# A Clique Based Asymmetric Rendezvous Scheme for Cognitive Radio Ad-Hoc Networks

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**Abstract.** Cognitive Radio (CR) is a promising technique to enhance the spectrum utilisation by enabling the CR users to opportunistic access the spectrum holes or channels. To exchange spectrum information most of the existing research have utilised a Common Control Channel (CCC). This results channel saturation, extreme transmission overhead of control information, and a point of vulnerability. To address this problem, Channel Hopping (CH) protocols have proposed for enabling Rendezvous (RDV). This paper presents a CH protocol based on clique system, called clique based channel hopping (CCH) for the purpose of RDV establishment. The proposed CCH is a role based blind RDV CH system where sender and receiver generates CH sequence based on h-clique and v-clique respectively. The CCH protocol satisfies the following requirements: (i) guaranteed RDV; (ii) no synchronisation; and (iii) symmetric and asymmetric channel model. Simulation results show that the proposed clique based channel hopping (CCH) scheme outperforms similar CH schemes in terms of average time-to-rendezvous (ATTR) and the degree of overlap in both symmetric and asymmetric channel scenario.

**Keywords:** Cognitive radio · Channel hopping · Rendezvous · Clique

## 1 Introduction

Cognitive radio ad-hoc networks (CRAHNs) is a dynamic multichannel environment whereby the channel status changes over time depending on surrounding radio users' activities. Hence, it is essential for a CR node to detect and identify its neighbours to initiate communication in CRAHNs, which corresponds to RDV. In a multi-channel wireless ad-hoc environment, RDV is the first key step for CR users to be able to communicate with each other. To achieve rendezvous, a CCC is often used as a common platform to exchange control information [1,2]. In CCC based protocol, two users tune the radio in the network wide or local common channel to exchange the control information. This common channel can be selected from unlicensed band or licensed band [3,4]. It is obvious that CCC


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based RDV schemes are very easy to deploy and efficient in centralized or coordinated network. Hence, in purely distributed ad-hoc networks (no coordination and no prior agreement), the performance of CCC based RDV protocols is limited to the factors; (i) single point failure, (ii) vulnerable to Primary User (PU) activity, (iii) channel saturation, and (iv) control channel jamming.

To overcome these performance instability, a channel hopping (CH) or parallel RDV is proposed in [5–7]. When a CR node wants to transmit a packet to its peer's, it switches from one channel to another by following a pre-defined [8] or random hopping sequence [9]. A desirable property of CH sequence scheme can guide any two users in the network to hop on the same channel in the same timeslot as soon as possible. Moreover, it should able to explore the temporal and spatial distribution of control channel in order to minimise the interference with license users. The authors in [10] proposed jump-stay based CH algorithm for both symmetric and asymmetric models without exploiting the time synchronization. However, ATTR in this case grows dramatically with the number of available channels as it does not have any preference to achieve rendezvous on a particular channel. Hence, the timeslots assignment on a given channel is not uniform and is a function of the LUs' activity [9]. The robustness against LUs' activity can be achieved by profiling (ranking) the available channels based on local channel sensing information. Only two CH sequences; AMRCC [9] and gQ-RDV [11] can be found in the existing literatures that consider channel quality to design CH sequence. Both of these protocols can guarantee rendezvous with symmetric channel information. However, there is no guarantee that they can achieve rendezvous on each available common channel with asymmetric channel information.

In this paper, we propose an asymmetric asynchronous channel hopping scheme by utilizing the clique system called clique based channel hopping (CCH). Our approach utilizes the mathematical concept of clique systems with rotation closure property to generate CH sequences that enable RDV on multiple channels. Moreover, the CCH scheme integrates the channel sensing information to assign the timeslots.

The rest of the paper is organized as follows: In Sect. 2, we presented the system model, channel activity model and followed by the RDV problem in CRAHNs. In Sect. 3, A detail description of channel hopping sequence generation is presented which includes grid formation, channel mapping and algorithmic analysis. In Sect. 4, simulation is performed to measure the performance of CCH protocol. Results show that, clique based CH sequence can guarantee to achieve RDV on number of available channels. We conclude our work in Sect. 5.

## 2 Preliminaries

### 2.1 System Model

We assume that there are $N$ CR users in a single hoop CRAHNs that coexists with a number if PUs. Based on the time and space, CRs may observe same or different same of set of channels. It is considered that there are two types of channels available in the system; (i) licensed channel which is licensed to PUs and (ii) unlicensed channel which is open to all. A CR can operate in both linseed and unlicensed band. The available channels are indicated as $C = C_1, C_2, \ldots, C_M$. We also consider that each CR is capable to detect the spectrum hole and can operate on these channels. THe channel set of $i$th and $j$th CRs can be expressed as $CR_i$ and $CR_j$ respectively. The common channel set between user $i$ and $j$ can be represented as, $G_{i,j} = CR_i \bigcap CR_j$.

### 2.2 Channel Activity Model

A channel activity can be modeled as continuous time Markov chain (CTMC) where a channel can be any of these states (i) idle state (ii) PU state and (iii) CR state. A channel state can move from idle to PU or CR state if it is used by PU or CR respectively. The channel state can move form CR to PU if the PU reappear on the channel used by CR, however the channel state cannot move from PU to CR. The transition diagram is shown in Fig. 1.

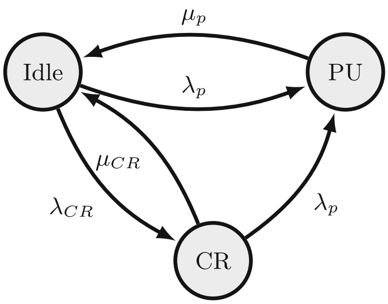



**Fig. 1.** Channel state transition diagram

Here the service request of both PUs and CR users modeled as a Poisson process with rate $\lambda_P$ and $\lambda_{CR}$ and is terminated with rate $\mu_p$ and $\mu_{CR}$. Hence the transition matrix $A$ can be written as:

$$\mathbf{A} = \begin{bmatrix} -(\lambda_p + \lambda_{CR}) & \lambda_p & \lambda_{CR} \\ \mu_p & -\mu_p & 0 \\ \mu_{CR} & \lambda_P & -(\lambda_P + \mu_{CR}) \end{bmatrix} \tag{1}$$

### 2.3 Problem Definition

In a multi-channel environment, the RDV problem can be described as a coordination problem where two suers have a set of channels to established communication with each other. However, RDV only achieved if both of the users are one the same channel at the same time. We assume that there are $P \geq 2$ CR users in the network, who share a set of available licensed channels, such as $X_i \subseteq X; (C \in X_0, X_1, X_2, \ldots, X_{N-1})$ (N is the number of available licensed channels and have labels that are the same for all CRs) that can be used for both control and data information exchange. Before initiating any data transmission, the intended nodes should first exchange control information between them to select common data channels. According to [10], nodes could have identical (i.e. $C_i = C_j$) or different available channel lists with at least one common channel, known as symmetric and asymmetric channel lists respectively. In CH-based solutions, the RDV process can be described as pairwise control channel establishment using sequences $X$ and $Y$ where $X$ and $Y$ are two CH sequences with period $T$, such as $(0, X[0]), (1, X[1]), \ldots, (T-1, X[T-1])$ and $(0, Y[0]), (1, Y[1]), \ldots, (T-1, Y[T-1])$. Hence, RDV sequences must have overlapped property in order to ensure any pair of nodes can establish communication, i.e. $\forall X, Y; \mid X \bigcap Y \mid \neq 0$.

## 3 Channel Hopping Sequence Design

The basic concept of this paper is inspired by the concept of clique. The clique is used in a social networks to identify the subset of people who all know each other. In this work, we use clique so that two users choose a set of channels from available channel list and jumps over the channel to achieve RDV. The size of the clique depends on the remaining energy of a CR node. In this section, we first provide a brief introduction of clique followed by CH sequence generation using clique.

**Definition 1.** Clique: Let us assume a finite universal set $U = \{0, 1, \ldots n-1\}$ of $n$ elements, where $n$ represents the cycle length. A clique $C$ under universal set $U$ is a collection of non-empty subsets of $U$, provided that it satisfies the intersection property: $\forall A, B \in Q : A \bigcap B \neq 0$.

For example $C = \{\{a, b\}, \{a, c\}, \{b, c\}\}$ is a clique under $U = \{a, b, c\}$. The basic idea of the CH scheme in CRAHNs is design hopping sequences so that two CRs can achieve rendezvous which is analogous to clique where two subsets have at least one intersection.

**Definition 2.** h-Clique: Given a finite universal set $U = \{0, 1, \ldots n-1\}$ of $n$ elements, where $n$ represents the cycle length. Let $l, 1 \leq l \leq \sqrt(n)$ and $m, 0 \leq m \leq n-1$ be two integers. An h-clique of $l$ and $m$ can be defined as follows:

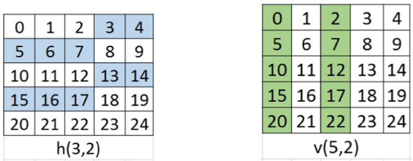
$$h(m,l) = \left\{ \left( \left\lfloor \frac{\sqrt{n}}{l} i \right\rfloor \sqrt{n} + m + j \right) (mod\, n), \quad i = 0, \ldots, m-1; j = 0, \ldots, \sqrt{n} - 1 \right\} \tag{2}$$

For instance, when $n = 25$, for $m = 3$ and $l = 2$, the $h(3, 2) = \{3, 4, 5, 6, 7, 13, 14, 15, 16, 17\}$. Here $m$ defines the starting position of the sequence such as $m = 3$ thus the sequence starts from 3. The purpose of $l$ is to define the size of the sequence which is $l\sqrt{n}$. Figure 2(a) Shows an example of h-clique of h(3, 2).

**Definition 3.** v-Clique: Given a finite universal set $U = \{0, 1, \ldots n-1\}$ of $n$ elements, where $n$ represents the cycle length. Let $l, 1 \leq l \leq \sqrt(n)$ and $p, 0 \leq p \leq n-1$ be two integers. An v-clique of $l$ and $m$ can be defined as follows:

$$v(p,l) = \left\{ \left( \left\lfloor \frac{\sqrt{n}}{l} i \right\rfloor + p + j\sqrt{n} \right) (mod\, n), \right.$$
$$\left. i = 0, \ldots, m-1; j = 0, \ldots, \sqrt{n}-1 \right\} \quad (3)$$

For example, $n = 25$, for $p = 5$ and $l = 2$, the $v(5,2) = \{0, 2, 5, 7, 10, 12, 15, 17, 20, 22\}$. Here $p$ defines the starting portion of the element modulus $n$, such as $p = 5(mod\, n) = 0$ and l defines the number of columns as shown in Fig. 2(b).




(a) h-clique of h(3,2)

(b) v-clique of v(5,2)

**Fig. 2.** CH sequence is generated by (a) h-clique and (b) v-clique for n = 25.

Upon joining in the network, a CR node will perform periodic sensing and ranked the available channel based on PU activity. Therefore, if a CR user has data to transmit it will construct a CH sequence based on h-clique and stay on each channel for $T$ duration where $T$ is the time required to exchange control information. The receiver is follow a CH sequence based on v-clique and visits the channel accordingly. The timeslot assignment for each channel is presented in Algorithm 1.

**Theorem 1.** Given two integers $l_1$ and $l_2$, $1 \leq (l_1, l_2) \leq \sqrt{n}$ and two random numbers $m$ and $p$, $0 \leq (m, p) \leq n-1$. The two users can achieve RDV within $\sqrt{n}\left(\left\lceil \frac{\sqrt{n}}{l_1} \right\rceil - 1\right) + \left\lceil \frac{\sqrt{n}}{l_2} \right\rceil$.

**Proof:** A sender generates a CH sequence based on h-clique which has $l_1 \times \sqrt{n}$ elements where the maximum distance between two successive elements can be written as $\sqrt{n}\left(\left\lceil \frac{\sqrt{n}}{l_1} \right\rceil - 1\right) + 1$. Same as the receiver generates a CH sequence based on v-clique with $l_2 \times \sqrt{n}$ elements. The maximum distance between two CH sequences is the sum of the distance of sender and receiver CH sequence. We should subtract 1 from the summation to avoid a double count of the common element.

**Algorithm 1.** CCH Algorithm

Input: (i) Number of available channels, $m$;
(ii) Transmission flag, $Flag_{Tx}$;
(iii) Channel rank;
(iv) Rescan period, $T_{out}$;

Output: (i) Channel map $CH_{map}$;
(ii) Channel timeslots $CH_{t\_slots}$;

**Begin**

**while** $mod(t, T_{out}) = 0$ **do**
  $[Avail_{CH}]$; {Available channel set}
  Rank($[Avail_{CH}]$) = $[CH_{List}]$
  $n =\mid Avail_{CH} \mid$
  $T_{slots} = n \times nn${Grid formation}
**end while**
**while** packets arrive **do**
  $q \leftarrow q + 1$
  **for** $i = 1 : n$ **do**
    m = randperm[0,n-1]
    construct h-clique $h(m(i), l_1)$ {Sender CH sequence generation}
    $T_{slots}(h(m(i), l_1) = CH_{list}(i)$
    $D = setdiff(T_{slots}, h(m, l_1))$
    $T_{new\_slots} = (n-1) \times (n-1)$
    **if** $T_{new\_slots} < D$ **then**
      $T_{new\_slots} = [D, d]$ {d is dummy variable to construct the grid}
    **else**
      $T_{new\_slots} = D$
    **end if**
  **end for**
**end while**
**for** $j = 1 : n$ **do**
  p = randperm[0,n-1]
  construct $v(p(j), l_2)$ {Receiver CH sequence generation}
  $T_{slots}(v(p(j), l_2) = CH_{list}(:, i)$
**end for**

**End**

A CH sequence in a time slotted architecture indicates the timeslots on which a node transmit or receive data to or from neighbors. Two CH sequence is called time synchronised if they start channel hopping at the same time as illustrated in Fig. 3, when $K = 0$. The value of $K$ indicates the time lag between two CH sequence. $K$ can be integer or fraction. If $K$ is integer, we called it slot asynchronised otherwise it is fractional asynchronised. Both slot and fractional asynchronised scenarios are depict in Fig. 3. In fractional asynchronised case, rendezvous may not be achieved if the overlap duration is smaller than the time required to exchange control information. The performance of CH sequence depends on time synchronisation. Figure 3 shows that the degree of overlap between two CH sequences is significantly changes with time asynchronisation for different value of $K$. Consequently ATTR will also fluctuate due to the same. Hence, CH sequence that designed for time synchronize environment may not suit for time asynchronise environment.

**Definition 4.** Rotation: For a non-empty set $X$ in a clique $C$ under $U = \{0, \ldots, n-1\}$ and a non-negative integer $i \in \{1, 2, \ldots, n-1\}$, we define $rotate(x, i)$ or $R(X, i) = \{(j + i) \ mod \ n \mid j \in x\}$. A clique $C$ is said to have the rotation closure property if $\forall X, X' \in C, i \in \{1, 2, \ldots n-1\} : X \bigcap X' \neq 0$.

For instance, the clique $C = \{\{a, b\}, \{a, c\}, \{b, c\}\}$ under $U = \{a, b, c\}$ satisfies rotation closure property. Thus, $X$ and $X'$ can still meet each other even though their clocks drifted. Thus, the rotation closure property holds for $C$. Two CR nodes adopting clique in $C$ to denote their h-clique and v-clique can meet at the same time even if their clocks drifted.

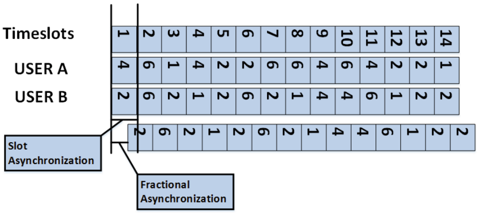



**Fig. 3.** Variation of degree of overlap in accordance with time synchronisation.

**Theorem 2.** Given two integers $l_1$ and $l_2$, $1 \leq (l_1, l_2) \leq \sqrt{n}$ and two random numbers $m$ and $p$, $0 \leq (m, p) \leq n-1$, then $R(h(m, l_1)) \bigcap R(v(p, l_2)) \neq 0$.

**Proof:** According to Definition 2 of h-clique, R(h) has at least $\sqrt{n}$ elements and any two successive elements must have distance either 1 of $n - \sqrt{n} + 1$. Same as Definition 3 of v-clique, R(v) has at least $\sqrt{n}$ elements and any two successive elements must have distance $\sqrt{n}$. Let $y_i$ for $i = 0, \ldots, \sqrt{n} - 1$, be $\sqrt{n}$ elements of $R(v)$, then we can write $y_{i-1} \leq y_i \leq y_{i-1} + \sqrt{n} + 1$. Thus in order to proof the theorem we need to show that $y_i$ is an element of $R(h)$. Let consider the smallest element of $x$ in $R(h)$ which is larger than $y' \in R(v)$, then $y' + 1 \leq x \leq y' + n - \sqrt{n} + 2$ as any two elements in R(h) must have less than or equal to $n - \sqrt{n} + 1$. Thus $y' \in R(v)$, $x \leq y' \leq x + \sqrt{n} - 1$ which implies that $y'$ is contained in R(h).

**Theorem 3.** Given two integers $l_1$ and $l_2$, $1 \leq (l_1, l_2) \leq \sqrt{n}$ and two random numbers $m$ and $p$, $0 \leq (m, p) \leq n-1$, then we have $\mid R(h(m, l_1)) \bigcap R(v(p, l_2)) \mid = l_1 \times l_2$.

**Proof:** From the Definition 2, $h(m, l_1)$ has a sequence of $\sqrt{n}$ contiguous and ascending elements and has at least one intersection with $v(p, 1)$ i.e. $|R(h(m, 1)) \bigcap R(v(p, 1))| = 1$. Now $h(m, l_1)$ has $l_1$ sequence which are disjoint and will have $l_1$ intersection with $v(p, 1)$. Same as $v(p, l_2)$ will have $l_2$ intersection with $h(m, 1)$. From this we can proved that $|R(h(m, l_1)) \bigcap R(v(p, l_2))| = l_1 \times l_2$. Figure 4 shows the graphical illustration of the Theorem 3. The first and second block of the Fig. 4, show the selection of timeslots according to $h(3, 2)$, and $v(5, 2)$, where $l_1 = 2$ and $l_2 = 2$. The third block of the Fig. 4 represents the timeslots where RDV is achieved. The no. of RDV is $l_1 \times l_2 = 2 \times 2 = 4$.

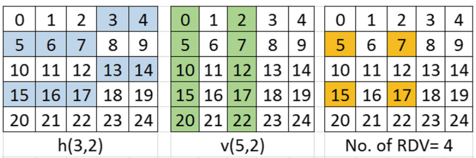



**Fig. 4.** Illustration of degree of overlap using clique channel hopping sequence.

# 4 Performance Evaluation

A MATLAB based simulation is used to evaluate the performance of the CCH protocol. A network with varying CR nodes is considered with the number of available channels ranging from 2 to 50 in a 800 m × 800 m area, where each of the nodes had an equal transmission radius of 100 m. In this work both licensed and unlicensed channels were considered with equal priority. CR nodes were considered asynchronous, which was implemented by imposing a random delay at network initialization. During the simulation, the CR nodes may synchronise themselves after achieving RDV. Each CR node starts with spectrum sensing. The sensing duration was set at 25 ms/channel and ≤1 ms/channel for fine and fast sensing respectively [12]. Fast sensing is performed by selecting samples of the PU Poisson traffic within its sensing period and later on performing fine sensing before jumping into a channel. The ranking table of CR nodes is based on channel availability and channel activity observed locally by a CR user. It is assumed that, if a packet arrives during the spectrum sensing or handshaking process, it is enqueued and remains in the queue till RDV is achieved. In this chapter, collision among control or handshake packets is not considered; however, in case of collision between a CR user packet and a PU packet, the CR user packet is dropped instead of being retransmitted after a backoff.

All the results presented in this chapter are averaged over 10000 iterations [13]. Each PU is randomly assigned a channel when a new packet needs to be transmitted and packet arrivals follow the Poisson distribution with exponentially distributed inter-arrival times.

## 4.1 Impact of Number of Channels

Figure 5 shows the impact of number of channels on the network performance which includes ATTR and RDV success rate. We have considered maximum 50 channels that are available for CR users to achieve RDV. Figure 5(a) shows that the ATTR is increasing with number of channels for all protocols including our proposed CCH as the CH sequence length is proportional to number of channels in the available channel set. However, the prosed CCH protocol exhibits superior performance compare to other protocols as it facilitates higher number of RDV in each CH sequence cycle. For gQ-RDV, the number of RDV on each cycle is fixed i.e. 2. In JS, the ATTR is at least three (3) times of the number of available channels. The ATTR of CCH is 20 for 30 channels, while it is 38, 70, and 117 for JS, gQ-RDV and basic AMRCC respectively. The higher the ATTR, the lower the RDV success rate which is shown in Fig. 5(b). RDV success rate is a design issue of the CH sequence design. In CCH, we have a very clear control by setting the two parameters $l_1$ and $l_2$. In JS, CR users have a guaranteed RDV on each channel however there is no control how many RDV can be achieved in each CH cycle. For instance, when there are 25 channels in the available channel set, the RDV success rate is 87% for CCH and 73%, 28%, and 3.5% for JS, gQ-RDV, and basic AMRCC.

### 4.2 Impact of Asymmetry

Due to temporal and spatial changes in radio environment, CR users may observe different set of channels and have different cardinality of the available channel set. The degree os asymmetry can be defined as $\alpha = \frac{|C_x|}{|C_y|}$, where $|C_x|$ and $|C_y|$ are the cardinality of the available channel set of user $x$ and $y$. As basic AMRCC doesn't support the asymmetric channel, we have excluded it from this analysis. We have considered two values for $\alpha$ and Fig. 6(a) illustrate the ATTR of CCH, JS, and gQ-RDV for $\alpha = 0.4$ and $\alpha = 0.8$. For simplicity we considered a fixed number of common channels between users. At each run, the common channels are selected randomly from the available channel set. A similar trend of ATTR is observed for all the protocols. The CCH outperforms than other two protocols. For instance, when the number of channel is 35 with degree of asymmetry is 0.8, the ATTR for JS and gQ-RDV is 14.44% and 131% higher than that of CCH. Interestingly, the performance gap between different protocols is increased with the degree of asymmetry. The same behaviour can also be observed for RDV success which is shown in Fig. 6(b).

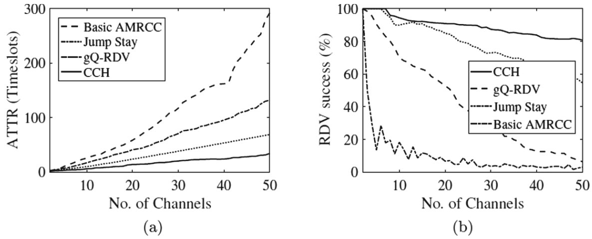



**Fig. 5.** Comparison of ATTR and degree of overlap with increasing number of available channels: (a) ATTR (b) Rendezvous success.

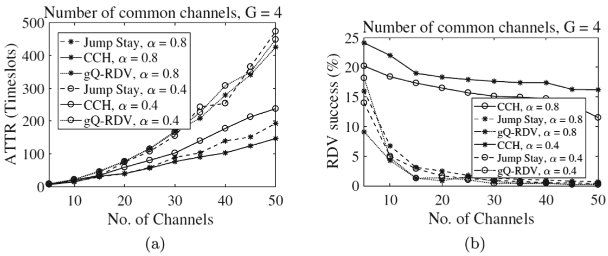



**Fig. 6.** Comparison of ATTR and degree of overlap when two users experience asymmetric set of channels: (a) ATTR (b) Rendezvous success

## 5 Conclusion

In this paper, a clique based asymmetric CH sequence is proposed to solve the RDV problem. Using a clique based system grantees that the nodes would meet within a bounded time. This method satisfies the both asynchornous and asymmetric blind RDV. We have performed algorithmic analysis in terms of ATTR and RDV success rate. Simulation results have shown that our CH scheme is highly resilient to dynamic spectrum allocation in CRAHNs. The extension of CCH for multiuser multihop communication would consider as our future works.

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