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A MAC protocol with an improved connectivity for cognitive radio networks

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Abstract

This paper presents a medium access control protocol that is designed for wireless cognitive radio ad hoc networks (W-CRAHN). The cognitive radio network consists of a number of channels and a group of secondary users or subscribers. Each subscriber has access to a certain number of the available channels. The channels vary in their availability to the secondary users according to the activity of the primary users, so some channels are more common (can be accessed by a large number of subscribers) than other channels (accessed by less number of subscribers). Subscribers inside the cognitive network are connected in pairs, and each pair has a set of channels in common, so the pair can choose from a dedicated list known as the common channel list (CCL) to establish a communication link. A feature of this proposed protocol is the "random pairing algorithm" which enables each subscriber to connect to each subscriber inside the network. In this work, we show how the proposed method helps in adding more flexibility and providing more freedom to the subscribers of the network as compared of the other previously suggested methods. This results in a better quality of service offered by the network.

Keywords: MAC protocol, Cognitive radio, Ad hoc network, Connectivity, Common control channel

1 Introduction

Cognitive radio (CR) is considered as an intelligent technology and an important part of the next fifth generation wireless systems. It promises a great utilization of the radio spectrum, and it enables more subscribers to access the network and exchange data. CR is a communication system that has the ability to make self-decisions in order to connect its subscribers (secondary users (SUs)) to the network whenever there is a particular section of the spectrum that is unoccupied by primary users (PUs) and use it for data exchange. Also, it has to be capable of predicting whenever a PU is going to utilize the spectrum band, which means the SU should leave the spectrum band, for the purpose of not disturbing the PU. Alternatively, the CR must maintain a good quality of service (QoS) level for its users by finding other opportunities for them to continue their activities [1]. The SUs of the cognitive radio are named as such because they, unlike the PUs, do not have the right for

spectrum band access at any given time, since the PU paid for the right of accessing the band at any given time in the first place. Therefore, the SU gains access to the band if the PU is not occupying it, or when the PU itself allows the SU to share the band, given that the SU will not disturb the activity of the PU in any sort of way. Maintaining a good level of QoS varies in many factors, such as packet loss rate, delay, and power consumption, as applications differ in their requirements [2].

The cognitive radio network (CRN) environment is heterogeneous, as it contains both licensed and unlicensed bands that are located at different locations with various communication technologies. Both primary and secondary networks exist within the same spectrum space, where the primary network provides communication for PUs that have priority to access the spectrum at any time, while the secondary network provides communication to SUs, and they detect the spectrum holes in order to access the network and communicate with their desired destination without disturbing the PU [3].

CR users perform communication with each other either in a multi-hop manner or through the CR base

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station. Therefore, there are three different access types in CR networks:

1. CR network access: CR users access their own CR base station through using licensed and unlicensed spectrum bands.
2. CR ad hoc access: CR users connect with other CR users using ad hoc connection through licensed and unlicensed spectrum bands.
3. Primary network access: CR users grant access to the primary base station using the licensed band [4].

Another connection scheme that could be of interest is the mesh network, which is a hybrid of different networks that are combined together [5]. It is possible to consider the CRN and the primary network as a mesh type since they sometimes work with each other to provide service for their subscribers.

On the other hand, the importance of the medium access control (MAC) protocol has pushed the research community to submit many proposals of the protocol, all for the purpose of improving the performance of wireless networks as well as CR systems. MAC protocols are important in wireless ad hoc networks as they are responsible for addressing multiple node channel sharing issues [6]. Some works have developed methods and algorithms to improve the existing MAC protocols, such as the work in [7] that proposed a concept named “fair access” that can be applied for any MAC protocol, which helps to give the nodes of the network an equal rate of transmission. Two main approaches have been followed in the development of CR MAC protocol; the first approach is the standardization that eventually lead to the development of the IEEE 802.22 WRAN, where cognitive radio SUs connect with each other through a base station that coordinates the data traffic. Those SUs can participate through spectrum sensing and provide channel information to the base station [8]. The other approach is specific protocol scenario, where those protocols are optimized for a particular procedure to meet the goals desired. Such protocols do not depend on a centralized controller to manage the traffic and the scheduling of users, such as ad hoc networks.

In this paper, we focus on a specific aspect, which concerned about controlling the scheduling and organizing processes of SUs in W-CRAHN. When two users decide to communicate with each other, they need to exchange control messages for accomplishing tasks like the searching for a common channel available to both parties. Such a goal to be accomplished requires some sort of a controlling mechanism for enabling SUs of the ad hoc network to know the network topology [8]. The reason behind such a method is that the network does not possess a centralized hub for exchanging network

information and parameters between the users. The most straight forward solution is to provide what is called the common control channel (CCC). It is worth mentioning that CCC is also considered as a solution to a phenomenon that is known as the deafness problem, which is the inability of a node that has access to a particular channel within the network to sense signals and make communication activities on another channel [9].

The rest of the paper is organized as follows. Related work and previous studies of the MAC protocol and its classifications from the point view of the control channel is presented in the next section. Section 3 presents the proposed system model. The fourth section discusses the working methodology of the MAC protocol, followed by displaying the simulation results in the fifth section. Conclusion and summary are provided at the end of the paper.

2 Related work

Based on the existence and form of CCC, it is possible to categorize MAC protocols into three types, according to the authors in [10], which are the dedicated common control channel (D-CCC) type, the non-dedicated common control channel (ND-CCC) type, and the no common control channel (N-CCC) type, which is the one that we are interested in. D-CCC is a fixed control channel that is independent from the rest of the communication channels within the wireless ad hoc network. CCC is assumed to be available by default, so SUs inside cognitive radio ad hoc network (CRAHN) exchange their control information and get to know the network topology through the CCC. This type is simple and easy when it comes to the processes of network start up, node joining, and information exchange throughout the network. But there are drawbacks that affect the performance and the efficiency of the D-CCC MAC protocol, where it might get saturated by the increment of SUs within the network. It can also be considered as waste of resources and could cause security issues, such as the denial of service (DoS) attacks [11]. Examples of D-CCC MAC protocols are the dynamic open spectrum sharing (DOSS) MAC protocol in [12], hardware constraint (HC) MAC protocol in [13], and opportunistic spectrum (OS) MAC protocol in [14].

ND-CCC has the same concept of providing CCC to perform the information exchange process, but the difference lies in the fact that the channel itself is not a fixed one. Instead, it is established by selecting an available channel from the pool of the system. Another feature unique to ND-CCC is that it is possible to divide SUs of CRAHN into smaller clusters or groups and then assign CCC to each cluster. This can be seen in the proposed protocols that are of this specific type, such as efficient dynamic adjusting (EDA) MAC protocol [15], and C-MAC protocol [16], where the channels are

broken into super-frames that contain a beacon cycle and a data transmission cycle. However, since the control channel is still available after all, the same issues that may appear in the dedicated type can affect non-dedicated type as well, although on a smaller scale since SUs are divided into several groups instead of a big single cluster.

In N-CCC, instead of relying on a fixed channel to exchange the network information between SUs, synchronization is implemented between the nodes to exchange control signals, or using the channel hopping for that matter [10].

An example of N-CCC is the synchronized (SYN) MAC protocol, which was proposed in [17], it depends on the idea of establishing a bundle of time slots that equal the number of channels available in CRAHN, and the slots will be reiterated over time. Each time slot duration is fixed in the case of time division multiple access (TDMA) networks [18]. Concurrent access (CA) MAC protocol has been proposed in [10]. This protocol is comparable to the SYN MAC from the point of establishing time slots, which are commensurate to the channel number within the network.

3 System model

The proposed system model in this paper is a CRAHN which is composed of a number of SUs and a number of channels. The channels belong to a primary network, so CRAHN will grant its SU access depending on the status of the channel occupancy by PUs of the primary network. There are different methods for SUs to occupy the channel while considering the existence of PUs. In [19], the authors proposed a multichannel sharing CRN through frequency division of the channel and provide the slots or sub-channels to PUs of the network. Each PU charges the SUs of the CRN in return for gaining to access the interference range of the occupied sub-channel, and SUs in turn must limit their interference threshold in order not to disturb PUs. As a result, both PUs and SUs can coexist in the channel at the same time. For this work, we assume that our cognitive radio paradigm is the interweave type, where SUs cannot access the channel unless it is not occupied by a PU [20].

Our main objective is granting the subscribers of the network a better accessibility and more freedom to move inside the network, without performance degradation.

Our work is based on CA-MAC protocol that was proposed in [10]. This protocol is an N-CCC type, where it adopts the principle of split phase and utilizes the available channels in the network to perform two phases at a different time. The first one is to perform signaling task where SUs perform the control information exchange.

Control information exchange is necessary in ad hoc networks, since there is no base station that feeds subscribers with the required information about the network layout and topology. That is why signaling must be performed as early as possible to enable users to start transmitting data early as well.

CA-MAC protocol depends on a time slotting structure and arranges channels in a descending order that depends on how many SUs can access this channel. This means that the channel with the highest number of SUs with granted access to it will be associated with the initial time slot, and the next slot is associated with the next most common channel and so on down to the least common channel. The reason behind this method is to start the signaling as early as possible, since the majority of SUs can access this channel. Once they finish signaling at the first time slot, they move directly into the second time slot, where they can start data transmission phase using any channel available for them.

SUs are connected in pairs and in a successive order where the first SU connects with the second one, the third one with the fourth one, and so on. A pair must have at least one channel that is available to access for both of its SUs to perform signaling and data transmission.

The main purpose is to improve the performance of CRAHN. To achieve this, we proposed some design schemes that we believe it can enhance the operation.

Random pairing algorithm is a feature that improves system flexibility. It provides a real world scenario, by making SUs connect randomly with each other within the network. This provides the system with more freedom and gives a more realistic feel to the simulation. Figure 1 demonstrates the random pairing algorithm.

4 Operation of the protocol

Due to the absence of a main network hub in the ad hoc network, SUs must know the status of each other (such as the channel distribution for each SU and the geographical location) to start up the network and manage the communication process. This is why SUs need to perform the control phase as early as possible.

The split phase multichannel term means that time is split into two phases. The first one is called the signaling phase, which is concerned about exchanging control information between SUs to know the network topology and to manage their channel access. The second one is the data transmission phase, which is concerned about exchanging data between SUs. CA-MAC protocol is of the N-CCC type, so it depends on the available channels in the network to provide the ability to perform both the control phase and the data transmission phase.

Channel availability (CA) is the probability that decides if a certain channel is available to an individual SU to access after performing spectrum sensing. The value of

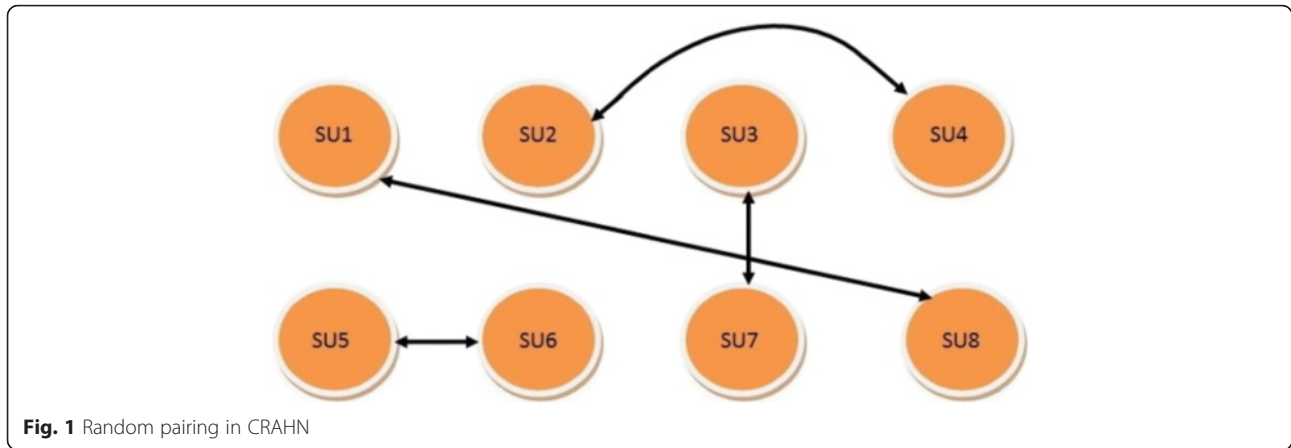


Fig. 1 Random pairing in CRAHN

the channel probability ranges from 0.1 up to 1.0. It cannot start from 0.0 because this means the network is completely offline. The value of CA determines the behavior of the network. This means that if the value of CA is small, few SUs have access to the channels inside the network, leading to a high average delay for the network, while for larger values of CA, the majority of the SUs have access, resulting in a small delay for the network. To reduce the complexity of the process, CA probability is assumed to be the same for all the channels and the SUs inside CRAHN. It is necessary to mention that at starting up of the CRAHN and prior to the beginning of the control phase, each two SUs inside the network have connected with each other in a random fashion to form a communication pair, and this pair has a number of channels to access.

At the start-up of the network, each SU will have a random value, which is considered as the SU probability to access a channel or not. This means that CA is a threshold that a SU must pass in order to gain access to the channel. The random variables that the SU possesses are compared with the channel availability, and then it is marked as “1” if the value is equal to or larger than CA (indicates that the SU can access the channel); otherwise, it is marked as “0” (the SU cannot access the channel). This bivalent parameter can be referred to as the channel access indicator $[\lambda_i^j]$, where j represents the channel counter and i represents the SU counter as seen in Eq. (1) [5].

$$\lambda_i^j = \begin{cases} 1 \\ 0 \end{cases} \quad (1)$$

CRAHN can be represented in a matrix that is called the network matrix (NM). The rows of the matrix represent the SUs, while the columns represent the channels of the network. NM is presented as a binary matrix, consisting of a combination of “1” and “0.” Observing NM yields some information regarding the accessibility of CRAHN, where a high SU number that has access means a high CA and a low activity for primary users.

An intermediate accessible SU number means that some channels are more common than others. A low number of accessible SUs result from a low CA and a high activity for primary users. NM structure is given in Eq. (2).

$$\begin{matrix} & \text{Chan}_1 & \text{Chan}_2 & \dots & \text{Chan}_C \\ \text{SU}_1 & \left(\begin{matrix} \lambda_1^1 & \lambda_1^2 & \dots & \lambda_1^C \\ \lambda_2^1 & \lambda_2^2 & \dots & \lambda_2^C \\ \lambda_3^1 & \lambda_3^2 & \dots & \lambda_3^C \\ \dots & \dots & \dots & \dots \\ \lambda_N^1 & \lambda_N^2 & \dots & \lambda_N^C \end{matrix} \right) & & & \end{matrix} \quad (2)$$

The next step is to prepare the channels for accessing. The summation of each column (representing the equivalent channel) in NM gives what is called the “weight” of the corresponding channel, where this process is done through adding all the SUs that can access that particular channel. The summation indicates the commonality of the channel which helps in sorting the channels to create a dedicated list called the sorted channel list (SCL). The channels inside the list are sorted in a descending order, with the first channel in the SCL being the most common, while the second most common takes the next slot in the list, and so on, with the least common channel taking the last slot in the list.

The channel order in SCL differs from the order that exists in NM. For example, a four-channel CRAHN exists, and the most common channel is channel no. 3, while the second most common one is channel no. 2, followed by channel no. 4 and channel no. 1, respectively. This means that SCL starts with channel no. 3 as the first time entry, followed by channel no. 2 and channel no. 4, and finally channel no. 1 is the last entry in SCL, since it is the least common channel in the network.

The channel access method applied here is TDMA-based, so the time slot number equals the channel number in the network. The reason behind this method of ordering is to give the SUs the chance to exchange the

necessary control data as early as possible during the signaling phase, since the majority of these SUs can access the first time slot, which is the most common channel. This leads to a high demand to gain access to the channel, while there is less demand to gain access to the channels that are less common during the signaling phase.

The following Eq. (3) demonstrates how the sorting is done in SCL in a descending order (k is a counter from 1 to C). The final form of SCL is given by Eq. (4) [5].

$$\sum_{j=1}^C \lambda_j^k \geq \sum_{j=1}^C \lambda_j^{k+1} \tag{3}$$

$$\begin{pmatrix} \text{Sorted_Ch_1} & \text{Sorted_Ch_2} & \dots & \text{Sorted_Ch_C} \\ \left(\sum_{j=1}^C \lambda_j^1 \right) & \left(\sum_{j=1}^C \lambda_j^2 \right) & \dots & \left(\sum_{j=1}^C \lambda_j^N \right) \end{pmatrix} \tag{4}$$

Pairing is the step where two SUs connect together as a transmitter and a receiver to exchange data. There is a set of channels that are considered common between the two connected SUs, and the organization of these channels can establish the common channel list (CCL), which contains the available channels between the transmitting SU and the receiving SU.

Forming CCL is done by taking the paired SUs and comparing each one's set of channels. The channels are recorded and sorted. Finally, they are extracted into a new list that is CCL of that particular pair, which will use the channels that are available to exchange data, under the condition that they are available to use.

The comparison is made based on comparing the access status for each SU for all channels inside the network, where the channels that are accessed by both SUs are recorded. The sorting is quite the opposite of that of SCL, where the channels in CCL are sorted starting with the least common channel of the set as the first entry and ending with the most common one.

For data communication, the pair chooses the first entry in its CCL, which happens to be the least common channel among the available set of channels. The reason behind favoring the least common channel in the set is to help the pair to exchange data as quickly as possible. This is because a less common channel is probably to face less competition from SUs when they intend to get access to it, thus leaving a higher chance for the pair to use that channel for transmitting and receiving data, after completing the signaling phase.

In the original CA-MAC protocol, pairs are connected in a successive order with their adjacent ones, where SU

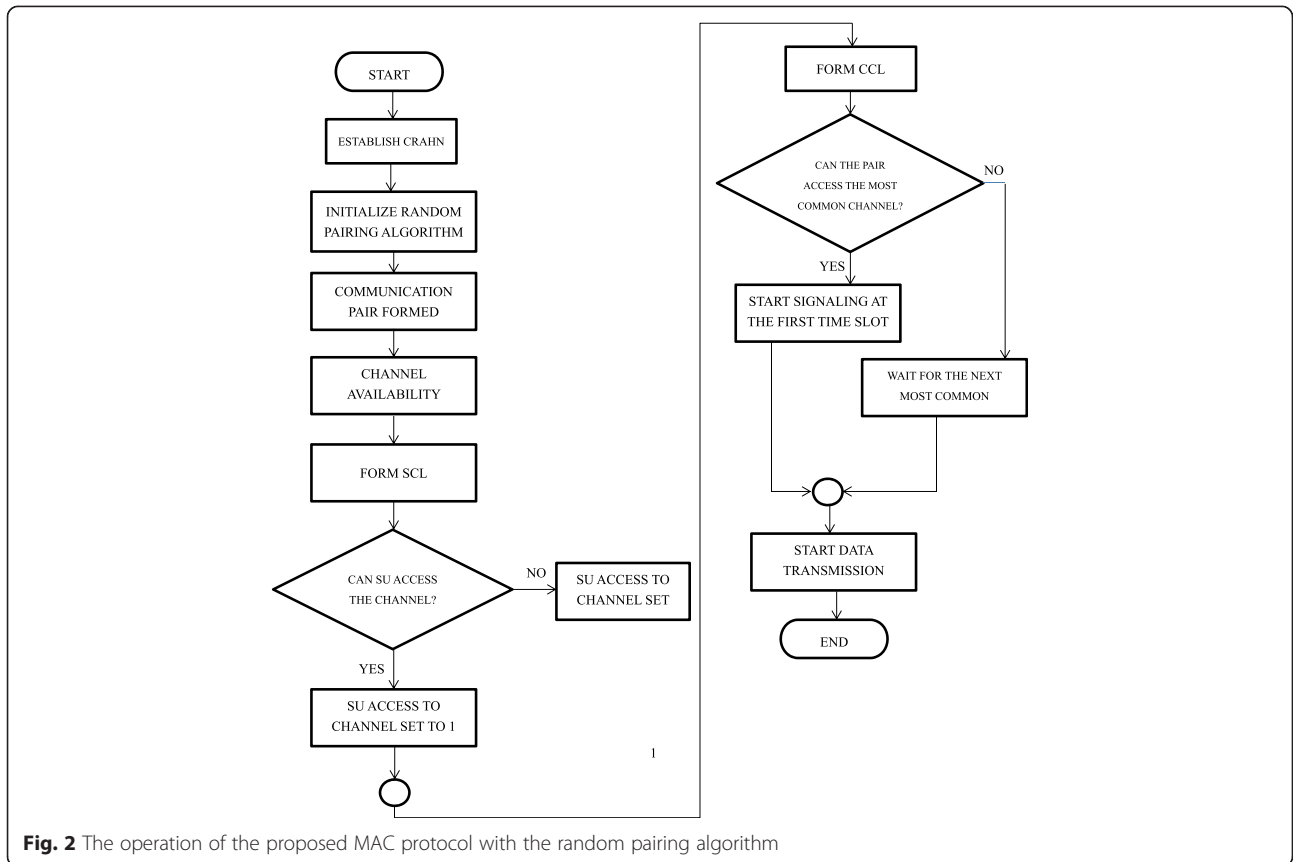


Fig. 2 The operation of the proposed MAC protocol with the random pairing algorithm

Table 1 Network matrix

SU	Chan			
	Ch 1	Ch 2	Ch 3	Ch 4
SU 1	0	1	0	1
SU 2	1	1	1	1
SU 3	1	0	1	1
SU 4	1	1	1	1
SU 5	1	1	1	1
SU 6	1	0	0	1
SU 7	1	1	1	1
SU 8	1	1	1	1

1 connects with SU 2, SU 3 connects with SU 4, and so on, as in Eq. (5).

$$\begin{matrix} \text{Pair-Tx} : \\ \text{Pair-Rx} : \end{matrix} \begin{pmatrix} \text{Ch}_1 & \text{Ch}_2 & \dots & \text{Ch}_C \\ \lambda_{\text{Tx}}^1 & \lambda_{\text{Tx}}^2 & \dots & \lambda_{\text{Tx}}^C \\ \lambda_{\text{Rx}}^1 & \lambda_{\text{Rx}}^2 & \dots & \lambda_{\text{Rx}}^C \end{pmatrix} \tag{5}$$

After the communication pair has been formed, it is time to compare the channel set of each SU. The comparison is done by choosing the column that contains 1's only, because the column represents the channel, and an all 1's column means that both SUs can access that channel. The channels that are in common (can be accessed by both SUs of the pair) are extracted.

The extracted channels are sorted into a vector in Eq. (6) with an ascending order based on the sorting in SCL. Common channel 1 is the least common one among the available channels in the set, while common channel C is the most common one.

$$\text{CCL} : [\text{Com Ch 1 Com Ch 2 ... Com Ch C}] \tag{6}$$

Signaling phase is the first step in initializing the communication, where the connected SUs start to access the most common channel available in their CCL. The channels that have been sorted in SCL are synchronized with time slots, where time slot no. 1 is given for the most common channel. The number of time slots is similar to the number of channels in CRAHN. The advantage of making common channels the first to be accessed is to give the utmost number of SUs the chance to access the network and start exchanging the control data as early as possible.

Table 2 Sorted channel list

Channel sort	Sorted Ch 1	Sorted Ch 2	Sorted Ch 3	Sorted Ch 4
Ch ID	4	1	2	3
Weight	8	7	6	6

Table 3 CCL of the communication pairs

Pair order	SUs of the pair	CCL of the pair			
		Ch 3	Ch 2	Ch 1	Ch 4
1	SU 2 SU 4	Ch 3	Ch 2	Ch 1	Ch 4
2	SU 6 SU 3	Ch 1	Ch 4		
3	SU 5 SU 7	Ch 3	Ch 2	Ch 1	Ch 4
4	SU 1 SU 8	Ch 2	Ch 4		

Data transmission phase starts right after a communication pair finishes its signaling phase, where it becomes ready to reserve a channel to be used for exchanging data between its transmitter and its receiver. The communication pairs start transmitting data using the reserved channels the moment they are ready for the process, and it can be observed that the association between channels and time slots do not apply in this phase.

In this phase, channels are not accessed based on their sorting and their association with time slots, which is the case in the signaling phase. For example, channel 1 is the most common channel in CRAHN, and we have two pairs that have access to this channel. Pair 2 can access channel 3 as well, while pair 1 can only access channel 1. So during the signaling phase, both pairs start their signaling phase via channel 1, because the majority of pairs can access it so they can exchange their control information using this channel. At the start of time slot 2, pair 1 and pair 3 are ready to access; pair 3 occupies channel 3, since it is available and is the first entry in CCL. Pair 1 on the other hand occupies channel 1 because it is the only available channel in its CCL. So, at data transmission phase, channels' sorting is not required, because all channels are needed for starting data transmission.

The system average access delay can be computed using the following eq. (7):

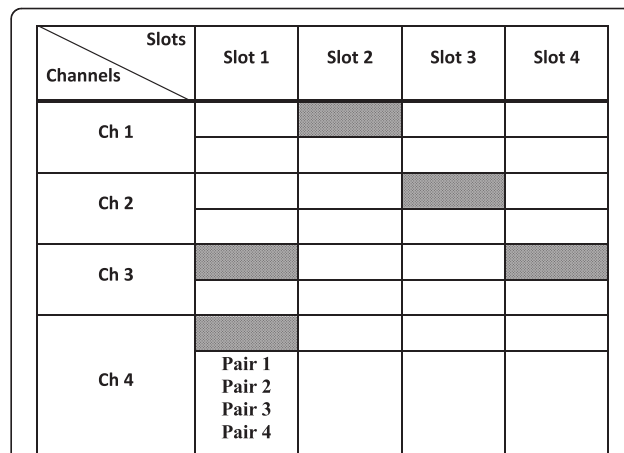


Fig. 3 Signaling phase of CRAHN

Channels \ Slots	Slot 1	Slot 2	Slot 3	Slot 4
Ch 1		Pair 2 starts data transmission		
Ch 2		Pair 3 starts data transmission		
Ch 3		Pair 1 starts data transmission		
Ch 4		Pair 4 starts data transmission		

Fig. 4 Data transmission phase of CRAHN

$$D_{avg} = \frac{1}{N_t} * \sum_t (N/2 - |R_t|) \tag{7}$$

N_t is the total number of pairs in the network, while R_t is the number of channels being occupied in each time slot. $N/2$ is the number of pairs inside CRAHN. In other words, it is a value that represents the variation between the total number of channels in the network and the number of empty channels in each time slot [5].

R_t is calculated through data transmission phase, where it is possible to know the number of channels being occupied by the communication pairs. To calculate the network system throughput, we define $[Th(t)]$ which is throughput at time slot t [5]:

$$Th(t) = |R_t| * \frac{\text{total Packets}}{\text{Slot duration}} \tag{8}$$

The total packets and the slot duration can be both defined depending on the capabilities of the network

intended to be used for CRAHN. The total throughput of the network can be acquired by Eq. (9) as follows [10]:

$$Th_s = \sum_t Th(t) \tag{9}$$

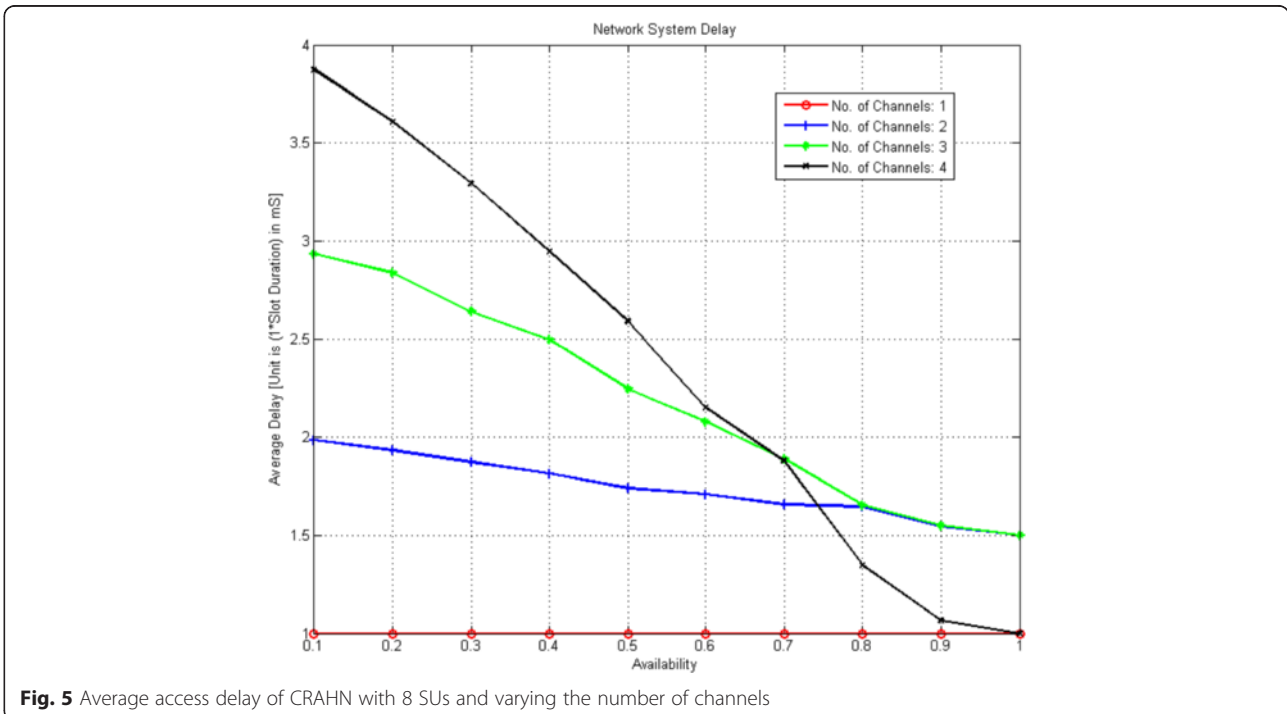
Our developed random pairing algorithm allows SUs inside the network to connect with other SUs even if they are not adjacent. For example, instead of SU 1 connecting with SU 2, SU 3 with SU 4, SU 1 can connect with SU 2, SU 3, or SU 4. The flowchart in Fig. 2 illustrates the operation of the protocol.

5 Simulation results

We used MATLAB as a simulation environment to establish a CRAHN that consists of 8 SUs and 4 channels. CA value is 0.7, while the slot duration is 10 ms and the number of packets is assumed to be 200. Monte Carlo simulation method was used to calculate network average delay and throughput.

The following tables provide the necessary information of the network structure and its configuration. Table 1 represents NM of CRAHN where the columns represent the channels, while Table 2 gives the summation of these columns and their sorting in a descendent order to acquire SCL.

As the random pairing algorithm enables SUs of the network to choose their desired partners to exchange their data with, we can see the arrangement of the



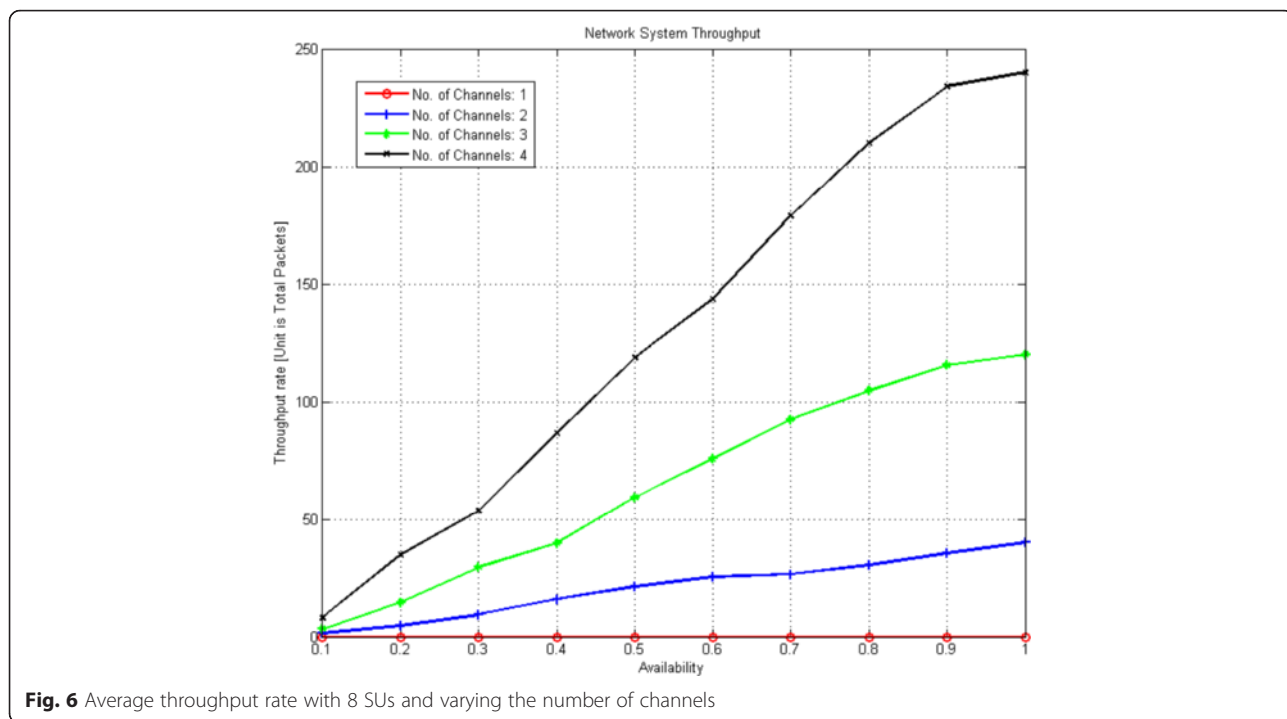


Fig. 6 Average throughput rate with 8 SUs and varying the number of channels

communication pairs and their CCL in Table 3 which contains the channels that are in common between the SUs of the pair.

The following figures represent the signaling phase and the data transmission phase, respectively. In Fig. 3, we see that all pairs start exchanging control information during the first time slot, since all of them have access to channel 4, the most common channel in the network.

In Fig. 4, all pairs start transmitting data at the second time slot, where each pair occupy the first channel entry in its CCL. Pairs 1 and 2 have similar entries in their CCL, and pair 1 manages to secure channel 4 for data transmission. This forces pair 4 to look at the second entry in its

CCL since the first entry is occupied by pair 3, and thus, channel 1 will be used by pair 4 to exchange data.

The next pair of figures demonstrates the analysis of the network’s performance. Starting with Fig. 5, it presents the average delay of CRAHN with varying the number of channels. If CA is small, the average delay is high, and it is higher when the number of channels increases. But as CA increases, the average delay starts to drop, and it decays quicker when the number of channels inside CRAHN increases. The system does not work with a single channel since the protocol is a split phase type, so the minimum number of channels required is 2.

Figure 6 gives the throughput rate of CRAHN, again with 8 SUs and varying the number of channels from 1

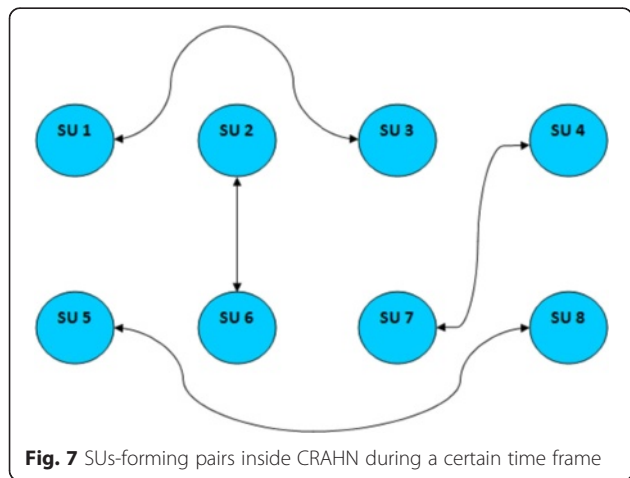


Fig. 7 SUs-forming pairs inside CRAHN during a certain time frame

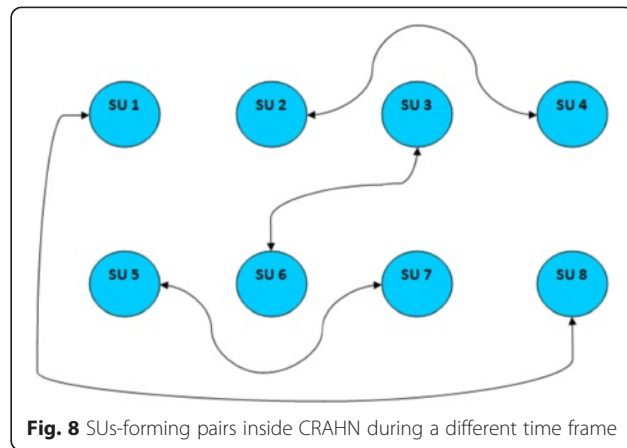


Fig. 8 SUs-forming pairs inside CRAHN during a different time frame

up to 4. We see that throughput starts at a very low rate when CA is low, but it rises quickly as CA increases, and if the number of channels is larger, the rate increases rapidly.

Figure 7 shows how SUs are connected as pairs inside the network, which occurred during a certain time frame.

Figure 8 demonstrates a different time frame where each SU has paired with a different subscriber, and this was made possible due to applying the random pairing algorithm.

We were able to match the performance of the original CA-MAC protocol that was proposed in [10] while enabling any two SUs within CRN to establish connection through applying the random pairing algorithm, thus giving the system a more dynamic behavior that is closer to a real world network design. In addition to the benefits of the random pairing algorithm of making the network more dynamic, it did not add overhead processing when initializing the signaling phase, as it is processed in earlier stages, thus leaving the signaling phase and the data transmission phase to be performed directly without additional interruptions.

6 Conclusions

In this paper, we proposed a MAC protocol with enhanced user connectivity in wireless cognitive radio ad hoc networks, where we developed an algorithm that provides the subscribers of the network with a better access. The results of the simulation showed that the algorithm offered a more flexible pairing process without affecting the overall performance of the system. The network exhibits a noticeable enhancement in performance when CA value is high, but the performance is also adequate when CA is between (0.5) and (0.7), which represents a good compromise.

Competing interests

The authors declare that they have no competing interests.

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