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An Extensive Asynchronous Symmetric Rendezvous Technique for Cognitive Radio Networks

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Abstract: With the current increase in wireless technology, spectrum is becoming scarce. By equitably allocating frequency bands to unlicensed and licensed clients, the cognitive radio network (CRN) reduces the growing inadequate utilization and spectrum scarcity. Secondary users (SUs) and unlicensed users can impulsively exploit the licensed users allotted free spectrum under CRN. The rendezvous procedure, in which SUs gather on widely used channels and create trustworthy linkages for efficient communication, is critical in creating CRN. Considering the dynamic context of CRNs, rendezvous methods that depend on the presumption of a common control channel (CCC) across SUs are less effective and impractical. Thus, the rendezvous among SUs is often accomplished via the channel hopping (CH) approach without CCC assistance, also known as blind rendezvous. The complete asynchronous symmetric rendezvous (CASR) technique presented in this paper ensures that SUs will rendezvous in a finite amount of time without the need for time synchronization. The CASR method uses the SU's MAC address to generate a unique identifier (ID) and create a CH sequence by dynamically adjusting the ID per the number of accessible channels for communicating. The CASR method achieved rendezvous assurance while maintaining an acceptable time to rendezvous by utilizing the distinct ID of each SU. The effectiveness of the CASR technique is theoretically evaluated and empirically tested through several simulation studies. According to simulation studies, CASR technique outperforms existing rendezvous techniques when considering average time-to-rendezvous.

Introduction

A new paradigm called the CRN was created to address the licensed spectrum's rising shortage and overuse issues (Wang et al., 2022). The open spectrum allotted to the primary users (PUs) or licensed users can be opportunistically used by SUs or unlicensed users through the CRN (also known as spectrum gaps or white spaces (Haykin, 2005). When utilizing the allocated spectrum in CRNs, PUs receive a greater priority. When the PUs are not using the licensed spectrum, the SUs can utilize it. They must leave or move to a different channel when the PUs reappear. The cognitive radio (CR), which may be described as a consequence of its cognitive capabilities and reconfigurability, is the primary technology for the CRN (Cabric et al., 2005; Thomas et al., 2005; Akyildiz et al., 2006). CR analyzes its radio conditions using its cognitive abilities and finds the temporarily unused spectrum region. The capacity to reconfigure CR enables it to dynamically adjust to the shifting spectrum environment (Jondral, 2005).

The rendezvous procedure, known as neighbour discovery, is crucial in configuring a CRN (Asifuddola et al., 2023; Yang et al., 2022). SUs meet on widely used channels and create communication links to share information. Typically, periodic beaconing has been used in ad hoc networks for creating communication linkages among network nodes by exchanging beacon messages across a predetermined communication channel (Paul et

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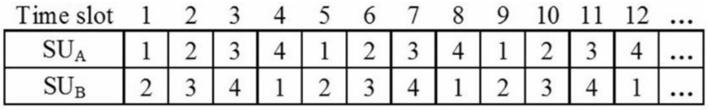
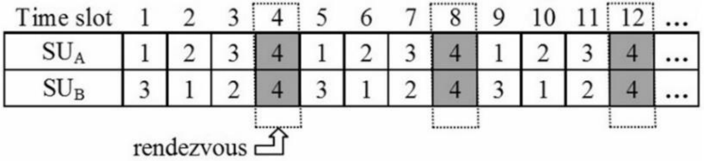
al., 2022; Hsieh et al., 2023; Chaudhari and Dinesh, 2023). Even so, with CRN, there is yet to be a predetermined channel for communication that may be used to spread beaconing data. Instead, SUs carries out sensing of the spectrum and dynamically determine the open, free channels via which the required communication linkages can be formed (Wang et al., 2023). The channels that SUs may perceive also change and shift over time due to differences in activity from the PU and SU geometric placement (Akyildiz et al., 2009). Finding a channel regularly accessible to all SUs in the highly dynamic CRN context is challenging since the available channels vary over time. As a result, the rendezvous procedure is a challenging task. As a result, it is crucial to establish common communication channels amongst SUs to exchange beacon data (Sengupta and Subbalakshmi, 2013). The rendezvous procedure (Liu et al., 2012) is an instance of SUs meeting on a channel that is often used to establish communication linkages. When both SUs simultaneously are on the identical channel for a length of time long enough to initiate a trustworthy link among them, rendezvous is considered to have taken place (Shin et al., 2010a).

For attaining the rendezvous amongst SUs in use, Rendezvous techniques may be divided into asymmetric and symmetric, asynchronous and synchronous, and distributed and centralized kinds when taking into account various CRN circumstances (Lo, 2011; Joshi et al., 2014). Distributed method operates independently of the central server and CCC, but centralized method demands a central entity and a preset CCC to govern the rendezvous process. Asynchronous methods do not need any temporal synchronization between SUs, while synchronous algorithms limit SUs to starting rendezvous procedures concurrently on the same time. Asymmetric algorithms take into account the varied channel availability of SUs, while symmetric algorithms presume that all SUs have the same set of accessible channels. The channel hopping (CH) approach, which considers a time-slotted scheme in which time is split into equal-sized slots, is used by most rendezvous methods. SUs hop between channels in a series (known as a CH sequence) to find possible neighbours, having one channel every time slot. However, SUs can shift to other channels during every time slot. Hopping with channels using one channel each time slot might not bring them to the rendezvous. For instance, if two SUs A and B create CH sequences of {2, 3, 4, 1} and {1, 2, 3, 4} correspondingly, and if they hop by their respective CH sequences (shown in figure 1a), rendezvous can never be reached. Rendezvous would be possible if the SUs hop to the identical channel within the identical time window, as shown in Figure 1b. Therefore, the CH sequence must be designed to ensure SU rendezvous in a finite time.



Time slot	1	2	3	4	5	6	7	8	9	10	11	12	…
SU_A	1	2	3	4	1	2	3	4	1	2	3	4	…
SU_B	2	3	4	1	2	3	4	1	2	3	4	1	…

(a) Rendezvous is not guaranteed in finite time



Time slot	1	2	3	4	5	6	7	8	9	10	11	12	…
SU_A	1	2	3	4	1	2	3	4	1	2	3	4	…
SU_B	3	1	2	4	3	1	2	4	3	1	2	4	…

(b) Rendezvous is guaranteed in finite time

Figure 1 (a & b). Rendezvous mechanism for channel hopping.

Time-to-rendezvous (TTR), measuring counts of time slots required for reaching rendezvous after all SUs had begun the rendezvous procedure, is the most important metric utilized to assess the accuracy of the rendezvous method. The rendezvous procedure may, however, begin at any moment in the CRN's asynchronous environment. In order to measure performance, the Expected TTR (ETTR) and maximum TTR (MTTR) are typically used. For the average-case and worst-case conditions, the rendezvous time is referred to as ETTR and MTTR, respectively (Chang et al., 2014; Chuang et al., 2013; Chuang et al., 2014).

The complete asynchronous symmetric rendezvous (CASR) technique presented in this paper assures the rendezvous in a limited time without requiring temporal synchronization between SUs. The proposed approach uses distinctive SU IDs to build the CH sequence based on dynamic ID manipulation by the number of accessible channels. The proposed approach uses distinctive SU IDs to build the CH sequence based on dynamic ID manipulation by the number of accessible channels. According to simulation data, the CASR method performed significantly better than current state-of-the-art rendezvous procedures.

Related work

Previous CH rendezvous methods use the random technique by various researchers (Kondareddy et al., 2008; Cormio and Chowdhury, 2010), where SUs randomly select CH sequences from a pool of accessible channels. Even though a random method could secure a rendezvous, it could ensure rendezvous within a set time because of the SUs' uncertain channel-switching behavior.

The deterministic rendezvous sequence (DRSEQ) approach was introduced by Yang et al. (2010) and ensured the rendezvous in a limited time for the

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symmetric scenario. DRSEQ produced the CH sequence with the pattern: $1, 2, \ldots, N, e, N; N-1, \ldots, 1$. In this case, e stands for an empty slot. When N represents the number of channels, DRSEQ has an MTTR of $2N+1$.

Liu et al. (2010) developed a ring-walk (RW) method in which potential channels are considered as vertices in the circular ring. SUs moves at varying speeds along the vertices. It is anticipated that SUs with higher velocity will catch SUs with lower velocities. The network size, however, could be constrained by RW's dependency on the quantity of SUs.

The modular clock (MC) method was created (Theis et al., 2011) by utilizing a feature of prime number modular arithmetic. Rate r with which SUs switch channels is the primary MC driving force. Only if the SUs choose separate rates does the MC ensure the rendezvous. Since the rate is arbitrarily determined, MC could not ensure SU rendezvous.

The jump-stay (JS) approach was suggested by Liu et al. (2012) and ensures the rendezvous of SUs in both asymmetric and symmetric scenarios. The two components of JS are jump and stay. SUs switch between accessible channels with $2P$ time slots for the jump phase here, where P represents the lowest prime integer, which is more significant than the total number of communication channels. P time-slotted stay phase follows each jump phase, during which SUs wait on a specific channel which can be specified using rate r. Rendezvous will be anticipated during the jump stage if two SUs choose rates that differ; otherwise, rendezvous takes place in the stay phase. The MTTR of JS in a symmetric structure has $3P$ time slots. The enhanced jump-stay (EJS) technique, which Lin et al. (2013) proposed as an extension to the JS method that significantly improves performance in asymmetric settings. EJS doesn't, however, show any more advancements in the symmetric mechanism.

Alternate hop-wait (AHW) is one of the rendezvous methods was introduced by Chuang et al. (2013). It uses the fundamental assumption that rendezvous is ensured when the first SU finishes a round if one SU hops amongst potential channels following a circular pattern (also known as hop mode). Meanwhile, the other SU awaits on a specific channel (also known as wait mode). The corresponding bits of an SU's unique ID determine its CH sequence. Later, an improved alternate hop-wait (E-AHW) technique was proposed by Chuang et al. (2014). This technique uses SU's MAC address as the distinctive ID. E-AHW provides an MTTR of 147P time slots in a symmetric structure, in which P represents the lowest prime number, which is higher than the overall number of possible channels.

Proposed Technique

This research considers CRN with N $(N > 1)$ SUs coexisting with a Pus group. Non-overlapping channels $C = \{c_1, c_2, \ldots, c_M\}$ that are specifically identified in the range $1, 2, 3, \ldots, M$ where M $(M > 1)$ make up the potential licensed spectrum. It is presumed that every SU has a CR and has an individual ID. While the PUs are not using them, SUs can opportunistically access any free, open channels in C. Spectrum sensing is used to find available, free channels. A pair of SUs attempting to rendezvous are presumed to share the same set of accessible channels. As was already explained, this method is known as a symmetric method. Considering a time-slot mechanism, wherein time is split into equal length slots. SUs only switch between the various channels once per a time slot, or one channel at a time. According to the IEEE 802.22, every time slot is configured to be $2t$ long (Stevenson et al., 2009), wherein t represents the time needed to build a communicating connection among SUs. It is considering two SUs (for example, SUA & SUB) who have equivalent accessible channels and try to connect by hopping on the channels that are available with a single channel for each time slot. The challenge remains to generate sequences of CH in a way which guarantees rendezvous on widely used channels among the SUs within a finite amount of time.

Basic principle

It is demonstrated using the MC method that if the CH sequence of SU_i with time slot $t+1$ is written as $j_i^{t+1} = (j_i^t + r_i) \, mod \, (p_i)$ and $r_i \neq r_j$ (SUs choose distinct rates), rendezvous may be assured to occur in p_i time slots. However, Rendezvous can't be ensured if all SUs choose the same rate. Therefore, the rates SUs choose must always be varied for rendezvous guarantees. Due to the rate being set at random, MC could not accomplish the rendezvous guarantee. The proposed technique ensures that SUs choose various rates throughout a set period. The main idea behind the proposed technique is the systematic application of distinctive IDs given to the SUs. The unique IDs bits are utilized to construct CH sequences of SUs. The proposed technique may identify almost all network devices since it uses a universal MAC address for a unique ID. By using their IDs, SUs can choose various speeds within a specific, constrained time frame when using the proposed method. The rates at which SUs switch between channels are determined by unique IDs bits. Whenever all bits are utilized, ID bits are rotated appropriately.

Algorithm 1. Comprehensive asynchronous symmetric rendezvous algorithm

Input: Unique ID, Number of available channels.

Output: sequence of channel hopping

```
Compute p, the subsequent prime $\geq m$
$j^0 \leftarrow primary$ channel index, select arbitrarily in $[0, m)$
Calculate len, the uid length
$itr \leftarrow 1, ptr \leftarrow 1$
Index_Table ⟵ distribute_Bits_into_Groups(p, len)
While not rendezvous
    if $(len\ /\ 2) \geq itr$
        $r \leftarrow select\_Rate(Index\_Table, ptr, uid)$
        for t=0 to $2p - 1$ do
            $j^{t+1}$⟵($j^t$+r)mod (p)
            if $m > j^{t+1}$ then
                $c \leftarrow c_{j^{t+1}}$
            else
                $c \leftarrow c_{j^{t+1}}$ mod m
            end if
            attempting rendezvous on c channel
        end for
        increment itr and ptr by 1
    else
        for t=0 to $2p - 1$ do
            $r \leftarrow select\_Rate(Index\_Table, ptr - 1, uid)$
            $c \leftarrow r \bmod m$
            attempt rendezvous on channel c
        end for
        $itr \leftarrow 1$
    end if
    if $ptr > len$ then
        $ptr \leftarrow 1$
    end if
end while
```

Algorithm 2. distribute_Bits_into_Groups(p, len)

y represents the number of groups having an additional bit

x represents the number of bits/group

g represents the number of groups

p represents the prime number

len denotes the unique ID bit sequence length

Index_Table(ptr, index) provides a table that lists each bit and its accompanying group index. With ptr being the index to the unique ID bit position and index demonstrates group index, with index starting equal to 0 and ptr=1

```
$g = (p - 1)\ /\ 2$
if $len > g$ then
    $x = len\ /\ g$
    $y = len \bmod g$
else
    $x = 1$
    $y = 0$
endif
```

```
$k = x \times (g - y)$
$limit = x$
while $ptr \leq len$ do
    $Index\_Table(ptr) = index$
    if $ptr \geq limit$ then
        $index = index + 1$
        $limit = limit + x$
        if $ptr \geq k$ then
            $limit = limit + x$
        endif
    endif
    $ptr = ptr + 1$
end while
```

Algorithm 3. Select_Rate(Index_Table, ptr, uid)

Index denotes the group that the bit at place ptr relates to, bit value represents the bit value at place ptr in uid, and r is the channel switching rate.

```
$index = Index\_Table(ptr)$
bitvalue= the bit value at position ptr form uid
$r = bitvalue + (2 \times index) + 1$
```

Every time a node (SU) initiates the rendezvous procedure, the CASR algorithm (described in Algorithm 1) is performed. The following are key factors influencing the algorithm:

- The lowest prime higher than or equal to m is called p.
- The number of channels that can be collected by spectrum sensing is m.
- t denotes the system's time slot.
- The rate at which SUs switch channels is measured by r.
- len is the size of an uid.

The unique ID bit sequence is referred to as uid.

The CASR method starts by determining the length of the uid in bits, the starting channel index j^0, and the number of channels that are now accessible p greater than or equal to the number of channels that are currently available (m). After grouping the uid bits into different logical groups, the algorithm creates an index table which links each bit to its matching group index. The function $selectRate()$ uses the index table to decide on rate r, which is applied when switching between channels. The method then moves into the hop/jump state when SU hops on accessible channels with the same rate for a $2p$ time slot iteration for $n = len/2$ iterations. For each time slot t, the channel index j is incremented by $r \bmod p$. The radio switches to the channel c_j, or the channel with index j in the list of possible channels if the channel index j is in the range $[0, m)$. If not, the radio is remapped using the mod operation to find the channel in $[0, m)$ and switch to it. At an iteration of $2p$ time slots, the method keeps the same rate r. This guarantees that the SUs overlaps by at least p time slots while maintaining the current rates. All m channels are covered by consecutive p periods. As a result, SU rotates between all accessible channels with the same r value throughout $2p$ time intervals. The method provides a stay length of $2p$ time slots per n iterations, during which SU wait for the channel given by the prior r value. The stay time is added after each twenty-fourth iteration when the MAC address is utilized as the unique ID since $n = 48/2$ in this case. The cycle is continued when the method returns to the hop-jump state following the stay phase. When the SUs have reached rendezvous, the procedure is finished. An innovative grouping notion is presented by the CASR method, in which distinct groups are logically created from bits of unique ID. The logical grouping ensures that the SUs choose various rates within the specified time. Based on the prime number p and the m channels, grouping is done. Calculating the number of groups using g is

$$g = (p - 1)/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

p represents the lowest prime number, greater than or equal to m. The length of uid could be smaller as the number of groups g if the system uses a local unique identity rather than a universal MAC address. In such circumstances, each group only has one bit. In every other case, the number of bits per group is determined as

$$x = len/g \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (2)$$

Bits are distributed across the groupings as evenly as feasible. If not, an extra bit is added to each group, starting with the least significant bit (LSB) and proceeding up to the most significant bit (MSB). The formula for determining how many groups have this additional bit, y, is $y = len \bmod g$. The number of groups for various possible channel counts are shown in Table 1. Group length, which is represented as glen, is the term used to describe the largest possible number of bits in the group. The method then determines the group index for every bit in the uid and generates a Table $IndexTable\,(ptr, index)$, which maps each bit in the uid on position ptr to the appropriate group index.

The method calls the function $selectRate(IndexTable, ptr, uid)$ to decide the rate that will be utilized for channel switching prior to beginning each iteration of $2p$ time slots. The function determines the rate r as follows.

$$r = bitvalue + (2 \times index) + 1 \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Here, the $index$ represents the group number that the bit at position ptr. Meanwhile, $bitvalue$ represents the bit value on position ptr in uid. Either 0 or 1 can represent the $bitvalue$. As rate r is a function of $bitvalue$ and $index$, the rates produced through bits from two distinct groups can never be equal. Figure 2 is an illustration of logical grouping when $m = 10$ is present. There are 5 groups (g), and the group index ranges from 0 to 4. Bidirectional arrows are used to represent several groups. Each group has two potential rates because each bit has two possible values (i.e., 1 or 0). The conceivable rates that the various groups might produce are listed at the top of each group. As a result, the method assures that there are at least two groups and that the rate values produced by the various groups do not overlap.

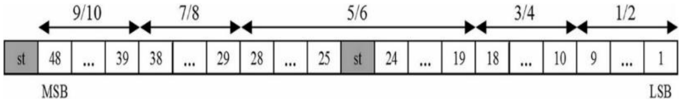


Figure 2. Logical group for unique IDs

Table 1. Channels available and group details

m	p	Number of groups g	Number of bits / groups
100	101	50	1
90	97	48	1
75	79	39	1 or 2
50	53	26	1 or 2
20	23	11	4 or 5
10	11	5	9 or 10
5	5*	2	24

Evaluation of performance

The rate r (selected by the SU) is the primary determinant of the CASR method and depends on the prime number p and the bits available in unique ID. With the restriction that the rates chosen by the two SUs should be distinct, the CASR method assures the rendezvous between two SUs during p time slots. Suppose it requires a particular interpretation for the LSB or MSB to prevent the rotation issue. In that case, we can guarantee the selection of various rates when the rates are selected based on the bits contained in MAC address within 48 iterations. The CASR method offers many interpretations for bits to construct various groups to optimize this interval. As a result, the chance of selecting various rates may be roughly divided into the following categories:

A. The SUs' associated ID bits vary (one SU utilizes a bit with a 1 value while the second SU employs a 0 value or vice versa).

B. SUs access many groups at once.

Theorem 1. The greatest amount of time needed for a rendezvous within an asynchronous environment is $2p \times glen$ whenever at least a one-bit delay exists between two SUs A and B.

Proof: The IDs of both SUs will vary by at least one bit since each SU has a distinct identification. Figure 3 presents some options for how the SUs may choose a rate. The shaded area shows the iteration when both SUs choose various r and rendezvous. The empty parts represent the bit position lag between the SUs. Figure 3a illustrates rate selection using two SUs whenever IDs vary in the LSB representing the first bit. The IDs that vary by exactly one bit have been selected as the worst-case situation. The groups created from the unique ID change depending on how many channels there are. For various channel availability levels, three situations are shown. For Figure 3a, a lag at 1 bit position is depicted in several scenarios. The instances where the IDs vary at the very last bit are shown in Figure 3b.

Case 1: $m = 10$, means that the second SU is in the 9th bit whenever one SU detects the 10th bit. Here, the ninth bit corresponds to group zero, whereas the tenth bit corresponds to group one, resulting in two distinct rates. Therefore, in the ninth iteration of the second SU, rendezvous may be guaranteed.

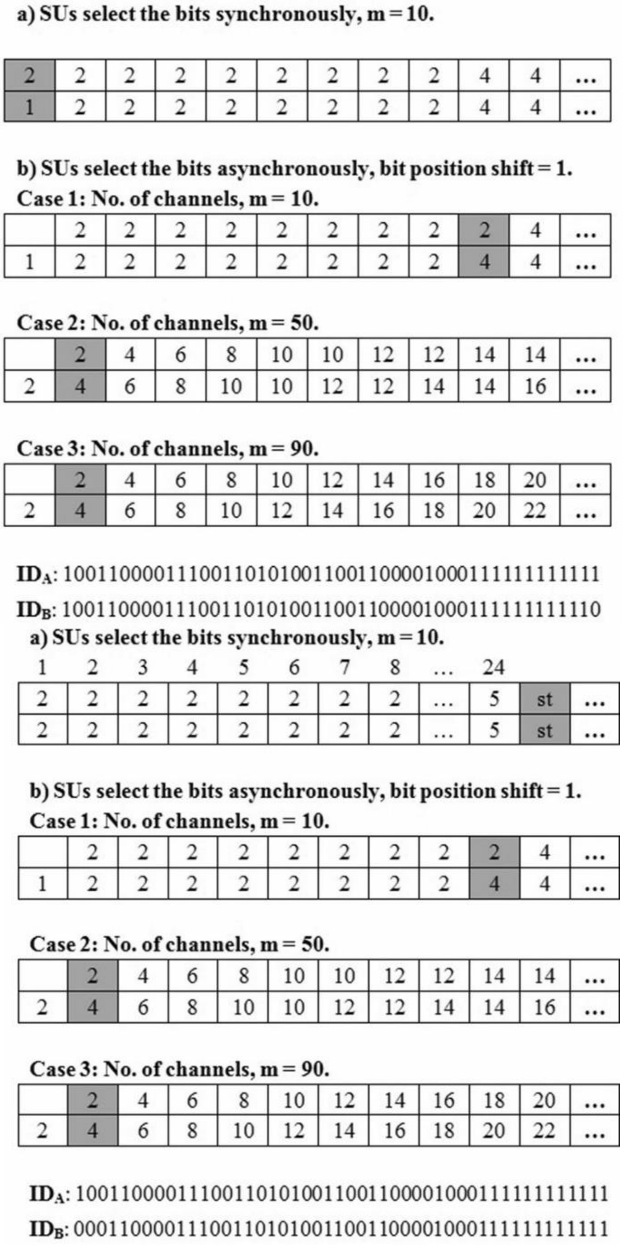
Case 2: $m = 50$, another SU will be included in the first bit whenever one SU detects the second bit. The first and second bits correspond to distinct groups, while the initial four groups only have one bit apiece, which causes rates to vary. Thus, the initial iteration of the rendezvous confirms it.

Case 3: $m = 90$, the initial SU will appear in the second bit whenever the second SU detects the first bit. Although each group only has one bit, the first and second bits correspond to distinct groups and produce various rates. Here, a rendezvous is guaranteed in the initial iteration. Similar to this, irrespective of the variance in ID bits, two SUs can guarantee selecting distinct rates across specific constrained iterations given by the group length provided there has been a minimum one-bit shift between the SUs.

Theorem 2. Since $2.05\,p$ is the ETTR's upper bound, rendezvous among the two SUs A and B often occurs almost immediately after the first repetition.

Proof: Rendezvous will probably occur whenever the SUs select various rates simultaneously, with at least p periods of overlap. For instance, according to the method, two groups exist when $m = 5$. The bit that the SUs use to produce the rate might come from one of the two groups. There are four possibilities when the SUs choose the bits from the two groups. The produced rates will change when the bit utilised by the SUs belongs to distinct groups. Therefore, there is a 50% chance that both will choose the same category. In addition, each group has two potential rates based on whether the bit is a 0 or a 1, yielding a potential combination of 2^2. As a result, picking the same rate inside a group has a probability of $\frac{2}{4} = \frac{1}{2}$, while picking the same rate overall has a probability of $k = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$. The SUs choose various rates with $1 - k\left(that\ is\ \frac{3}{4}\right)$ probability and meet up in $2p$ rendezvous. Similarly, the SUs will rendezvous within $4p$ time periods with the possibility of $\frac{1}{4} \times \frac{3}{4}$. Rendezvous is assured after 24 repetitions, and the likelihood that SUs cannot rendezvous will decrease. There are more groups as there are channels, increasing the likelihood that various rates will be selected. Consequently, the ETTR may be expressed as follows:

Here, the lowest prime number represented by p is greater than or equal to m, $g = (p-1)/2$, M is the upper limit on number of channels that may be created, and $k = g/(2 \times 2^g)$. This expression's ETTR is $\leq 2.05p$ after being evaluated up to the limit $M = 100$. The number of groups and the likelihood that the SUs will select at various rates rises along with the number of accessible channels. Therefore, a higher ETTR will be achieved by increasing the maximum number of channels.



a) SUs select the bits synchronously, m = 10.

2	2	2	2	2	2	2	2	2	4	4	…
1	2	2	2	2	2	2	2	2	4	4	…

b) SUs select the bits asynchronously, bit position shift = 1.

Case 1: No. of channels, m = 10.

	2	2	2	2	2	2	2	2	2	4	…
1	2	2	2	2	2	2	2	2	4	4	…

Case 2: No. of channels, m = 50.

	2	4	6	8	10	10	12	12	14	14	…
2	4	6	8	10	10	12	12	14	14	16	…

Case 3: No. of channels, m = 90.

	2	4	6	8	10	12	14	16	18	20	…
2	4	6	8	10	12	14	16	18	20	22	…

ID$_A$: 100110000111001101010011001100001000111111111111

ID$_B$: 100110000111001101010011001100001000111111111110

a) SUs select the bits synchronously, m = 10.

1	2	3	4	5	6	7	8	…	24		
2	2	2	2	2	2	2	2	…	5	st	…
2	2	2	2	2	2	2	2	…	5	st	…

b) SUs select the bits asynchronously, bit position shift = 1.

Case 1: No. of channels, m = 10.

	2	2	2	2	2	2	2	2	2	4	…
1	2	2	2	2	2	2	2	2	4	4	…

Case 2: No. of channels, m = 50.

	2	4	6	8	10	10	12	12	14	14	…
2	4	6	8	10	10	12	12	14	14	16	…

Case 3: No. of channels, m = 90.

	2	4	6	8	10	12	14	16	18	20	…
2	4	6	8	10	12	14	16	18	20	22	…

ID$_A$: 100110000111001101010011001100001000111111111111

ID$_B$: 000110000111001101010011001100001000111111111111

(a) Unique IDs of A and B differ in the first bit. (b) Unique IDs of A and B differ in the last (48th) bit

Figure 3. Multiple possibilities for the rate choosing for the two SUs

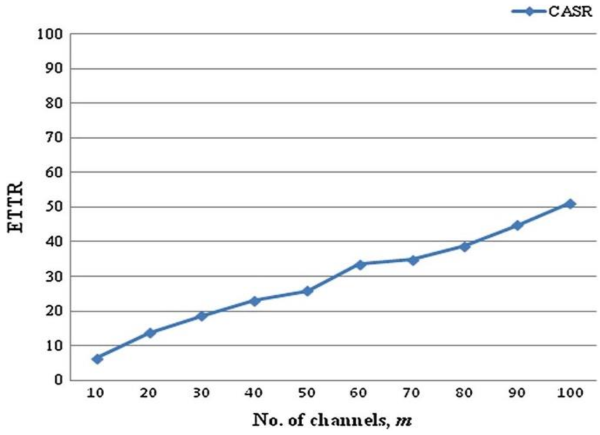
Theorem 3: Rendezvous is guaranteed throughout $50p$ time slots provided two SUs A and B simultaneously pick the bits and variation in associated IDs arises after the 24th bit.

Proof: The choice of distinct rates can't be guaranteed during the 24 iterations whenever the two SUs pick the bits simultaneously and the variations in the IDs appear only upon completion of 24 bits (shown in fig. 3a). A stay period is inserted after each n iterations, where n equals the length of the ID bit sequence divided by two, as indicated in Section 3.2. Therefore, $n = 48/2$ and the stay duration are included every 24 iterations when MAC addresses are utilized. In this instance, SUs choose the bits synchronously, and the IDs are identical until the 24th bit. This shows that the r values chosen from the SUs are constant through the 24th iteration. Thus, the prior values for r of the SUs are the identical as they approach the 25th iteration. Now, throughout the $2p$ time slots duration, both SUs are waiting on a channel chosen based on the prior values of r over the stay period. Both SUs remain at identical channels for the $2p$ time period length because their preceding r values are identical. As SUs remain on the identical channel over the $2p$ time slot duration, it assures SU rendezvous in iteration number 25th. There are two time slots for every iteration, so the MTTR equals $25 \times 2p = 50p$ time slots.

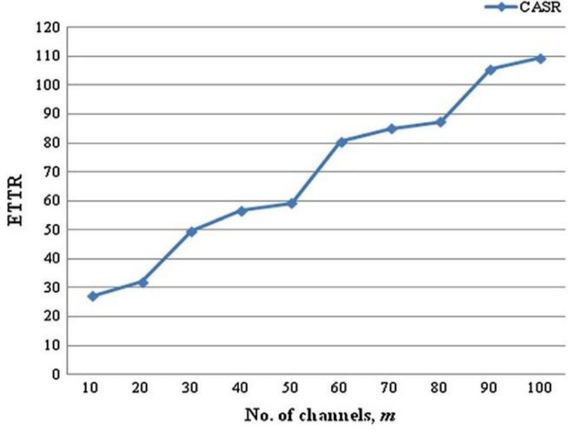
Simulations and Comparison Analysis

A comprehensive programming framework that can handle numerical computation and user interface aspects is necessary for rendezvous procedure simulation. C and Matlab programming are utilized as investigational tools to examine the efficiency of the CASR method. We used Matlab 7.11 to create the CASR method and run various simulation tests. Simulation scenarios are created by describing the CRN context in accordance with the presence of PUs and SUs and their network properties. This involves determining the fundamental characteristics, including the quantity of SUs and PUs, the SUs' observed accessible channels, and the nodes' transmission range. Pairwise rendezvous among SUs have been considered in the symmetric concept while simulations. As a result, throughout the rendezvous procedure, the observable channels of the two SUs are identical. The input parameters determine the number of SUs and PUs, while the geometrical positions of SUs were created at random. Several accessible channels and SUs' individual IDs are the main characteristics of the rendezvous process. The time delay t between the SUs also affects how outcomes will take place. SUs can utilize distinct bits (bits in various places) or be in various positions during the repetition of 2p time slots because of their asynchronous structure. All of these variables were considered throughout the simulations, and TTR is calculated for the execution of each rendezvous procedure. The consistency and stability of the CASR method are assessed using an essential parameter called ETTR. With the goal of getting the best value of ETTR, every simulation experiment is conducted and averaged for more than 1,000 separate runs.

The majority of simulation experiments fall into one of two groups. Rendezvous configurations are created entirely at random in the first scenario. The second scenario explicitly includes the worst-case scenarios while performing simulations. The CASR method performs significantly better than the theoretical results whenever method parameters are created at random. The average TTR for various values of m is shown in Figure 4a. The radio must scan additional channels as m increases, which causes the TTR to increase. Additionally, simulations are run with scenarios that are worst-case explicitly included to guarantee the effect of worst-case situations. The simulations' results are shown in Figure 4b. The combined outcome of these two situations (illustrated in Figures 4a and 4b) yields an average TTR of $0.95p$. Consequently, the outcome supports the theoretical result and represents a significant improvement in the value predicted theoretically.



(a) In random scenario



(b) In explicit scenario

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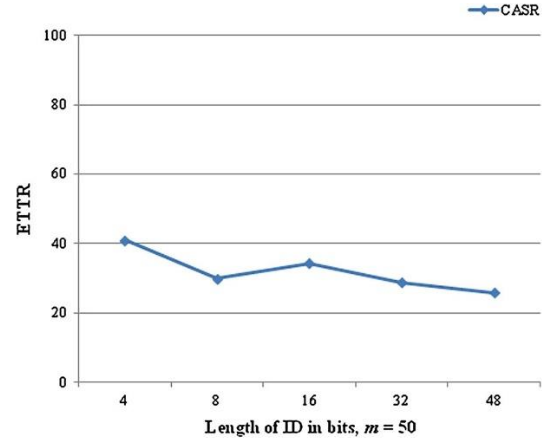


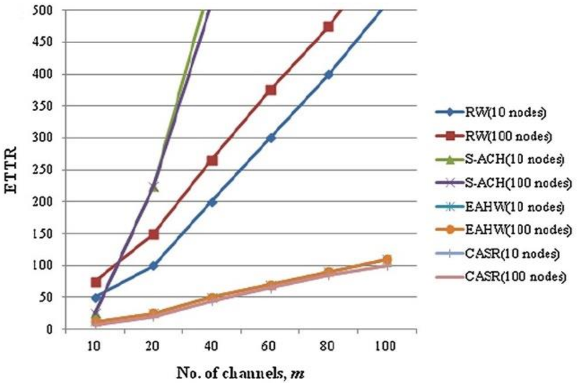
(c) Against different ID lengths (in bits).

Figure 4. Average TTR variation in various scenarios

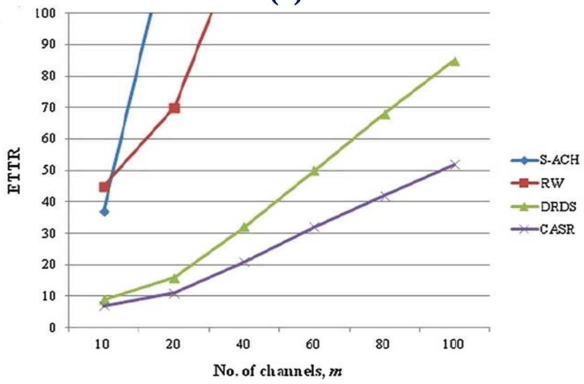
Additionally, different lengths of the unique ID are evaluated against the behavior of the CASR algorithm. The CASR method is simulated using unique IDs of various lengths to examine the effect of ID length on TTR. Figure 4c displays the change in ETTR across various unique ID lengths. M is assumed to have a value of 50. Figure 4c shows that ETTR does not drastically vary when the unique ID length increases. As the length of ID is 4, the CASR method displays a larger ETTR. This is because when ID length grows, a corresponding decrease in ETTR balances out an increase in MTTR.

We executed CASR technique and some advanced rendezvous techniques (i.e., DRDS (Gu et al., 2013), S-ACH (Bian and Park, 2013), EJS (Lin et al., 2013), JS (Liu et al., 2012), RW (Liu et al., 2010), E-AHW (Chuang et al., 2014) and AHW (Chuang et al., 2013) employing C programming and carried out multiple simulations in different contexts for further assess the effectiveness of CASR compared to the available rendezvous techniques. The efficiency of various rendezvous techniques in a comparable context is then evaluated and compared to the simulation results obtained by CASR. During the simulations, a symmetric approach, in which the accessible channels for the SUs are comparable, has been considered. We assume there are 100 SUs. All ID-based methods have a length of 48. The final ETTR is determined as an average of the 1000 runs of ETTR, every one of which is simulated for 1000 separate runs with variable numbers of channels available. Figure 5 presents the outcomes of the comparisons.

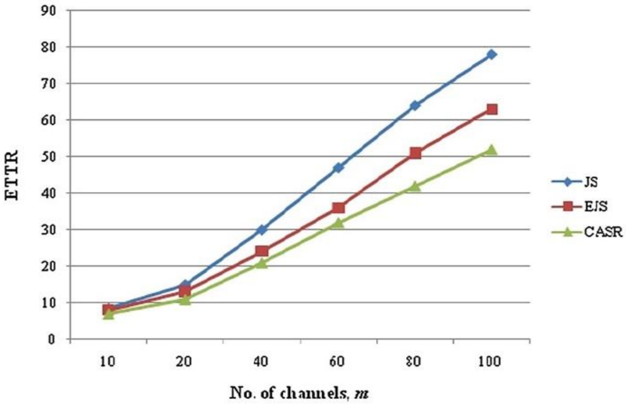
The efficiency is first examined through a rise in SUs (network size). A similar situation is run with 100 and 10 SUs, respectively. Figure 5a shows that while the network size has little or no impact on the ETTR of CASR and ETTR of E-AHW, it marginally raises the ETTR of S-ACH. This is because the CH sequence is generated using the global MAC address as a unique ID. However, RW uses SU's unique identity, which grows as more SUs are created. As a result, network size substantially impacts ETTR of RW. A different simulation is executed with the network's increased channel count. Figure 5b shows that the number of channels significantly influences the ETTR of all methods. The number of channels significantly affects RW and S-ACH because both methods rely significantly on it. For fewer channels, ETTRs of CASR and DRDS are equivalent. Yet, when the number of channels increases, CASR's accuracy improves. This is because the ETTR of CASR is significantly lower than that of DRDS. Therefore, CASR performs substantially better than the remaining techniques when more channels are available.



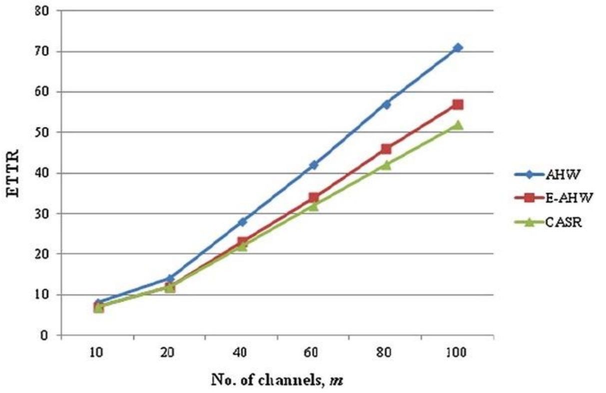
(a)



(b)



(c)



(d)

Figure 5 (a, b, c, and d). Comparison of Average TTR in the symmetric method

The effectiveness of CASR is compared with that of EJS and JS, two of the most well-known rendezvous techniques suggested for CRNs. Figure 5c presents the simulation outcomes. As demonstrated by the figure, the ETTRs of CASR, EJS, and JS are almost identical despite having fewer channels. Despite this, CASR outperforms JS and EJS with more channels since having more channels increases the likelihood that SUs would select different rates, improving the likelihood of a rendezvous. The increasing number of channels has an enormous effect on JS. Lastly, the outcome of the comparison between the ETTR of E-AHW and AHW ETTR of CASR is presented in Figure 5d. It is clear from the figure that CASR, E-AHW, and AHW have almost identical ETTR with fewer channels. However, CASR shows a significantly lower ETTR, particularly since the number of channels is more significant. This is additionally a result of the probability of a rendezvous rising with the number of channels. For example, the CASR, E-AHW, and AHW techniques have roughly identical ETTR whenever the counts of channels equals 20 or less. Still, in comparison to E-AHW and AHW, CASR has a lower ETTR if it equals 50 or more. Additionally, the ETTR and MTTR of E-AHW when utilizing the MAC address are 13P=6 and 147P, respectively, higher than the predicted values for CASR.

Conclusion and future work

The paper's primary goal is to realize pair-wise rendezvous among SUs in CRN using the symmetric concept. Using the ID-based rendezvous method CASR is recommended, which ensures SU rendezvous in a limited amount of time without the need for synchronization of time. The CASR method creates CH sequence using MAC address as unique ID. The set of free, accessible channels determines how unique ID is dynamically changed. The ID manipulations are connected to the CH sequence generation. The reduction of average TTR (ETTR) is the primary goal of the CASR method. The performance of the CASR method is theoretically predicted and empirically tested through simulated tests. Compared to the current rendezvous techniques, simulation outcomes show that the CASR method is more feasible and produces superior ETTR. The further development of CASR to incorporate both asymmetric and symmetric scenarios is one area of potential future research.

Conflict of Interest

The authors declare no conflict of interest.

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