same as that of the random algorithm when \(M\) is large.

By conducting extensive simulations, we show that for both the MTTR and the ETTR, our algorithm is comparable to the simple random algorithm and it outperforms several existing algorithms, including JS/I [21], GCR [10], RPS [21], AMRR [22] and FMRR [23].

The rest of this paper is organized as follows: In Section II we consider the two-user rendezvous problem and show how...
one can construct the CH sequences from the quasi-random algorithm. In Section III, we conduct extensive simulations to compare the performance of our quasi-random algorithm with that of some best-performed channel hopping algorithms in the literature. Finally, we conclude the paper in Section IV.

II. CONSTRUCTIONS OF THE CH SEQUENCES

As mentioned in Section I, our main idea is to leverage the construction of the CH sequences in [19] by selecting at random an arbitrary channel in the available channel set of an SU as its ID. For this, in Section II-A, we first generalize the concept of the strong symmetrization mapping in [19] to map a ternary ID to a CH sequence. We show in Section II-B that the 4B5B encoding scheme can be used as a strong ternary symmetrization mapping. In Section II-C we then propose the quasi-random algorithm.

A. Strong ternary symmetrization mapping

We first generalize the concept of strong symmetrization class in [19] for binary vectors to ternary vectors with the elements in \{0, 1, 2\}. A ternary digit in \{0, 1, 2\} is called a trit in this paper.

**Definition 1 (Strong ternary symmetrization mapping)**

Consider a set of \(M\)-trit codewords (with size \(K\))

\[
\{w_i = (w_i(0), w_i(1), \ldots, w_i(M - 1)), i = 1, 2, \ldots, K\}.
\]

Let

\[
\text{Rotate}(w_i, d) = (w_i(d), w_i(d + 1), \ldots, w_i((d + M - 1) \mod M)),
\]

be the vector obtained by cyclically shifting the vector \(w_i\) \(d\) times. Then this set of codewords is called a strong ternary \(M\)-symmetrization class if \(w_i(0) = 2\) for all \(i\), and for either the time shift \((d \mod M) \neq 0\) or \(i \neq j\), (at least) one of the following two properties is satisfied:

(i) There exist \(0 \leq \tau_1, \tau_2 \leq M - 1\) such that 
\[
w_i(\tau_1) = 1, w_j((\tau_1 + d) \mod M) = 0\text{ and } w_i(\tau_2) = 0, w_j((\tau_2 + d) \mod M) = 1.
\]

(ii) There exist \(0 \leq \tau_1, \tau_2 \leq M - 1\) such that 
\[
w_i(\tau_1) = w_j((\tau_1 + d) \mod M) = 1, \text{ and } w_i(\tau_2) \neq w_j((\tau_2 + d) \mod M).
\]

A one-to-one mapping from the set of integers \([1, \ldots, K]\) to a strong ternary \(M\)-symmetrization class is called a strong ternary \(M\)-symmetrization mapping.

In comparison with the original definition of the strong symmetrization class in [19], here we require that the first trit of every vector is 2. Also, we replace the condition in (ii) by 
\[
w_i(\tau_1) = w_j((\tau_1 + d) \mod M) = 1\text{ (instead of 0)}.
\]

Also, we note that the strong ternary symmetrization mapping is stronger than the “ternary symmetrization mapping” in Lemma 2 of [19] that only requires the codeword to be cyclically unique. Such a stronger property enables us to construct CH sequences that behave as if they were random.

### Algorithm 1: The 4B5B strong ternary symmetrization mapping

**Input:** An integer \(0 \leq x \leq 2^L - 1\).

**Output:** An \(M\)-trit codeword 
\[
(w(0), w(1), \ldots, w(M - 1)), \text{ where } M = \lceil L/4 \rceil \times 5 + 6.
\]

1. Let \((\beta_1(x), \beta_2(x), \ldots, \beta_L(x))\) be the binary representation of \(x\), i.e., \(x = \sum_{i=1}^{L} \beta_i(x)2^{i-1}\). If \(L\) is not an integer multiple of 4, append 4 (\(L \mod 4\) 0’s) to the binary representation of \(x\) to form a \([L/4] \times 5\)-bit binary vector.
2. Use the 4B5B encoding scheme to encode the \([L/4] \times 4\)-binary vector into a \([L/4] \times 5\)-bit codeword.  
3. Add the 6-trit delimiter 200001 in front of the \([L/4] \times 5\)-bit codeword to form a \((\lceil L/4 \rceil + 5 + 6)\)-trit codeword.

B. 4B5B encoding

Analogous to [19], we show that the 4B5B encoding scheme can be used for constructing a strong ternary symmetrization mapping. In such an encoding scheme, each piece of 4 bits is uniquely mapped to a 5-bit codeword (see Table I). One salient feature of the 4B5B encoding scheme is that each 5-bit codeword has at most one leading 0 as well as at most two trailing 0’s. Thus, encoding the \(L\)-bit integer results in a \([L/4] \times 5\)-bit codeword that does not have 4 consecutive 0’s. Instead of adding the 6-bit delimiter 100001 in [19], we add the 6-trit delimiter 200001 in front of the \([L/4] \times 5\)-trit codeword to construct an \(M = \lceil L/4 \rceil \times 5 + 6\) codeword. The details of the mapping from an \(L\)-bit integer to an \(M\)-trit codeword is shown in Algorithm 1.

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**Table I: The 4B5B Encoding Table**

| 4B data | 5B code |
|---------|---------|
| 0000    | 11110   |
| 0001    | 01001   |
| 0010    | 10100   |
| 0011    | 10101   |
| 0100    | 01010   |
| 0101    | 01101   |
| 0110    | 01110   |
| 0111    | 01111   |

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**Lemma 2** For \(L \geq 1\), the 4B5B mapping in Algorithm 1 is indeed a strong ternary \(M\)-symmetrization mapping with \(M = \lceil L/4 \rceil \times 5 + 6\).
**Proof.** Since the first element in the 6-trit delimiter 200001 is 2, we know that \( w_i(0) = 2 \) for all \( i \). From the 4B5B encoding scheme, we know that the substring of 4 consecutive 0’s only appears in the 6-trit delimiter and thus it appears exactly once in the \( M \)-trit cyclically shifted codeword \((w(d), w(d+1), \ldots, w((M-1)+d) \mod M)\) for any integer \( 0 \leq d \leq M - 1 \). Now consider the codeword \((w_i(0), w_i(1), \ldots, w_i(M-1))\) and the cyclically shifted codeword \((w_j(d), w_j(d+1), \ldots, w_j((M-1)+d) \mod M)\).

*Case 1.* \((d \mod M) = 0\) and \( i \neq j \): In this case, the 6-trit delimiters of two \( M \)-trit codewords are aligned. Choose \( \tau_1 = 5 \) and we have \( w_i(\tau_1) = w_j(\tau_1) = w_j((\tau_1 + d) \mod M) = 1 \). Since \( i \neq j \), we have from the one-to-one mapping of the 4B5B encoding scheme that there exists \( 0 \leq \tau_2 \leq M - 1 \) such that \( w_i(\tau_2) \neq w_j(\tau_2) = w_j((\tau_2 + d) \mod M) \). Thus, the condition (ii) in Definition 1 is satisfied.

*Case 2.* \((d \mod M) = 1, 2, 3, 4:\)

Let \( k = (d \mod M) \). Choose \( \tau_1 = 5 \) and we have \( w_i(\tau_1) = w_j(5) = 1 \). Also, choose \( \tau_2 = 5 - k \) and we have \( w_i(\tau_2) = w_j(\tau_2 + d) \mod M = w_j(5) = 1 \). Since we assume that \( L \geq 1 \), we know that \( M \geq 11 \). Thus, \( (\tau_1 + d) \mod M \neq 0 \) and \( w_i((\tau_1 + d) \mod M) \neq 2 \). This then implies that \( w_j((\tau_1 + d) \mod M) \) is either 0 or 1. If \( w_i((\tau_1 + d) \mod M) = 0 \), then condition (i) in Definition 1 is satisfied. On the other hand, if \( w_j((\tau_1 + d) \mod M) = 1 \), the condition (ii) in Definition 1 is satisfied.

*Case 3.* \((d \mod M) = M - 1, M - 2, M - 3, M - 4:\)

This is the same as Case 2 once we interchange \( i \) and \( j \).

*Case 4.* \((d \mod M) = 5:\)

In this case, Choose \( \tau_1 = 5 \) and we have \( w_i(\tau_1) = 1 \). Since we assume that \( L \geq 1 \), we know that \( M \geq 11 \) and thus \( w_i(10) \neq 2 \). This then implies that \( w_j(10) = w_j((\tau_1 + d) \mod M) \) is either 0 or 1. Note that in this case we also have \( w_i(4) = \ldots = w_i(4) = 0 \) and \( w_j((t + 5) \mod M), t = 1, \ldots, 4 \), cannot be all 0’s. Thus, there exists \( 1 \leq \tau_2 \leq 4 \) such that \( w_i(\tau_2) = 0 \) and \( w_j((\tau_2 + d) \mod M) = 1 \). If \( w_j(10) = 0 \), the condition (i) in Definition 1 is satisfied. On the other hand, if \( w_j(10) = 1 \), the condition (ii) in Definition 1 is satisfied.

*Case 5.* \((d \mod M) = M - 5:\)

This is the same as Case 4 once we interchange \( i \) and \( j \).

*Case 6.* \((d \mod M)\) is not in \( \{M - 5, M - 4, M - 3, M - 2, M - 1, 0, 1, 2, 3, 4\}\):

In this case, the 6-trit delimiters of the two \( M \)-trit codewords do not overlap. Then we have \( w_i(1) = \ldots = w_i(4) = 0 \) and \( w_j(t + d) \mod M, t = 1, \ldots, 4 \), cannot be all 0’s. Thus, there exists \( 1 \leq \tau_2 \leq 4 \) such that \( w_i(\tau_2) = 0 \) and \( w_j((\tau_2 + d) \mod M) = 1 \). On the other hand, we have \( w_j(1) = \ldots = w_j(4) = 0 \) and \( w_j((t - d) \mod M), t = 1, \ldots, 4 \), cannot be all 0’s. Thus, there exists \( 1 \leq ((\tau_1 + d) \mod M) \leq 4 \) such that \( w_i(\tau_1) = 1 \) and \( w_j((\tau_1 + d) \mod M) = 0 \).

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**C. The quasi-random algorithm**

In this section, we propose the quasi-random algorithm for guaranteed rendezvous in the symmetric, anonymous, asynchronous, and heterogeneous setting, where each SU has a single radio. Our quasi-random algorithm is an extension of the construction in [19] without the need of the unique ID assumption. For this, we first introduce the modular clock algorithm in [2] (see Algorithm 2). In addition to the available channel set, the algorithm needs three parameters: the period \( p \) that is an integer not smaller than the number of available channels \( n \), the slope \( r \) that is relatively prime to \( p \), and the bias that is an integer selected from \( \{0, 1, \ldots, p - 1\} \). If the clock \( k \) in Line 3 of the algorithm is not greater than \( n - 1 \), then a channel is selected at random from the available channel set.

**Algorithm 2:** The modular clock algorithm

**Input:** An available channel set \( c = \{c(0), c(1), \ldots, c(n - 1)\} \), a period \( p \geq n \), a slope \( r > 0 \) that is relatively prime to \( p \), a bias \( 0 \leq b \leq p - 1 \), and an index of time \( t \).

**Output:** A channel \( X(t) \in c \).

1: For each \( t \), let \( k = ((r \ast t + b) \mod p) \).
2: If \( k \leq n - 1 \), let \( X(t) = c(k) \).
3: Otherwise, select \( X(t) \) uniformly at random from the available channel set \( c \).

One well-known property of the modular clock algorithm in Algorithm 2 is the rendezvous property from the Chinese Remainder Theorem.

**Proposition 3** (Theorem 4 of [2]) Suppose that user 1 (resp. user 2) uses the modular clock algorithm in Algorithm 2 to generate its CH sequence with the period \( p_1 \) (resp. \( p_2 \)). If \( p_1 \) and \( p_2 \) are relatively prime, then under the assumption in (7), these two users will rendezvous within \( p_1p_2 \) time slots.

Now we combine the modular clock algorithm in Algorithm 2 and the strong ternary symmetrization mapping in Algorithm 1 to construct a CH that can provide guaranteed rendezvous. Such an algorithm is called the quasi-random algorithm in this paper and its detail is shown in Algorithm 3. The idea is to randomly select a channel \( c \) as its ID from the available channel set and then map \( c \) to an \( M \)-trit codeword by the 4B5B strong ternary symmetrization mapping in Algorithm 1. Then we interleave \( M \) sequences according to the ternary value of its \( M \)-trit codeword. Specifically, for user \( i \), we select two primes \( p_{i,0} \) and \( p_{i,1} \) such that \( n_i \leq p_{i,0} < p_{i,1} \). A 0-sequence (resp. 1-sequence) of user \( i \) is then constructed by using the modular clock algorithm with the prime \( p_{i,0} \) (resp. \( p_{i,1} \)). The slope parameter and the bias parameter are selected at random. A 2-sequence is a “stay” sequence in which channel \( c \) is used in every time slot. Then the CH sequence of a user is constructed by interleaving \( M \) \{0/1/2\}-sequences according to its \( M \)-trit codeword. Let \( \{X_i(t), t \geq 0\} \) be the CH sequence for user \( i \), \( i = 1 \) and 2. The insight behind our construction is that the two users will rendezvous immediately at time 0 during the 2-sequence if both users select the same channel as their IDs and their clocks are synchronized. On the other hand, either their clocks are not synchronized or their IDs are different, the strong ternary symmetrization mapping in...
Definition 1 ensures that there exists some time $\tau$ such that the subsequence $\{X_1(\tau), X_1(\tau + M), X_1(\tau + 2M), \ldots\}$ and the subsequence $\{X_2(\tau), X_2(\tau + M), X_2(\tau + 2M), \ldots\}$ are generated by the modular clock algorithm with two different primes. These two users are then guaranteed to rendezvous from the Chinese Remainder Theorem for the modular clock algorithm in Proposition 3. The result and the detailed proof is shown in the following theorem.

**Algorithm 3**: The quasi-random algorithm

**Input**: An available channel set $c = \{c(0), c(1), \ldots, c(n - 1)\}$ and the total number of channels $N$.

**Output**: A CH sequence $\{X(t), t = 0, 1, \ldots\}$ with $X(t) \in c$.

1: Randomly select a channel $c$ from the available channel set. Use the 4B5B $M$-symmetrization mapping (Algorithm 1) to map $c$ to an $M$-trit codeword $(w(0), w(1), \ldots, w(M - 1))$ with $M = \lceil\log_2 N\rceil/4 \ast 5 + 6$.

2: Select two primes $p_1 > p_2 \geq n$.

3: For each $s = 1, 2, \ldots, M - 1$, generate independent and uniformly distributed random variables $r_0(s) \in [0, p_0 - 1]$, $r_1(s) \in [1, p_1 - 1]$, $b_0(s) \in [0, p_0 - 1]$ and $b_1(s) \in [0, p_1 - 1]$.

4: For each $t$, compute the following two variables:

   a. $q = t/M$.
   b. $s = (t \mod M)$.
   c. If $w(s) = 2$, let $X(t) = c$.
   d. If $w(s) = 1$, let $X(t)$ be the output channel from the modular clock algorithm in Algorithm 2 with the period $p_1$, the slope $r_1(s)$, the bias $b_1(s)$, and the index of time $q$.
   e. If $w(s) = 0$, let $X(t)$ be the output channel from the modular clock algorithm in Algorithm 2 with the period $p_0$, the slope $r_0(s)$, the bias $b_0(s)$, and the index of time $q$.

**Theorem 4** (The MTTR bound) Suppose the assumption in 1 hold and the two users use the quasi-random algorithm in Algorithm 3 to generate their CH sequences. Then these two users will rendezvous within $M_{p_1_1}p_2_1$ time slots, where $M = \lceil\log_2 N\rceil/4 \ast 5 + 6$ and $N$ is the total number of channels.

Since there are two primes between $[n, 3n]$ 20, these two users will rendezvous within $9M_{p_1_1}p_2_1$ time slots.

**Proof.** Let $d$ be the clock shift between these two users. Suppose that user 1 (resp. 2) selects $c_1$ (resp. $c_2$) to construct its codeword. Note from Algorithm 3 that for $t \in \{\tau, \tau + M, \tau + 2M, \ldots\}$, user 1 uses a $w_1(\tau)$-sequence and user 2 uses a $w_2(\tau + d)$-sequence. Let $X_i(t)$, $i = 1$ and 2, be the channel selected by user $i$ at time $t$. In view of the definition of a strong ternary symmetrization mapping in Definition 1, we consider the following two cases.

**Case 1.** $d \mod M = 0$ and $c_1 = c_2$.

From Step 1 of Algorithm 3 these two users use the same codeword. Since $(d \mod M) = 0$, the 6-trit delimiters of these two users are aligned. Thus, for $t \in \{0, M, 2M, \ldots\}$, we know from Step 7 of Algorithm 3 user 1 (resp. 2) stays on channel $c_1$ (resp. $c_2$). Since $c_1 = c_2$, both users rendezvous at time 0.

**Case 2.** $(d \mod M) \neq 0$.

There are two subcases.

**Case 2.1.** There exist $0 \leq \tau_1, \tau_2 \leq M - 1$ such that $w_1(\tau_1) = 1$, $w_2((\tau_1 + d) \mod M) = 0$ and $w_1(\tau_2) = 0$, $w_2((\tau_2 + d) \mod M) = 1$.

In this case, for $t \in \{\tau_1 + M, \tau_1 + 2M, \ldots\}$, user 1 uses a 1-sequence and user 2 uses a 0-sequence. The 1-sequence of user 1 is generated from the modular clock algorithm with the prime $p_{1_1}$ and the 0-sequence of user 2 is generated from the modular clock algorithm with the prime $p_{2_0}$. If $p_{1_1} \neq p_{2_0}$, then we conclude from Proposition 3 that these two users will rendezvous within $M_{p_{1_1}p_{2_0}}$ time slots.

On the other hand, if $p_{1_1} = p_{2_0}$, then we have

$$p_{2_1} > p_{2_0} = p_{1_1} > p_{1_0}.$$ Now for $t \in \{\tau_2, \tau_2 + M, \tau_2 + 2M, \ldots\}$, user 1 uses a 0-sequence and user 2 uses a 1-sequence. The 0-sequence of user 1 is generated from the modular clock algorithm with the prime $p_{1_0}$ and the 1-sequence of user 2 is generated from the modular clock algorithm with the prime $p_{2_1}$. Since $p_{2_1} \neq p_{1_0}$, we know from Proposition 3 that these two users will rendezvous within $M_{p_{1_0}p_{2_1}}$ time slots.

**Case 2.2.** There exist $0 \leq \tau_1, \tau_2 \leq M - 1$ such that $w_1(\tau_1) = w_2((\tau_1 + d) \mod M) = 1$, and $w_1(\tau_2) \neq w_2((\tau_2 + d) \mod M)$.

In this case, for $t \in \{\tau_1 + M, \tau_1 + 2M, \ldots\}$, user 1 uses a 1-sequence and user 2 uses a 1-sequence. The 1-sequence of user 1 is generated from the modular clock algorithm with the prime $p_{1_1}$ and the 1-sequence of user 2 is generated from the modular clock algorithm with the prime $p_{2_1}$. If $p_{1_1} \neq p_{2_1}$, then we conclude from Proposition 3 that these two users will rendezvous within $M_{p_{1_1}p_{2_1}}$ time slots.

As commented in 19, one way to reduce the ETTR is to avoid introducing “stay” modes that repeatedly examine the same channel pairs of two users. As such, the slope $r$ chosen in Line 3 of the algorithm is an integer in $[1, p - 1]$ and it is selected independently for $s = 1, 2, \ldots, M - 1$. As the slope $r$ is nonzero, there is no “stay” mode in this algorithm except the case $s = 0$ (with $w(0) = 2$). On the other hand, the bias $b$ chosen in Line 3 of the algorithm is an integer in $[0, p - 1]$. For $s = 0$, we have $w(0) = 2$ and the quasi-random algorithm outputs the randomly selected channel $c$ from the available channel set. Since all the slopes and biases for $s =
1, 2, ..., M − 1 are generated independently and uniformly, it is straightforward to verify that the quasi-random algorithm selects each available channel independently with an equal probability in the first M time slots, i.e., \{X(t), t = d, d + 1, d + 2, \ldots, d + M − 1\} are independently and identically distributed (i.i.d.) random variables with \(P(X(t) = c(\ell)) = 1/n\) for all \(\ell = 0, 1, \ldots, n − 1\). As such, the quasi-random algorithm behaves as if it were a random algorithm for every consecutive M slots. On the other hand, \(X(t)\) and \(X(t + qM)\) are correlated through the modular clock algorithm as they both have the same value of \(s\) and thus the same slope \(r\) and bias \(b\). Such a correlated property ensures that the MTTR is bounded as shown in Theorem 4. In the following theorem, we use the i.i.d. property and the MTTR bound in Theorem 4 to derive an ETTR bound for the quasi-random algorithm.

**Theorem 5 (The ETTR bound)** Suppose the assumption in (4) hold and the two users use the quasi-random algorithm in Algorithm 3 to generate their CH sequences. Then the ETTR is upper bounded by

\[
\frac{n_1 n_2}{G} + 9M n_1 n_2 \cdot (1 - \frac{G}{n_1 n_2})^M,
\]

where \(M = \lceil \lceil \log_2 N \rceil /4 \rceil \ast 5 + 6\), \(N\) is the total number of channels, and \(G\) is the number of common channels between these two users.

Note that the first term in (4) is the ETTR of the random algorithm. Clearly, the second term in (4) converges to 0 as \(M \to \infty\). Thus, the ETTR of the quasi-random algorithm is almost the same as that of the random algorithm when \(M\) is large. On the other hand, if \(M\) is very small, then the ETTR bound in Theorem 5 could be much larger than the ETTR of the random algorithm. Also, as \(M\) is very small, the quasi-random algorithm will hop to the ID channel very often and this might, in fact, increase the ETTR if the ID channel is not a rendezvous channel. As such, for the practical use of the quasi-random algorithm, one should avoid using a very small \(M\). One easy way to do this to repeat the L-bit binary representation for several times in Step 1 of Algorithm 1. Or better yet, one may add a random binary vector in front of the L-bit binary representation to protect the user from jamming attack. However, we note that increasing \(M\) also increases the (theoretical) MTTR bound in Theorem 4.

**Proof.** The proof of this theorem is similar to the argument for the ETTR bound in (10) of [19]. Let \(h = G/n_1 n_2\) be the probability that the two users hop on one common available channel by using the random algorithm. Clearly, the ETTR of the random algorithm is \(1/h\). Also, let \(H = 9M n_1 n_2\) be the upper bound for MTTR in Theorem 4. Since each user selects a channel independently and uniformly from its available channel set in the first \(M\) time slots of the quasi-random algorithm, we then have

\[
\begin{align*}
E[T] &= \sum_{t=1}^{H} t \cdot P(T = t) \\
&= \sum_{t=1}^{M} t \cdot h(1-h)^{t-1} + \sum_{t=M+1}^{H} t \cdot P(T = t)
\end{align*}
\]

\[
\leq \sum_{t=1}^{\infty} t \cdot h(1-h)^{t-1} + H \cdot P(T > M) \\
= \frac{1}{h} + H \cdot (1-h)^M.
\]

In Figure 1 we provide an illustrating example for the constructions of the CH sequences of Algorithm 3 for a CRN with two users, \(SU_1\) and \(SU_2\). In this example, we assume that there is a clock drift of three time slots between these two users. Suppose that there are \(N = 15\) channels, and each user has a single radio, i.e., \(m_1 = m_2 = 1\). The available channels for \(SU_1\) is \([0, 1, 2, 3, 4, 5, 6]\) and the available channels for \(SU_2\) is \([6, 7, 8, 9, 10]\). Thus, \(n_1 = 7\) and \(n_2 = 5\). Thus, we can simply choose \(p_{1, 0} = 7, p_{1, 1} = 11, p_{2, 0} = 5,\) and \(p_{2, 1} = 7\). Suppose that \(SU_1\) randomly selects a channel \(c = 1\) from the available channel set (as its ID). From Table I we know the 5B code for 1 (i.e., 0001) is 01001. According to the 4B5B strong ternary symmetrization mapping in Algorithm 1, we then add the 6-trit delimiter 200001 in front of the 5B code 01001. This then leads to the 11-trit codeword \((w(0), w(1), \ldots, w(10)) = (2, 0, 0, 0, 0, 1, 0, 1, 0, 0, 1, 0)\).

For each \(s = 0, 1, \ldots, 10\), we generate independent and uniformly distributed random variables \(r_{1, 0}(s) \in [1, 6], r_{1, 1}(s) \in [1, 10], b_{1, 0}(s) \in [0, 6], b_{1, 1}(s) \in [0, 10]\) and these are shown in Figure 1. Therefore, at \(t = 0\), we have \(w(0) = 2\). Thus, \(X(0) = c = 1\) (as shown in Figure 1). Similarly, \(\{X(t), t = 11, 22, \ldots\}\) are also \(c\) (i.e., 1). Now for \(t \neq 0, 11, 22, \ldots\), we compute \(s = (t \mod 11)\) and \(q = [t/M]\). If \(w(s) = 1\), we use \(r_{1, 1}\) and \(b_{1, 1}\) to generate the \(X(t) = c((r_{1, 1} \ast q + b_{1, 1}) \mod p_{1, 1})\) if \((r_{1, 1} \ast q + b_{1, 1}) \mod p_{1, 1}\) is not larger than \(n_1\), i.e., 7. Otherwise, we randomly choose a channel from the available channel set (see e.g., \(t = 10\) in Figure 1). Similarly, if \(w(s) = 0\), we use \(r_{1, 0}\) and \(b_{1, 0}\) and \(p_{1, 0}\) as the input of the modular clock algorithm to generate \(X(t)\).

For \(SU_2\), suppose that it selects channel 6 (as its ID). From the 4B5B strong ternary symmetrization mapping in Algorithm 3 its 11-trit codeword is \((w(0), w(1), \ldots, w(10)) = (2, 0, 0, 0, 0, 1, 0, 1, 1, 1, 0, 0)\).

The CH sequences for \(SU_2\) are generated similarly as shown in Figure 1. Note that these two SUs will rendezvous on the common channel (i.e. channel 6) at \(t = 14\) and \(t = 28\), respectively.

**D. Multi-radio CH sequences**

Now we consider the multiple radio setting. Suppose that user \(i\) has \(m_i \geq 1\) radios, \(i = 1\) and 2. It is possible that \(m_i = 1\) in this setting. As shown in [21], if we generate independently the channel hopping sequence for each radio by using the single-radio algorithm in Algorithm 3, then it fails to improve the MTTR bound by using multiple radios. To further improve the MTTR bound in the multiple radio setting, we follow the approach in [23]. We first divide the \(n_i\) available channels as evenly as possible to the \(m_i\) radios.
Corollary 6 Suppose that the assumption in (7) holds. User 1 uses the multiple radio algorithm in Algorithm 4 to generate its CH sequence. Then both users rendezvous within 9M[n1/m1] · [n2/m2] time slots, where

\[ M = \lceil \log_2 N \rceil /4 \ast 5 + 6. \]

III. SIMULATION RESULTS

In this section, we conduct extensive simulations to compare the performance of our quasi-random (QR) algorithm with several multi-radio channel hopping algorithms in asynchronous heterogeneous CRNs, including the random algorithm, JS/I [21], RPS [21], GCR [19], AMRR/M (for optimizing MTTR) [22], AMRR/E (for optimizing ETTR) [22], and FMRR [23]. Our simulations are performed with event-driven C++ simulators. The simulation setting is the same as that in [23]. Specifically, we assume that each SU is aware of its available channel set and the total number of channels \( N \). To model the clock drift, each user randomly selects a (local) time to start its CH sequence. For each set of parameters, we generate 3,000 different available channel sets for the two users and perform 1,000 independent event-driven runs for each pair of the available channel sets. We then compute the maximum/average time-to-rendezvous as the measured MTTR/ETTR. The simulation results are obtained with 95% confidence intervals. Since the confidence intervals of ETTR are all very small in our simulations, for clarity, we do not draw the confidence intervals in the figures.

A. Impact of the number of channels when the number of common channels is fixed

In this simulation, we vary the total number of channels \( N \) from 64 to 192 with fixed \( n_1 = n_2 \) uniformly chosen in \([14, 16]\), \( m_1 = 2 \), \( m_2 = 4 \), and the number of common channels \( G = 2 \). In Figure 2(a), we show the MTTR results of all the algorithms. It is well-known that the MTTR of GCR [10] and that of AMRR/M [22] are \( O(\frac{n_1n_2}{m_1m_2}) \) (with the requirement that the number of radios for each user has to be larger than 1) and the MTTR of FMRR [23] is \( O(\frac{n_1n_2}{m_1m_2}\log(\log N)) \). Even though the MTTR of our quasi-random (QR) algorithm is \( O(\frac{n_1n_2}{m_1m_2}\log N) \) in theory, the simulation results in Figure 2(a) show that the MTTR of our algorithm is comparable to those of these three algorithms (i.e., GCR, AMRR/M, FMRR) and that of the random algorithm. Also, the MTTR of JS/I is \( O(N^3) \) and its MTTR is significantly worse than the other algorithms.

In Figure 2(b), we show the ETTR results of all the algorithms. As shown in Figure 2(b), our algorithm performs much better than the other schemes, and it is almost identical to the ETTR of the random algorithm.

Figure 1. An illustrating example of the quasi-random algorithm with two users.
B. Impact of the number of channels when the number of common channels is proportional to the number of channels

In this simulation, we vary $N$ from 64 to 192 and $n_1 = n_2 = N/2$, $G = N/8$ with fixed $m_1 = 3$ and $m_2 = 6$. Since $n_1$, $n_2$ and $G$ are linear functions of $N$, it then follows from Corollary 6 that the MTTR of our QR algorithm is now $O(N^2 \log(N))$. As shown in Figure 3(a), the MTTR of our algorithm is increasing in $N$, and it is also comparable to those of GCR, AMRR/M, FMRR and random algorithms.

In Figure 3(b), we show the ETTR results of all the algorithms in this simulation setting. Once again, our algorithm performs much better than the other schemes, and it is almost identical to the ETTR of the random algorithm.

C. Impact of the number of radios

In this simulation, we fix $N = 160$, $n_1 = n_2 = 40$, and $G = 20$. We then measure MTTR and ETTR for various settings of $(m_1, m_2)$. The simulation results are shown in Figure 4. As expected, both MTTR and ETTR decrease when the numbers of radios $m_1$ and $m_2$ are increased. This is because the probability of finding a common channel for rendezvous is increased when the numbers of radios $m_1$ and $m_2$ are increased. The results shown in Figure 4(a) and (b) are consistent with the findings in the simulations in the previous two settings.
simple to implement in the symmetric, asynchronous, and
in [19] and is thus more robust to jamming attack. It is very
Our QR algorithm does not require the unique ID assumption
and a comparable MTTR to the best bound in the literature.
algorithm that has a comparable ETTR to the random algorithm
are decreasing in $G$. Clearly, both MTTR and ETTR are
Fig. 5. The effect of the number of common channels on MTTR and ETTR
for various common channels $G$ with $n_1 = n_2 = 64, m_1 = m_2 = 5$.

D. Impact of the number of common channels

In this simulation, we fix $N = 160, n_1 = n_2 = 64, m_1 = 5, m_2 = 5$, and vary $G$ from 3 to 27. The simulation results are shown in Figure 5. Clearly, both MTTR and ETTR are decreasing in $G$. Once again, both the MTTR and the ETTR of our QR algorithm are almost identical to those of the random algorithm and they are better than those of the other algorithms.

IV. Conclusion

In this paper, we proposed the quasi-random (QR) CH algorithm that has a comparable ETTR to the random algorithm and a comparable MTTR to the best bound in the literature. Our QR algorithm does not require the unique ID assumption in [19] and is thus more robust to jamming attack. It is very simple to implement in the symmetric, asynchronous, and heterogeneous setting with multiple radios.

There are several possible extensions of this work: (i) in this paper, we only considered using the 4B5B encoding scheme. There are other encoding schemes proposed in [19] that might be also applicable to our QR algorithm. (ii) We only consider two-user rendezvous in this paper. It would be of interest to see how the QR algorithm performs in the multiuser rendezvous problem.

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