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Cooperative and fair MAC protocols for cognitive radio ad-hoc networks

Aghus Sofwan[1] · **Salman A. AlQahtani**[1]

Abstract A secondary user (SU) in multichannel cognitive radio ad hoc network (CRAHN) has a limited transmission range, which may raise a hidden multichannel sensing problem. In addition, CRAHNs can be deployed ubiquitously, and SUs from any CRAHNs could co-exist utilizing the spectrum. This situation leads to the fairness issue of spectrum resource sharing between the SUs. Both cooperative and fairness issues are important to CRAHN performance. In this paper, a cooperative and a non-cooperative multichannel (MC)-MAC protocol is proposed. In order to address the fairness issue, a fair multichannel (FMC)-MAC protocol for CRAHN is proposed, which orientates to the fairness in resource sharing. In this FMC-MAC, the SU keeps the current backoff (CB) counter when a PU appears to claim the intended channel. These proposed MAC protocols are simulated using NS2 and compared with other protocols. In addition, a mathematical model using Markov chain is constructed for FMC-MAC and the performance measures are derived. From results, the MC-MAC protocol has enhanced the network utilization and the cooperative scheme has significantly enhanced the packet delivery ratio and decreased the end-to-end delay of SUs in high traffic. The cooperative protocol enhances packet delivery ratio up to 15 % and decreases end-to-end delay down to 32 %, compared to the non-cooperative one. The FMC-MAC protocol with other two existing protocols. From the comparison results, a higher fairness has been shown by FMC-MAC CB while still maintaining a high throughput.

Keywords Cognitive radio ad hoc network · Multichannel MAC · Cooperative MAC protocol · Fairness

1 Introduction

The dramatic increase of wireless communication technology causes the demand for the spectrum usage to extremely grow high. Hence, the frequency spectrum becomes a limited resource. There is a situation in which some radio frequency spectrums appear to be fully utilized by the users, meanwhile, the other spectrums appear to be under-utilized [3]. According to the report of the Federal Communication Commission (FCC), experiments show more than 80 % of the spectrums are unused at a given time and geographic variations [4]. The report exhibits inefficiency of the resource allocation usage rather than scarcity of the spectrum resource. It indicates the current static allocation of the frequency spectrum does not handle spectrum utilization efficiently. Furthermore, this observation has led to a new paradigm in utilization of the frequency spectrum. A cognitive radio (CR) is considered as a technology innovation in enhancement of spectrum efficiency, by sharing the spectrum between users [5, 6]. It enables a secondary user (SU) to use the frequency spectrum opportunistically when a primary user (PU) that has a frequency legacy does not utilize it. Therefore, the cognitive radio network (CRN) is expected to become a universal platform for the wireless network development. In which, the platform can define a limited identity disclosure for user detection purpose, i.e., identity of the user. Furthermore, an SU easily enables to identify not only the PU but also other SUs from different network.

The non-infrastructure based networks, e.g., cognitive radio ad hoc network (CRAHN), is independent on any

✉ Salman A. AlQahtani
salmanq@ksu.edu.sa

[1] Department of Computer Engineering, College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia

infrastructure backbone. The CRAHN brings a novel paradigm in designing of medium access control (MAC) protocol. The SU of the CR network does not only deliberate spectrum sharing with other SUs, but also consider the detection and protection of the PU [7]. There are several issues of MAC layer that can be addressed in devising MAC protocol [8], such as control channel design, spectrum sensing policy, cooperative spectrum sensing, and multichannel problem. These MAC layer issues are to be considered when MAC protocol for the CRAHN is designed. In this paper, we considered these aspects when we designed the proposed MAC protocol for CRAHN. By exploiting a multichannel communication, we can achieve a higher network throughput than by using one channel [9]. Utilization of multichannel in the traditional wireless ad hoc network can significantly enhance the total throughput, since transmission can be performed on different channel in parallel while avoiding interferences and collisions. We adapt the multichannel communication scheme explained in [9] into CRAHN paradigm, and then we apply it in our proposed protocol for non-cooperative SUs scheme.

The most essential issue of CR paradigm is SUs' activities must not interfere with the PUs that has the licensed channels [10]. In the CRAHN, the protocol must focus not just to avoid collision between nodes, but also which is the most important, to prevent the SU interfere with the PU. Therefore, an efficient multichannel MAC (MC-MAC) protocol is considered to address a hidden PU problem in CRAHN. Moreover, the CRAHNs can be deployed ubiquitously, and the SUs of any CRAHN could co-exist with each other in utilization of the frequency spectrum in any CRAHN coverage. Most of the proposed medium access control (MAC) protocols for CRAHN that are available to date consider the two-state model in detecting the channel utilization by the PU, which are busy and idle. If an SU detects a particular channel is busy, then it defines the channel is being occupied by the PU, even though the channel has been used by another SU from different CRAHNs. If the node that occupies the channel that turns out is not a PU, the SU loses a chance to compete in utilizing the channel. This situation suffers from fairness, because the coexisting SU will keep using the channel for a longer time. And the other SUs have a problem to obtain the channel equitably. Therefore, the fairness policy is considered in this paper by proposing a novel protocol for CRAHN to provide a balance utilization of multichannel resources between SUs from different CRAHNs based on their network origins.

The main contributions of this paper are as follows. First, we proposed a MC-MAC protocol for CRAHN. This protocol is an adaptation of the multichannel communication scheme used in the traditional ad hoc network in M-MAC protocol as described by So and Vaidya [9] into CR platform. In the conventional multichannel ad hoc network, the MAC protocol focuses primarily only on a mechanism to avoid possible data collision between neighbor nodes. Hence protocol proposed by So and Vaidya [9] did not consider sensing activity of PU presence. In our proposed protocol for CRAHN, the sensing PU presence is applied. Further, in order to prevent the SU from interfering with the PU, it is important to provide a reliable PU sensing. The SUs in a neighborhood make collaboration to acquire the hidden PU presence. A proactive reporting by SU in transmitting the detection of the PU presence result to neighbor SUs is introduced. Whenever an SU hears a PU appearance, it immediately informs to all SUs in the neighborhood. We apply this proactive SU idea into the proposed MC-MAC protocol and we call this version as cooperative MC-MAC protocol. Therefore, we will have two versions of MC-MAC known as cooperative and non-cooperative MC-MAC. Second, in order to address the fairness issue, a fair multichannel MAC protocol for CRAHN is developed which orientates to the fairness in resource sharing. The three-state channel detection model from SU's point of view, into the FMC MAC protocol is applied. An SU of any CRAHN, which has been lowest in the channel utilization, has a possibility to increase its channel occupancy. Since the SU has been in unfairness experience, it has an opportunity in compensation for channel utilization [11]. A mathematical model using Markov chain is developed for FMC-MAC in which the SU keeps the current backoff (CB) counter when a PU appears to claim the intended channel.

The remainder of this paper is organized as follows. In Sect. 2, the related works are presented. In Sect. 3, we discuss the system model and description. In Sect. 4, we explain the proposed MC-MAC protocols with non-cooperative, cooperative and fairness features. In Sect. 5, the mathematical model of the FMC-MAC protocols is developed and analyzed. Section 6 discusses the analytical and simulation results of the proposed protocols. Finally, concluding remarks are presented in Sect. 7.

2 Related works

Extensive and challenging studies have been conducted for the CR technology in the last decade, including in the MAC protocol of this field. A number of protocols have been proposed in the literature. As mentioned earlier, in the multichannel networks, the frequency spectrum can be divided into a common control channel and several data channels. All control messages are exchanged on the control channel. It is very difficult to avoid this multichannel hidden problem if only using the IEEE 802.11 with Distributed Coordination Function (DCF) mechanism. To solve this problem, there is a mechanism using the ad hoc traffic indication message (ATIM) windows as in the IEEE 802.11 power saving mode (PSM), as was proposed by So and Vaidya [9]. The protocol synchronizes the communication using periodical beacon interval, which consists of ATIM and data windows. At beginning of each beacon interval, each node listens on the control channel to negotiate channels for channel reservation in ATIM windows. After the ATIM window, nodes switch to their agreed reserved channels and exchange message during at the data window. A similar mechanism is also applied for CRN with distributed control, as proposed in multichannel MAC protocol for CR (MMAC-CR) [12]. Implementing this ATIM window scheme potentially yields a longer delay. During this window duration, although an SU already has a right to use the channel, it is still prohibited to send data through a channel. The node has to wait for the data window part for sending data.

Furthermore, if the SU detects the PU presence during channel utilization, then the SU usually coordinates with others using common control channel to exchange control message [13]. MAC protocol with dedicated common control channel has been proposed by many authors which are not applied for CRN [14, 15]. Recently, CH-MAC protocol that designed to work in multichannel dynamic spectrum access networks was also proposed using a common control channel [16]. Other protocols only apply the both sender SU and receiver SU in handling the hidden PU problem, without neighbor participation, which the PU sensing solely obtained from the both SUs [14–16]. A cooperative mechanism can be performed by exchanging a status report between SUs in a neighborhood. A collaborative reporting of PU appearance is very significant in CRAHN. Given that an SU can't perceive all neighbor PUs, reports are needed exchanging between SUs to prevent the hidden PU node problem detecting.

A multichannel MAC protocol for the CRAHN, called CR-MAC was proposed by Kamruzzaman [17]. The protocol integrates spectrum sensing at the physical layer and packet scheduling at the MAC layer. The CR-MAC protocol applies the ON–OFF model for stating PU's channel utilization. It considers two-state sensing, which denotes the PU's presence and absence in a channel. Both states only define the PU's occupancy on the channel. A cross-layer based opportunistic cognitive radio multichannel MAC (OCM-MAC) protocol for a distributed network, which does not need any centralized controllers was proposed by Hang and Xi [18]. The OCM-MAC protocol allows SUs to sense and use the available frequency channel without influencing the PUs. The OCM-MAC uses the two-state (ON–OFF) model for PU channel utilization. A cross medium layer MAC (LM-MAC) protocol to provide an efficient link maintenance in cognitive radio ad hoc network was proposed by Li et al. [19]. The protocol uses ON and OFF to denote the PU's active and inactive state on the licensed band scheme. Other authors proposed an opportunistic spectrum access MAC protocol for single channel and multichannel CRNs [2]. The protocol also considers a two-state model of the PUs' behavior, which follows ON (busy) and OFF (idle). The two-state model only considers the channel is occupied by a node. It can't distinguish the node is either a PU or an SU.

A multichannel MAC protocol called the opportunistic spectrum access with backup channel (SWITCH) for CRAHN was proposed by Kalil et al. [20]. The protocol is a decentralized, asynchronous, and contention based MAC protocol. It employs a backup channel feature to make the SU extremely robust to the appearance of PUs. Other authors proposed a decentralized predictive MAC protocol for CRAHNs [21]. The protocol is a multichannel and synchronization-based multi-transceiver MAC protocol. It divines the presence of the PU using historical prediction and protects the PU from the interference of SUs. A concurrent access MAC (CA-MAC) protocol for CRAHNs without a common control channel was proposed by Timalsina [22]. The protocol has the ability to perform parallel transmission on multiple channels. Recently a MAC protocol based on carrier sense multiple access/collision avoidance (CSMA/CA) with mobility support for CRAHN [23]. However, all these proposed protocols do not consider the coexistence of an SU from different CRAHNs, so there is not a treatment for fairness [20–23]. Furthermore, each SU does not record all activities of the nodes in its neighborhood. Accordingly, there is no possibility at all for an SU to participate in the maintenance of a high fairness.

The fairness policy was considered for various types of resources in literature [1, 24–26]. An underlay cognitive radio system in which the SUs can use the same spectrum of the PUs was explored [24]. They use Jain's index to measure the fairness of the SU based on SINR during channel assignment in CRN. A system fairness based on the minimum sensing performance between the sub-bands of the wideband spectrum for centralized CRN was proposed by Liu et al. [25]. Other authors evaluated the fairness of secondary network coexistence scheme [26]. The scheme considered an SU as a coordinator of the secondary network. The coordinator has a role to achieve the fairness of its network. The fairness was considered in designing the fairness-oriented MAC protocol (FMAC) for centralized CRN by Yanxiao [1]. The authors consider the three-state sensing model to distinguish whether the occupied channel is utilized by a PU or another SU. The protocol performs a renewal process in which it always renews all SUs' backoff time counters, whenever a PU comes back to use the channel.

In contrast to all previous works, the proposed protocols considered the multichannel scenario and take into considerations the cooperative and fairness issues. The cooperative MC-MAC protocol is developed to address a hidden PU problem in CRAHN, which consider the neighbor participation. Also, the fair multichannel (FMC) MAC protocol with the aim of achieving fairness among co-existing SUs from multiple CRAHNs is developed. The FMC-MAC considers the three-state detection model to distinguish PUs and co-existing SU presences.

3 System model and descriptions

In this section, we present in detail the models and assumptions that are used in designing proposed MC-MAC and FMC-MAC protocols. We consider the network environments with CRAHN operation. The networks can have two types of users: PUs and SUs. We assume that PUs are stationary, while SUs are moving at the low speed. Each PU possesses an exclusive right to use the licensed channels. The SUs can be around or inside the PU range, as shown in Fig. 1. PU coverages are drawn with a solid circle. SUs originate from C different CRAHNs. Each SU hears all packets that run through its neighborhood. It records the packet traffic for the latest Δ time into a table as its history. Δ denotes the duration time of SU records the packets, where t_{curr} and t_{pre} represent the current time and the previous time of recording, respectively. The SU picks information from the packet such as: node id, the origin CRAHN id, and the user type of the sender. Therefore, an SU can perceive the number of packets from each node that traverses around for a duration time of Δ, as shown in Fig. 1. The SU always shifts the recording to the current time, so that it keeps the size of Table in small size. Later, it uses this history as knowledge in applying a fairness policy for channel utilization. i.e., SUs collect the traversed packet information from neighbors at the latest Δ time as the knowledge.

The system model considers two types of channels, which are a common control channel and several data channels (DC). SUs use the control channel to negotiate a channel, to perform synchronization, and to report PU appearance in a channel to others SUs. We assume that this channel operates in ISM spectrum (e.g., a channel of wireless local area network) as a dedicated channel. It gives a reliable control message exchange between SUs for exploiting the available and free of PU appearance impact channels. When the CRAHN is established, the protocol scans channels of ISM spectrum and then chooses one of the vacant channels as the common control channel for the ad hoc network. Meanwhile, the SU uses DC to transmit data to the intended SU. The DCs are the licensed channels belong to PU. The channels are non-overlapping so the packets transmitted on different DC do not interfere with each other.

Each SU at initialization is equipped with two half-duplex transceivers. This transceiver only performs one

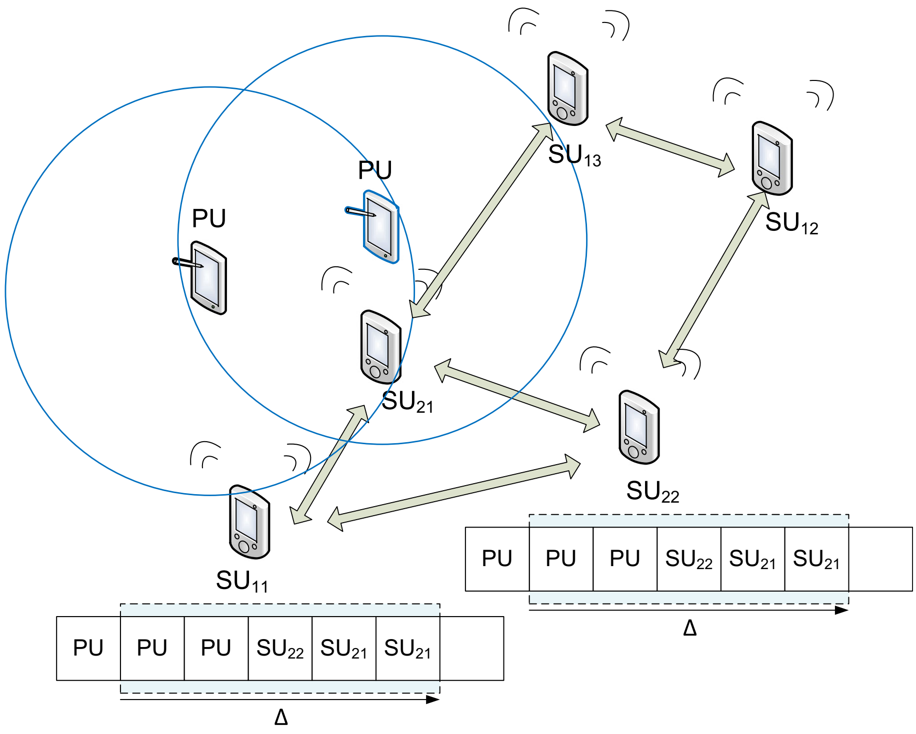


Fig. 1 Illustration of system model with the PU coverages and SUs

activity, either transmitting or receiving data at one time. The first transceiver has the function as the fixed interface to accommodate channel access transaction, broadcasting control messages, and cooperative among SUs through common control channel. This transceiver listens constantly to the control channel. Thus, it provides a reliable transaction for exchanging control mechanism between SUs. The second transceiver operates as a switchable interface to handle transmitting data on data channels. When an SU is ready to send data, it tunes this interface to a channel for data transmission that agreed with the intended SU.

The SUs apply a channel reservation (CHR) at the beginning of a beacon interval. A channel reservation is performed by SUs before applying data transmission. To accommodate the distributed coordination among SUs in reserving and accessing the channels, the proposed protocol adapts the CSMA/CA mechanism of IEEE 802.11 with a distributed coordination function (DCF) mode. This mode relies on continuous channel sensing of wireless communication. Suppose a node needs to transmit data. It will send data if the channel is sensed as continuously more idle than a DCF interframe space (DIFS) duration. Otherwise, it takes a backoff procedure by selecting a backoff value BV in the range of a CW, where CW is contention window. The backoff value is decremented when the medium is detected as being vacant longer than the DIFS duration. The node has a right to transmit data when its backoff value reaches zero. There are two types of intervals that enable each data to have different priority when competing to obtain a medium: DIFS and Short Interframe Space (SIFS).

4 The proposed multichannel mac protocols

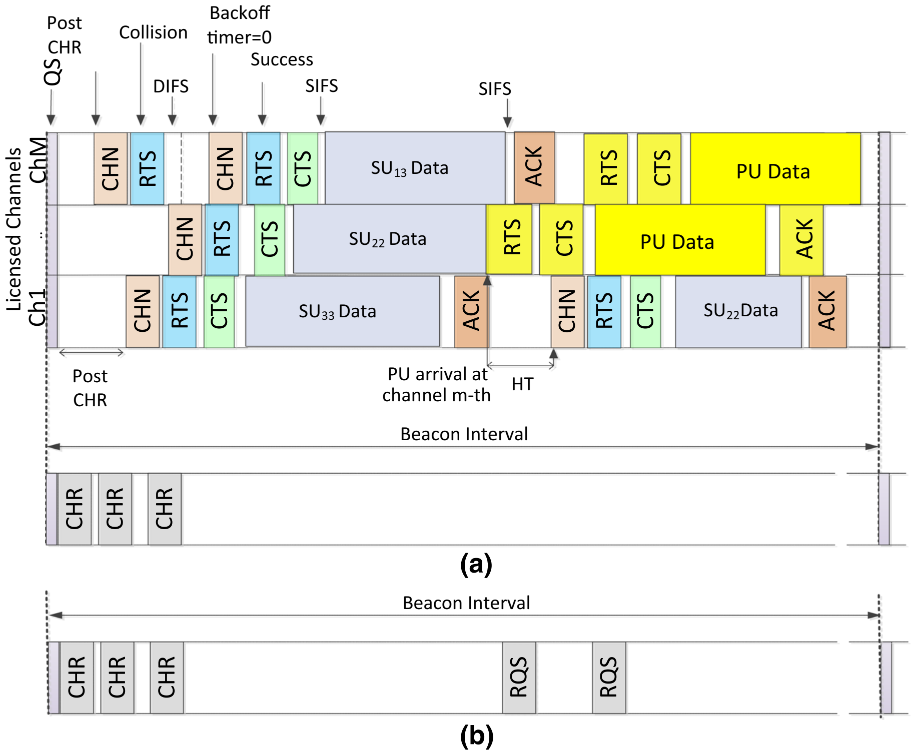
4.1 Cooperative and non-cooperative MC-MAC protocol

As with most MAC protocols of CRAHN, the protocol has three main phases, which are sensing phase, contention phase, and transmission phase. At the first phase, each SU performs a sensing to see whether a PU occupies a channel. The SU performs quick sensing (QS) directly to a certain channel to gather the channel status at the beginning of a beacon interval. The SU randomly detects a certain channel during this phase. Then it adds the status into its channel status table (CST). An SU may exchange a sensing result to neighbor SUs through the control channel, and an SU may have more channel status in its table from its neighbors. Later, SU uses the channel table to decide the best channel when it is ready to send data. At the second phase, suppose that an SU wants to transmit data through the licensed channel. After performing the channel reservation (CHR), the SU has agreed with an intended SU through common control channel to use a channel. The SU then immediately will make a channel negotiation (CHN), as shown in Fig. 2(a). It checks its CST to see whether a certain channel is free or not from PU presence. In the case that the channel is unoccupied then the SU will start channel contention. It performs a backoff procedure in case of many SUs compete to obtain the channel. A backoff value BV of SU is selected to define a backoff timer. When the backoff value counter reaches zero, the SU has a right for using the channel for data transmission. At the last phase, when the SU wins the contention, it enters a transmission phase. Then it sends an RTS frame to the intended SU. The receiver will reply with a CTS frame if it is ready to receive data. When the sender receives a CTS frame from the receiver, it senses the channel by checking its channel table, which indicates whether a channel is busy or not. Note that the channel table may be updated by its neighbor at any time, i.e., by RTS broadcast of neighbors. If the channel is vacant of PU, subsequently it immediately transmits the data. The receiver transmits an ACK frame when data receiving is accomplished. Note that the protocol forces all SUs to sense the channel before performing a data transmission.

In the cooperative MC-MAC protocol, all SUs perform a collaborative in detecting PU presence at channel, and then forward this information to other neighbor SUs. An SU performs a proactive reporting of PU appearance. The cooperative scheme uses the reporting message from its neighbor as additional information to know PU presence, whereas the non-cooperative doesn't. This protocol has similar phases as the non-cooperative one where it performs the sensing, the contention, and the transmission phases. When an SU detects a PU appearance at a channel, the SU does not only keep this channel status for itself, but it also immediately broadcasts this status to neighbor SUs. The cooperation process works as follows. Suppose that one PU transmits an RTS frame that indicates it wants to use a channel to communicate with another PU. An SU that hears this RTS immediately broadcasts an emergency request channel (RQS) frame to its SUs neighbor through the common control channel, as shown in Fig. 2(b). The RQS frame contains node id, a requested channel of PU, and location PU that claims the channel. The SUs in its neighborhood receive the RQS know the range of PU, and update their channel tables. The non-cooperative scheme does not implement RQS frame, which indicates a PU appearance at around to other SUs. There is no an RQS frame exchanging in the common control channel, as shown in Fig. 2(a).

There are two benefits of this cooperation action. Firstly, an SU that wants to transmit data into channels perceives

Fig. 2 Overview of the proposed protocol: **a** without cooperative of SUs scheme and **b** with a cooperative scheme



the channel is not free, although it doesn't see the PU presence directly. This SU cooperative action prevents an SU to send data into the channel when it receives the broadcast message. Secondly, in the case that an SU still has a communication with another SU in the channel, and one of the parties hears the RQS frame through the control channel, they must leave the channel immediately, and a handoff is performed to another channel if there is a left-over channel, otherwise they will contend the channel in the next beacon interval. The pseudo code of MC-MAC protocol for each SU for both schemes described above can be written as shown in Table 1.

Table 1 MC-MAC protocol pseudo code

The pseudo code of MC-MAC protocol

```
•  Initialization at the beginning of the beacon interval
           is_free_flag := 1;
           is_free_nearPU := 1;//prepared for cooperative scheme
•  Each of SU chooses a certain channel and performs a quick scan.
•  Channel negotiation
      a.  for the non-cooperative scheme: scan busy channel
          scanf(bschan)
          if (is_free_flag==0)
               backoff ()
        else channel is_idle:=1
      b.  for the cooperative scheme: scan busy channel and a PU of the neighbor
          scanf(bschan);
          scanf(nearPU);
          if ((is_free_flag==0)||(is_free_PU==0)
               backoff ()
        else  channel is_idle:=1
•  Upon the channel is idle, then sendRTS()
•  Upon receiving a CTS frame, it sense channel before transmits the data
      a.  for the non-cooperative scheme : scan busy channel
      b.  for the cooperative scheme : scan busy channel and a PU of the neighbor
•   If receiving an RTS from a PU, send an RQS frame to neighbor SUs
           sendRQS()
•  If receiving an RQS from a neighbor SU during performs a communication
      a.  for SU sender : mhSend.stop()
      b.  for SU receiver: mhRecv.stop()
```

4.2 The FMC-MAC protocol

In this section, we describe the proposed FMC-MAC protocol. We also develop its mathematical analysis model and derive its performance measures. FMC-MAC protocol is developed over the non-cooperative MC-MAC. The fairness is based on the CRAHN's origin for the SU. The FMC-MAC provides a mechanism in which each SU keeps the history of traffic of all nodes, which traverse in its neighborhood. Based on the history, each SU can autonomously determine the fairness index value of its neighborhood. Furthermore, it can actively maintain the fairness index at a high value. The FMC- MAC considers the three-state detection model to distinguish PUs and co-existing SU presences.

The FMC-MAC protocol also has similar phases as the MC-MAC protocol. In addition, the protocol considers fairness issue. During the sensing phase, an SU adds the status into its CST. The SU checks the channel, whether it is occupied by the signal of a PU or an SU. It explores the signals, which refer the traversed data from nodes, and then collects the status into its table as knowledge, as shown in Fig. 1. Later, the SU will use this knowledge in the next stage for balancing the fairness. We consider that each SU makes a channel reservation with the intended SU if it has the packet to transmit after sensing at the beginning of the beacon interval.

At the contention phase, an SU that wants to transmit data through the licensed channel immediately performs a channel negotiation. It checks its CST to see whether a certain channel is busy. There are three possible actions that refer to the status of the channel. First, if the channel is occupied by a PU, then the SU leaves the channel as it is. Second, if the channel is occupied by another SU, i.e., the occupier SU, afterward the SU sees the history of the CRAHN's occupier in utilizing any of the channels. In the case where the CRAHN's occupier SU has been using the channel for the longest time, and the fairness is less than the threshold value, accordingly, the SU sends a HOLD frame to ask the occupier to release the channel. Otherwise, it allows the occupier SU to continue using the channel. Third, if the channel is free, then the SU performs a backoff procedure in the case where many SUs are competing to obtain the channel. At the transmission phase, the protocol performs the similar procedure as the MC-MAC's. The SU sender and the intended one perform RTS and CTS transactions.

As mentioned before, the fairness is based on channel utilization between CRAHNs instead of individual SUs. An SU autonomously maintains the fairness in the equal resource utilization between CRAHNs. It considers the transmitted packets from all SUs with the same CRAHN identity to reflect that the CRAHN has utilized the channel. Each SU hears all packets that traverse around its neighborhood, as shown in Fig. 1. An SU records packets from all SUs for the latest duration time of Δ into its table as its knowledge. The SU uses the knowledge to identify an SU from certain CRAHNs, in spite of whether it has been occupying the channel for a long time. We assume that the more packets identified that originate from a particular CRAHN, the longer the CRAHN has used the channel resource. Let x_{mr} be the number of packets from the r-th network that traverses at the m-th channel. Then, the number of resource utilizations by the r-th CRAHN can be obtained as follows,

$$x_r = \sum_{m=1}^{M} x_{mr} \tag{1}$$

x_r denotes the total number of packets of the r-th CRAHN that utilizes the resource. We consider the fairness in the utilization of channel resources based on the CRAHN's origin for the SU. We use Jain's index in calculating the fairness with resource allocation X that represents the number of channel utilizations by a CRAHN, as defined below,

$$f(X) = \frac{\left[\sum_{r=1}^{C_r} x_r\right]^2}{C_r \sum_{r=1}^{C_r} x_r^2} \tag{2}$$

where $C_r \leq C$. r denotes the CRAHN id of a particular packet, $r \in c$. An SU individually obtains the index value with a range of $0 \leq f(X) \leq 1$. The larger value for the index indicates that resource sharing tends to be fairer.

We apply a fairness policy for each SU in our protocol as follows. Whenever an SU wants to use a channel, it senses the channel and whether it is busy. If the channel is not vacant because of another SU's occupancy, then the SU checks its table and calculates the fairness locally. If the SU occupier from the CRAHN has been utilizing the channel for the longest time, and the fairness is lower than the static threshold index value, the SU can ask the occupier to hold its activity in the channel. This action provides an opportunity for other SUs to compete in obtaining the current channel. It also balances the spectrum resource; hence, it can maintain a high fairness.

The pseudo code of the FMC-MAC protocol for each SU for the scheme described above, can be written as shown in Table 2.

5 Performance analysis

In terms of mathematical analysis development, we use a Markov chain model in obtaining the τ value of the SU channel access probability. The value relates to the

Table 2 FMC-MAC protocol pseudo code

Pseudo code of the FMC-MAC protocol

```
• Initialization at the beginning of the beacon interval
    is_free_flag:= 1;
• Each SU chooses a certain channel and makes a quick scan.
• Collecting knowledge of the transmitted packet from the neighborhood.
• Making a list of the number of traversed packets based on the SU network origin.
• Channel negotiation
    scanf(bschan)
    if(holdflag==0)
        if (is_free_flag==0)
            if (occupiedbyPU==1)
                backoff ()
        else
            If (occupiedbySU==1)
                If (occupierSU is member of CRAHN that has the most transmitted packet) && (the fairness is low)
                send HOLD frame to the occupier
        else
            the channel is_idle:=1
• Upon the channel being idle, then sendRTS().
• Upon receiving a CTS frame, it senses the channel before transmitting the data, scanning the busy channel.
• If receiving an RTS from the PU during a performing communication,
        c.  for an SU sender: mhSend.stop().
        d.  for an SU receiver: mhRecv.stop().
• If receiving a HOLD frame from another SU, set holdflag:=1.
• If releasing a channel, reset holdflag:=0.
• In case a PU reclaims the channel,
        a.  An SU that is occupying the channel must release the channel, and then moves to another empty channel.
        b.  An SU that is in the backoff state > 0, waits at the current channel while keeping its current backoff
            counter: mhBackoff_.paused() or moves to another empty channel.
```

performance of FMC-MAC protocol. An SU channel access analysis in the available channel slot implements the CSMA/CA mechanism of IEEE 802.11 with DCF. Moreover, we consider an RTS/CTS mechanism as the channel access method of the SU. Furthermore, we define the throughput that applies this method as a function of the numerical value τ.

5.1 FMC-MAC Markov chain model

We consider a two-stage Markov chain model to represent an SU process in FMC-MAC protocol under single-channel consideration, i.e., at channel m-th, as shown in Fig. 2. Then, we extend this consideration to develop an M multichannel one. There are N, which are the total number of SUs that compete to use the channel, i.e., $N = \sum_{c} N_c$ and $c \in [1, C]$. Let W be the number of CW. We consider a state space, which is denoted by $S \in [0, W - 1]$. To accommodate analysis purposes, we consider the time slot of the channel as the focus of analysis. We assume p_m and q_m are constant values. The former value denotes the probabilities of a slot at channel m-th that cannot be accessed by an SU because of a PU's presence, and conversely the latter represents the probability of the slot that can be accessed by an SU. When SUs that want to access the channel perceive that the channel is idle, they generate a backoff time counter randomly in the range $[0, W - 1]$ at the first stage. Afterward, each of them goes from state $i = 0$ to state i with a probability of $(1 - p_m)/W$. At the backoff state $i > 0$, an SU either moves from state i to state $i - 1$ as long as the channel is vacant with the probability of v_m or stays at the same state because the channel is not idle with a probability of $1 - p_m - v_m$. Whenever a PU reclaims a channel slot, the SU sees its table, and then it decides the next step, whether it remains and waits while the PU utilizes the channel and keeps the current backoff (CB) time counter with the probability of p_m/W or it moves to another vacant channel at state $j = 0$ also with the probability of p_m/W, as shown in the second stage in Fig. 3.

Based on the Markov chain model, hereafter, we have several elements of one-step transition probabilities, as follows,

$$P_{m0,i} = (q_m + p_m)/W = 1/W, \quad \text{for } i \in S \tag{3}$$

$$P_{mi,i-1} = (p_m/W) + v_m, \quad \text{for } i \in [1, W - 1] \tag{4}$$

$$P_{mi,i} = 1 - p_m - v_m + (p/W), \quad \text{for } i \in [1, W - 1] \tag{5}$$

$$P_{mi,j} = p_m/W, \quad \text{for } i \in [1, W - 1];\ j = 0 \tag{6}$$

where $P_{mi,j}$ denotes the transition probability of going from state i to state j at channel m-th. From this point, we have elements $P_{mi,j}$, and then we can develop a matrix of transition probabilities; i.e., $\left[\overrightarrow{P}\right]_{mi,j} = P_{mi,j}$. Let $\overrightarrow{b}_m$ be the vector of stationary probabilities of the Markov chain, $\overrightarrow{b_m} = [b_{m0}, b_{m1}, \ldots, b_{mW-1}]$. b_{m0} denotes the stationary probability of the Markov chain with state 0 at channel m-th. After this, we are going to calculate the vector of stationary probabilities using the following equation,

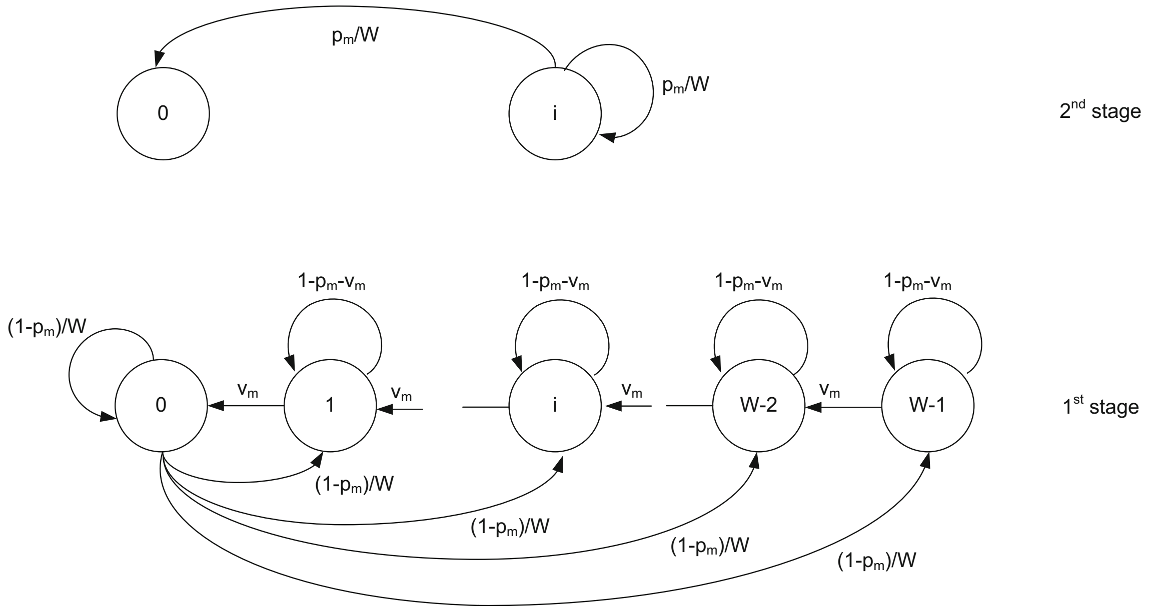


Fig. 3 State transition diagram of Markov chain model

$$b_{m\,i} = \sum_{j=0}^{W-1} b_{mj} P_{mj,i}\ , \quad i \in [0,\ W-1] \tag{7}$$

From (5), we have the equilibrium equations of the Markov chain model as follows

$$b_{m0} = b_{m0}/W + b_{m1}(v_m - p_m/W) + p_m/W \sum_{l=2}^{W-1} b_{ml} \tag{8}$$

$$b_{mi} = b_{m0}/W + b_{mi}(1 - v_m - p_m + /W) + b_{m\,i+1}(v_m + p/W) \tag{9}$$

To obtain a non-trivial solution, we substitute one of the equations above with a condition as follows,

$$\sum_i b_{mi} = 1, \quad i \in [0,\ W-1] \tag{10}$$

By using the matrix calculation, from (7) and (10), we then obtain the stationary probability at state 0 as follows,

$$b_{m0} = \frac{\kappa^{W-1} + \sum_{i=1}^{W-2} (-1)^i \delta^i \kappa^{W-1-i}}{\varsigma + \sum_{i=1}^{2} (-1)^i \left(\frac{1-W}{W}\right)^{i-1} \kappa^{W-i} + \sum_{i=1}^{W-2} (-1)^i \kappa^{-i} \delta^i \left(\left(\frac{1-W}{W}\right) \kappa^{W-2} + \gamma \delta^{W-1}\right)} \tag{11}$$

where

$$\varsigma = \sum_{i=1}^{W-2} i W^{-1} \kappa^i \delta^{W-2-i} (1-\gamma)$$

$$\delta = p_m/W - v_m - p_m$$

$$\kappa = v_m - p_m/W$$

$$\gamma = p_m/(v_m W - p_m)$$

In a general case, we consider $W \gg 1$ and can simplify $1 - W \cong -W$

$$b_{m0} = \frac{\kappa^{W-1} + \sum_{i=1}^{W-2} (-1)^i \delta^i \kappa^{W-1-i}}{\varsigma + \sum_{i=1}^{W-2} (-1)^i \kappa^{-i} \delta^i \left(\gamma \delta^{W-1} - \kappa^{W-2}\right) - \sum_{i=1}^{2} \kappa^{W-i}} \tag{12}$$

As any SU transmission occurs when the backoff counter is zero, i.e., at state 0, we can utilize b_{m0} from (12) as the probability τ_m, which is the probability of an SU that transmits into the channel.

5.2 FMC-MAC protocol performance measures

Based on the FMC-MAC developed analytical model, the performance measures used to evaluate the proposed FMC-MAC protocol are derived in this section as follows.

5.2.1 SU packet transmission probability

In this subsection, we concentrate on an analysis of the probabilities that influence the transmission of the SU packet. We consider a beacon interval on a channel m-th, as shown in Fig. 1. There are four possible activities at a certain slot during the interval. The first possible activity is a PU that is still occupying the channel slot with a probability of p_m. For the second possible activity, there is no activity for a node, either PU or SU, in the slot; i.e, the slot is vacant with a probability of v_m. This probability is referred to as the probability of q_m. The probability of a channel slot being vacant for $(N - m + 1)$ SUs access in channel m-th can be defined as follows,

$$v_m = q_m (1 - \tau_m)^{N-m+1} \tag{13}$$

For the third possible activity, there is a successful transmission of an SU in the slot with a probability of α_m. The probability that exactly one SU successfully transmits data on the given slot can be obtained as,

$$\alpha_m = q_m \tau_m (N - m)(1 - \tau_m)^{N-m} \tag{14}$$

The last possible activity is a collision of multiple SUs in the slot. We denote the probability of this activity as β_m, as follows,

$$\beta_m = q_m - v_m - \alpha_m \tag{15}$$

5.2.2 SU throughput

In this section, we only focus on the analysis of SU throughput. We consider a system in which each SU packet transmission applies an RTS/CTS access mechanism. We also assume that channel reservation time is excluded from our analysis. Let Th_m be the normalized SU throughput at the m-th channel, defined as the fraction of time that the channel is used for a successful SU transmission.

$$Th_m = \frac{\alpha_m T_s}{v_m \sigma + \alpha_m T_s + \beta_m T_{cs} + p_m T_{cp}} \tag{16}$$

where σ is the duration of an empty time slot. T_s denotes the average time that an SU successfully transmits a packet through the channel. T_{cs} represents the mean time of the collision slot. Because we assume an SU applies an RTS/CTS access mechanism, we can derive the mean time of an SU transmitting a packet through the given channel slot, i.e., T_s, as follows,

$$\begin{aligned} T_s = {} & T_{CHN} + T_{RTS} + SIFS + D_p + T_{CTS} + SIFS + D_p \\ & + T_{Header} + T_{packet} + SIFS + D_p + T_{ACK} + DIFS \\ & + D_p \end{aligned} \tag{17}$$

where T_{CHN} denotes the time that an SU sees its table during channel negotiation. T_{RTS}, T_{CTS}, and T_{ACK} denote the duration time of RTS, CTS, and ACK frames, respectively. $SIFS$ and $DIFS$ are the length of the short interframe space and DCF interframe space with time unit, respectively. D_p represents the time of the propagation delay. T_{Header} and T_{Packet} denote the duration time of the packet header transmission and the average time of the packet transmission, respectively.

In addition, as in the case when the collision of an SU with another SU occurs only during channel negotiation, we obtain the average time of the collision slot, T_{cs}, as in the following equation,

$$T_{cs} = T_{CHN} + T_{RTS} + DIFS + D_p \tag{18}$$

T_{cp} refers to the average time when an SU releases the channel whenever a PU wants to reclaim the channel from an SU. Because we assume the PU traffic follows Poisson's arrival with an arrival rate λ during an SU's packet transmission, we obtain a time for release of the channel at λ of the packet length. Moreover, we consider the time in which the SU changes its channel to another channel, i.e., T_{sc} denotes the switching channel time. Then, we obtain the time of collision with a PU as follows,

$$T_{cp} = \lambda T_{packet} + T_{sc} \tag{19}$$

The total throughput from all M channels can be calculated by using the following equation,

$$Th = \sum_{m=1}^{M} Th_m \tag{20}$$

6 Results and discussion

In this section, we evaluate and discuss the performance of the proposed protocols for CRAHN. We use network simulator-2 (NS-2) tool version ns-2.33 [27] to evaluate the performance of the proposed protocols. We have adapted the existing 802.11 MAC protocol in the NS-2 to suit the FMC-MAC protocol characteristics. A summary of the simulation parameters is as follows. All SUs move with a similar speed in a rectangular defined area, with a size of 1000 m × 1000 m. The channel operates at a communication with an effective channel rate of 1 Mbps. The number of channels $M$is five. Propagation is the two-ray ground reflection model. The interface queue of the simulator is 50. The number of channels M is five. We set a burst to the period ratio of PU activities on the channel which indicates the probability of PU presence, $p = p_m = 0.5$, and number of CW, $W = 32$, unless otherwise stated. The lengths of the RTS, CTS, and ACK frames are 352, 304, and 304 bits, respectively. The data header is of 432 bits. The durations of SIFS and DIFS are 8 and 16 microseconds, respectively. The duration of recording the traversed packets Δ is set to 3 s. The beacon interval duration is 100 ms. In terms of the routing protocol, we concentrate our attention on a reactive single path for CRAHN, which is ad hoc on demand distance vector routing. We define the number of SUs in each CRAHN, i.e., N_c is 10. For instance, the number of SUs equals 30; it denotes the number of CRAHNs equals 3.

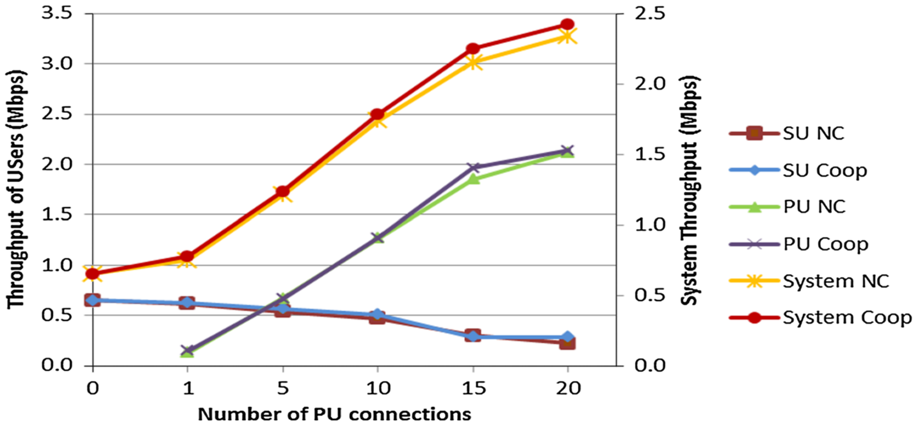


Fig. 4 The throughput against number of PU connections for five SU connections with five licensed channels

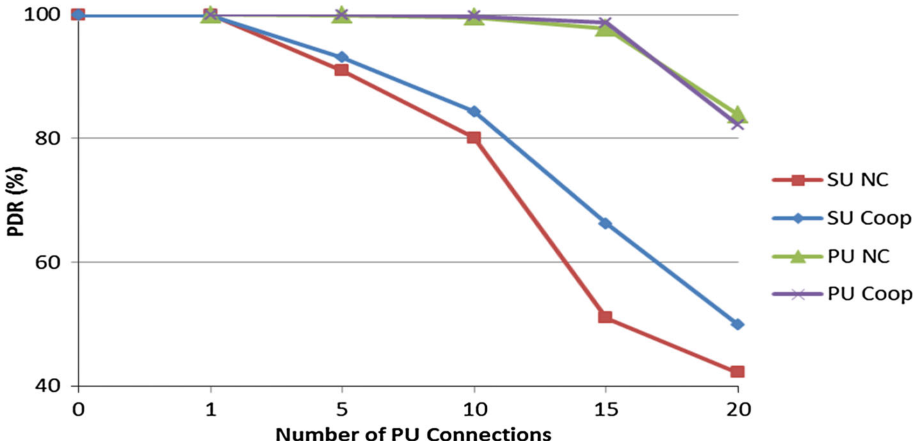


Fig. 5 Packet delivery ratio (PDR) versus varying of PU connections for five SU connections with five channels

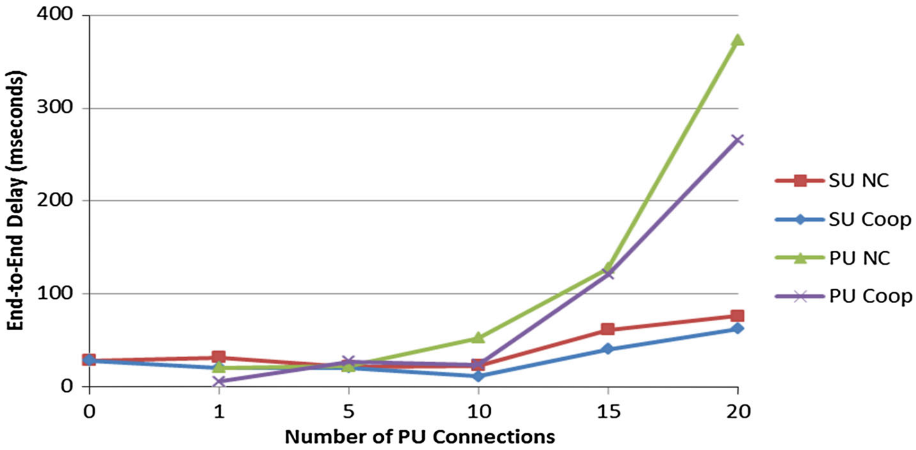


Fig. 6 End to end delay of the users against a number of PU connections for five SU connections with five licensed channels

6.1 Comparison of non-cooperative and cooperative MC-MAC protocols

Three metrics are considered for comparing the outcomes of the cooperative and the non-cooperative protocols. These metrics are throughput, packet delivery ratio, and end-to-end delay. We calculate the rate of successful packet delivery over the channel of CRAHN as the throughput. Packet delivery ratio is computed as the ratio of packets which are received by the receiver node over the number of packets sent by the sender node. End-to-end delay consists of delays associated with route discovery, quick spectrum sensing, channel negotiation, queuing, propagation, channel switching and transmission times.

Figures 4, 5 and 6 show the performance of MC-MAC protocol with cooperative and non-cooperative issue in terms of throughput, packet delivery ratio, and end-to-end delay metrics using NS2. Our investigation focuses on the impact of PUs appearances into existing SU connections. We assume one connection is performed by a sender node and a receiver node. We consider that there are 10 SUs make 5 SUs connections, and the PUs are varying. Figure 4 depicts the throughput of SU, PU, and network for the non-cooperative and cooperative scheme. The throughput of SU is degraded by the appearance of PU. The NC and Coop notations shown in the figure represent the non-cooperative and cooperative schemes, respectively. As expected, an SU will stop its activity whenever it hears a PU wanting to use the channel; consequently, the throughput of SU decreases. Moreover, when the number of PU connection is five which is same as SU's, the throughput of PU is still better than that of SU. This indicates the PU that holds the legacy of channel always has the higher priority. The SUs have increased the efficiency of spectrum utilization in the CR behavior. The figure also shows that the cooperative scheme demonstrates its superiority to another scheme at a high traffic of PU connections, e.g. number of PU connections is 15. As PU connection increases, collected information of the SU increases. Therefore, the SU has more knowledge to make the right time to transmit data. As a result, the network throughput of the collaborative scheme is higher than that of non-cooperative. The obtained network throughput enhancement is 5 %.

Figure 5 illustrates packet delivery ratio of the SU with varying of PU connections. The collaborative scheme doesn't demonstrate an enhancement over the non-cooperative scheme when the number of PU connections is a small. It implies the PU traffic on the network is still low either, e.g., number of PU connection is one. The enhancement of SU's packet delivery ratio starts when the number of PU connections is 5. Also the cooperative scheme increases the SU's packet delivery ratio at higher traffic of PU connections. The figure shows a great enhancement of SU's packet delivery ratio of up to 15 % performed by the cooperative compared to the non-cooperative scheme. The packet delivery ratio enhancement implies that the protocol can significantly prevent losses of the data transmitted by SU, because the cooperative SU provides a report broadcasting mechanism in the neighborhood. Then an SU postpones transmitting a data packet into the channel when it receives a report of PU presence from its neighbor. This situation indicates the hidden terminal problem is solved by the cooperative scheme.

Figure 6 exposes the end-to-end delay of users in the experiment according to the scenario above. The PU delay increases as the number of PU increases. It is due to the contention of PU among themselves in obtaining the limited channels. Recall that the number of channel is 5, whereas the number of PU connections increase up to 20. The SU delay increases as the number of PU increases. The SU must hold its activity when the PU appears. Consequently, the SU has a longer delay as the number of PU connections rises. Furthermore, the end-to-end delay SU with the cooperative scheme is lower than that without cooperative, since recovery time of SU with cooperative is shorter than another. The figure also shows the cooperative scheme can decrease SU delay down to 32 % compared to the non-cooperative scheme, e.g., Delay of the scheme with the number of PU connection is 15 yields 40.9 ms compared to 61.4 ms. As the number of PU connections increases, the cooperative SUs at around have more data of PUs locations. An SU can make the best ad hoc route to transmit the data packet to an intended SU. Hence, the SU obtains the least end-to-end delay.

6.2 Performance analysis results of FMAC-MAC protocols

The performance of FMC-MAC protocol is studied in terms of the throughput and fairness of SUs. We compare the FMC-MAC protocol, which uses the CB counter approach, called FMC CB, to the renewal backoff (RB) counter approach adopted from [1]. We also compare the FMC CB protocol to the existing 802.11 multichannel MAC protocol, which is combined with a two-state detection model, i.e., a two-state multichannel (TMC) protocol [2].

Figure 7, 8, 9, 10, 11, 12, 13 and 14 expose the performance of FMC-MAC protocol and comparison of that to RB [1] protocol or/and TMC protocols [2] in terms of SU throughput and fairness. Figure 7 depicts the throughput SU analysis comparison of the FMC CB and RB approaches, with a varying number of SUs. We can see that when the number of SUs increases, the throughput curves rise, reach the peak value, and then decline. The throughput of RB is better than that of CB at the low number of SUs. The RB curve sharply reaches the maximum value when the number of SUs is 70 and then decreases steadily. In contrast, the CB approach has greater throughput than the RB approach for a high number of SUs. The FMC CB curve reaches the maximum throughput when the number of SUs is 90 and then also decreases steadily while maintaining a better throughput than that of RB. The reason behind this phenomenon is that having more SUs will increase the traffic. Furthermore, it increases the chance of SU transmission conflicts.

Figure 8 shows the simulation and analytical results of the SU throughput comparison from FMC CB and TMC approaches. The simulation result using the NS-2 tool is similar to the analytical result. The FMC CB demonstrates its superiority to the TMC at all numbers of CRAHNs. This performance shows that the FMC CB approach enables

Fig. 7 Comparison of SU throughput (analytical) between the FMC KCB and RB approaches, with a varying number of SUs

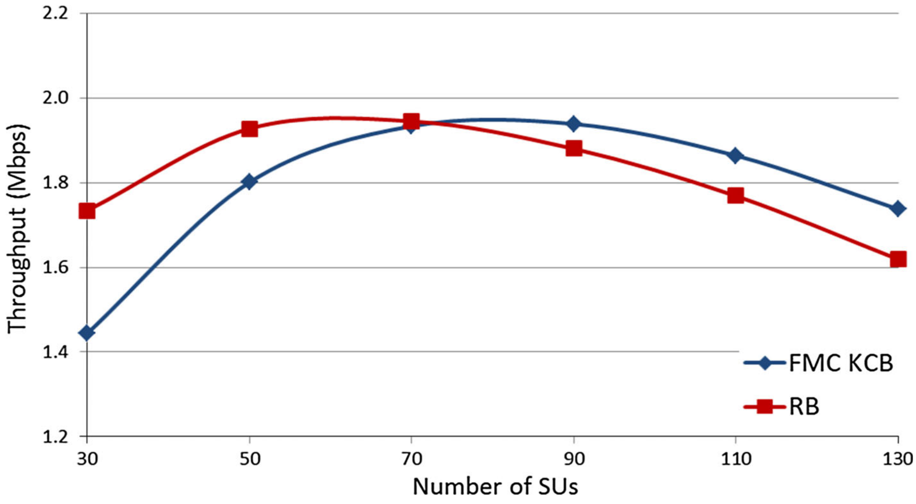


Fig. 8 SU throughput (simulation and analytical results) of the FMC KCB and TMC approaches with a varying number of SUs

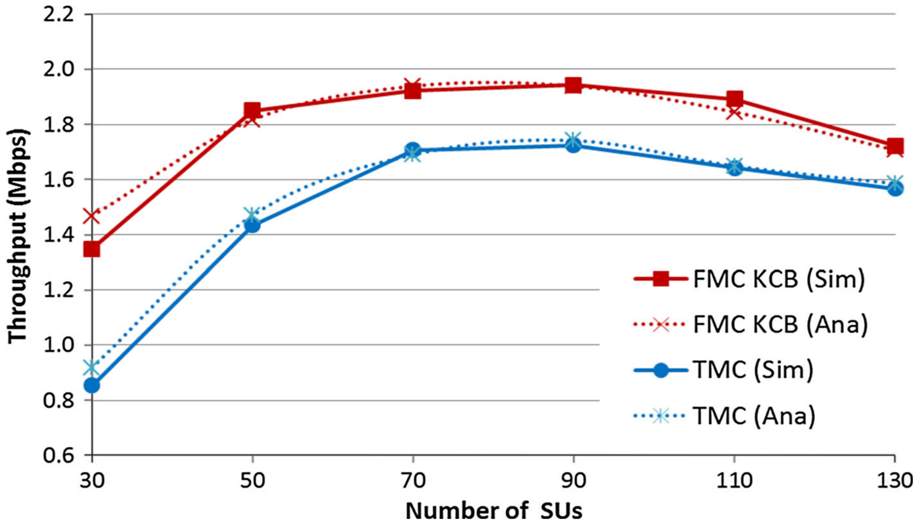
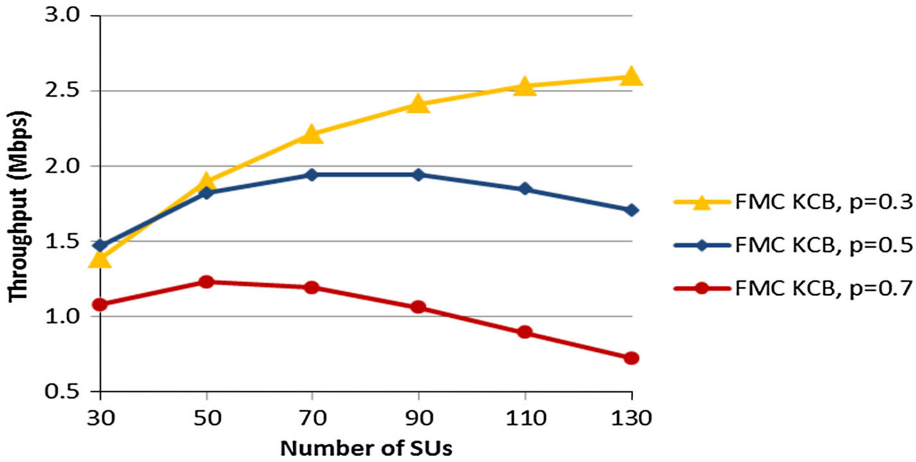


Fig. 9 SU throughput of the FMC KCB versus number of SUs with $W = 32$ and varying p



each SU to perceive another SU from a different CRAHN. An SU from a particular CRAHN can make an ad hoc connection with other SUs from other CRAHNs. Suppose a particular SU wants to make a connection with another SU from the same CRAHN, and both SUs are located far from each other. There are SUs from different CRAHNs

Fig. 10 SU throughput of the FMC KCB versus number of SUs with $p = 0.5$ and varying W

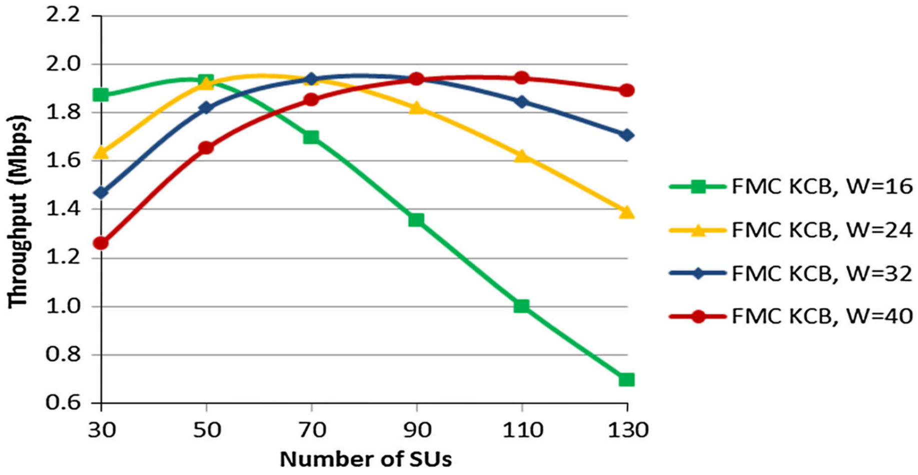
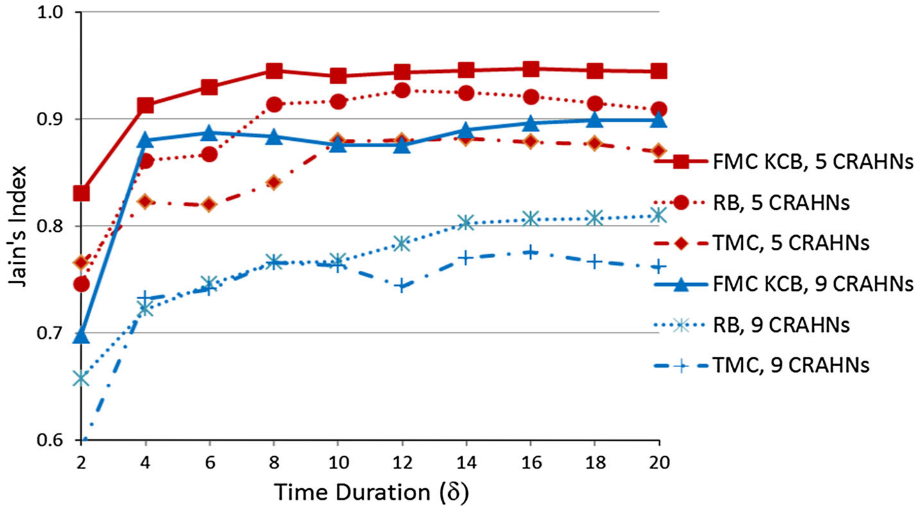


Fig. 11 Fairness for FMC KCB, RB, and TMC approaches for 5 and 9 CRAHNs, with a simulation time from $t = 2\ \delta$ to $t = 20\ \delta$



between them. In this situation, the protocol FMC CB allows both SUs to perform an ad hoc connection through an SU from other CRAHNs. This increases the chance that the SU will make a successful connection. Furthermore, it enhances the SU throughput of the network. In contrast, the TMC approach only enables an SU to see other SUs from the same CRAHN. The SU can only make an ad hoc connection with other SUs from its CRAHN. Therefore, the ability of the FMC CB approach to make an ad hoc connection is greater than that of TMC. Furthermore, the FMC CB approach provides better throughput than the other approach.

Figure 9 shows SU throughput of FMC CB approach versus the number of SUs and varying probability of PU presence p in the channel, e.g., $p = 0.3$, 0.5, and 0.7. The maximum value of SU throughput increases as p decreases. The smallest throughput is obtained when p is high, i.e., $p = 0.7$. This is due to SU has a higher probability to use the channel when p is lower. Therefore, this increases the chance that the SUs will make successful transmissions and achieve a higher throughput.

Figure 10 exposes SU throughput of FMC CB approach with $p = 0.5$ and for varying contention window W. The figure shows all contention window can achieve the same maximum throughput. However, the more W value can provide high throughput with more SUs. This is caused by the higher W value give more chances to more users to select backoff timer counter during performing the contention phase. The higher W value decreases the possibility of SU to select the same BV. Therefore, it can avoid the chance of conflict between SUs, hence it results high throughput.

Figure 11 exposes the fairness simulation result of the FMC CB, RB, and TMC approaches. We use the simulator to obtain the tracing of the transmitted packet from all SUs. We group the number of packets based on its CRAHN identity. Then, we calculate the fairness using a formula similar to (2) for network level instead of individual level

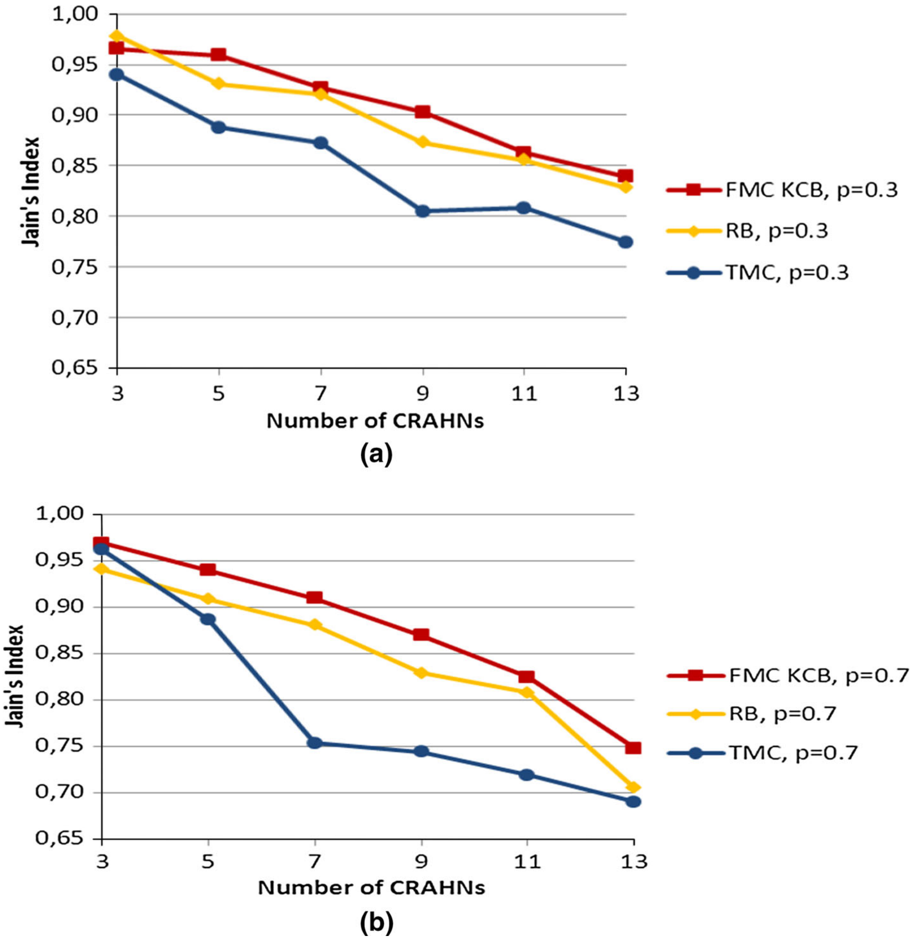


Fig. 12 Comparison of fairness for FMC KCB, RB, and TMC versus number of CRAHNs with $W = 32$, **a** $p = 0.3$, **b** $p = 0.7$

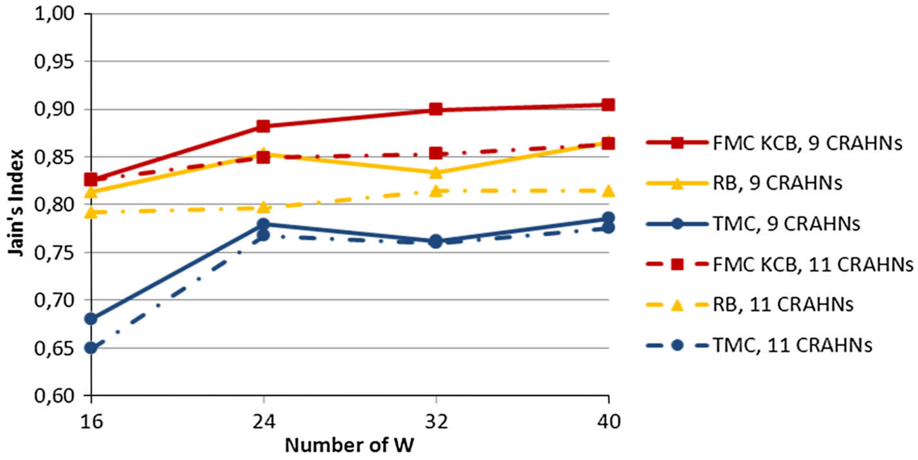
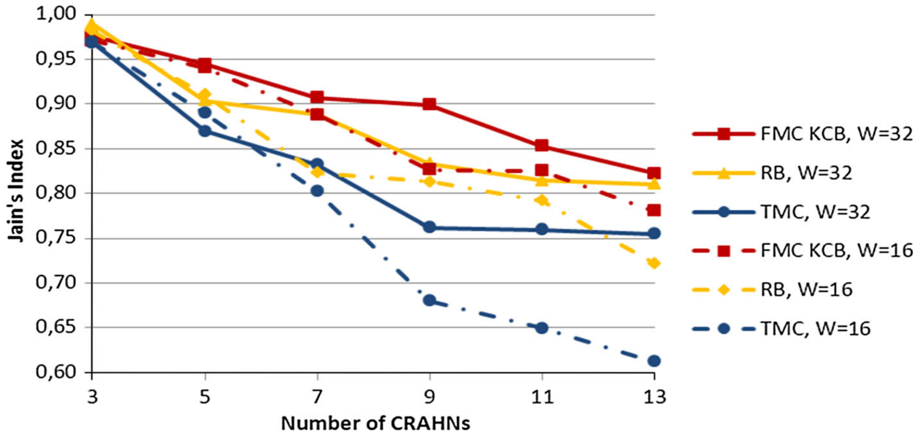


Fig. 13 Comparisons of fairness for the FMC KCB, RB, and TMC versus W, for the number of CRAHNs are 9 and 11

for some δ duration time, which $\delta = 1$ s. The figure shows that the FMC CB approach is fairer than the other two approaches. The FMC CB approach achieves a high index value in a short duration, and then it keeps the value stable. The RB approach exposes a similar pattern to the FMC CB approach, but it is stable in the lower index value than the FMC CB approach. This good performance is achieved by the individual SU's action that maintains the fairness autonomously. The TMC approach has a poorer performance than the others because it does not perform the fairness policy as explained in the previous section. These results indicate that the fairness policy as performed by the SU in our proposed protocol can reveal a high fairness value. In other words, the protocol can balance spectrum

Fig. 14 Comparison of fairness for the FMC KCB, RB, and TMC for varying of number of CRAHNs, with $W = 16$ and 32



resource sharing. In addition, the fairness performance of the FMC CB approach is better than that of the RB approach, for the number of CRAHNs are five and nine. Recall Fig. 10. Although the throughput performance of the former is less than that of the latter, the number of CRAHNs for the FMC CB approach is 5. Moreover, the FMC CB approach is more superior to the RB approach when the number of CRAHNs increases. From the figure, we perceive that the more CRAHNs exist that utilize the spectrum, the more the fairness index decreases. However, the FMC CB index value decreases considerably less than the others when the number of CRAHNs increases. In the case where the number of CRAHNs increases from five to nine and the time duration = 20 δ, the decrement of Jain's index for the FMC CB, RB, and TMC approaches are 4.58, 9.91, and 10.81 %, respectively. Therefore, our protocol is more robust in terms of fairness than the other two approaches.

Figure 12(a) exhibits simulated results of the fairness for the FMC CB, RB, and TMC versus the number of CRAHNs C, with $p = 0.3$. As the number of CRAHNs increases the Jain's index value decreases. The reason of this phenomenon is that having more CRAHNs, which is the higher value of C_r, provides the bigger value of the denominator in (2) results the lower index value. In addition, although index values of all approaches decrease as the number of CRAHNs increase, the FMC CB performance is better than the others. Figure 12(b) exposes the Jain's index of the FMC CB, RB, and TMC versus the number of CRAHNs, with $p = 0.7$. The fairness performance of FMC CB is still better than two others. Moreover, comparing to the index value with $p = 0.3$, the index value decreases as p value increases. However, we also observe that our protocol performance decreases considerably less than the others when p value rises. In the case where the number of CRAHNs is seven and p increases from 0.3 to 0.7, the decrement of Jain's index for FMC CB, RB, and TMC are 1.75, 4, and 11.93 %, respectively. Hence, our protocol is more robust to maintain the fairness in a high probability of PU presence.

Figure 13 exposes the fairness performance of FMC CB approach compared to RB and TMC approaches. The Jain's index value increases as the number of W increases. The increase of Wdecreases the possibility of SU has the same backoff value. It diminishes the conflict between SUs, therefore, increases the successful transmission. Furthermore, each SU has collected more data traversed, and can autonomously manage fairness policy with more knowledge, yielding preferable fairness performance. The index value of our protocol performance is better than the RB approach and superior to the TMC approach, in all numbers of W. Moreover, the fairness index value decreases as the number of CRAHNs increases from nine to eleven. The index values of both FMC CB and RB decrease more than that of TMC approach, when the number of CRAHNs increases. However, the index value of the FMC CB is the highest one among them, indicates our protocol has the best performance. For instance, with the number of contention window $W = 40$ and number of CRAHNs is eleven, the Jain's index value of FMC CB, RB, and TMC are 0.8634, 0.8147, and 0.7754, respectively.

Figure 14 shows comparison of fairness for FMC CB, RB, and TMC versus the number of CRAHNs, with $W = 16$ and 32. Generally, we notice the fairness index value decreases as the number of CRAHNs increases, as expected to refer to (2). We also note that the fairness performance of the proposed protocol increases as the number of W increases. Furthermore, the fairness index value slightly increases when the numbers of CRAHNs are three and five, and that value significantly rises when the number of CRAHNs is greater than five. Similar to Fig. 13, with the more of W value gives more chance to more CRAHNs to avoid the conflict. Hence an SU can manage resource sharing autonomously with a good fairness performance result.

7 Conclusions

In this paper, we proposed a multichannel (MC) MAC and a fair multichannel (FMC) MAC protocols for CRAHN, which aims to address a hidden PU problem and to achieve a high fairness among co-existing SUs that originate from multiple CRAHNs, respectively. The former proposed protocol considers cooperative and non-cooperative features. The protocol design applies many aspects such as a dedicated common control channel usage, a local SU spectrum sensing, collaborative report sensing between SUs, and deployment multichannel scheme. Moreover, we evaluate and compare the performance of the cooperative and non-cooperative scheme in terms of throughput, packet delivery ratio, and end-to-end delay. From the simulation results, we conclude that the proposed protocol provides some enhancements. Thus, the protocol protects the PU from SU interference. Detection of PU presence by using cooperative SU scheme yields a significant enhancement result in terms of SU's packet delivery ratio compared to the non-cooperative scheme, which is up to 15 %. The cooperative scheme also decreases the SU end-to-end delay, which is down to 32 %.

The latter proposed protocol is a fair multichannel (FMC) MAC protocol for CRAHN, which aims to achieve a high fairness among co-existing SUs that originate from multiple CRAHNs. The proposed protocol deliberates each SU actively and autonomously maintains the fairness in its neighborhood. From the simulation results, we conclude that the throughput performance of the proposed protocol is better than that of RB for a high number of CRAHNs and is superior to TMC for all numbers of CRAHNs. Moreover, in terms of fairness, we observe the performance with varying probability of PU presence. From the simulation, we conclude our protocol is more robust than RB and TMC to maintain the fairness in a high probability of PU presence. We also notice the FMC CB protocol performs the highest fairness among others in varying number of contention window. These results declare that the fairness policy in our protocol can remarkably balance the spectrum resource sharing.

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Aghus Sofwan received the Bachelor's and Master's degree in Electrical Engineering from Diponegoro University, and Gadjah Mada University in Indonesia, in 1995 and 2002, respectively. He is currently pursuing the Ph.D. degree in Computer Engineering at King Saud University, KSA. His research interests include signal detection, array signal processing techniques, and cognitive radio wireless network.

Dr Salman Ali AlQahtani is currently an associate professor at the Department of Computer Engineering, College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia. He serves also as a senior consultant in computer communications, integrated solutions and digital forensics for few development companies and government sectors in Saudi Arabia. Dr. AlQahtani's main research activities are in Radio Resource Management (RRM) for wireless and cellular networks (3G, 4G, Wimax, LTE, LTE-Advanced, Femtocell, Cognitive radio,…) with focus on Call Admission Control (CAC), Packet Scheduling, radio resource sharing and Quality-of-Service (QoS) guarantees for data services. In addition, his interests also include performance evaluation of packet switched network, system model and simulations and integration of heterogeneous wireless networks. Finally, my interests also extend to the area of digital forensics.