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# A Fair Multi-Channel Assignment Algorithm With Practical Implementation in Distributed Cognitive Radio Networks

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**ABSTRACT** Designing an efficient spectrum assignment (SA) mechanism is a key issue for realizing dynamic spectrum access in cognitive radio network. In multi-channel selection based SA schemes, secondary users (SUs) are able to utilize multiple channels simultaneously to enhance the network throughput. However, a fairness problem may happen if few SUs utilize too many idle data channels that other SUs are left with no idle channels, thus increasing the blocking probability and reducing the fairness. Aiming at improving the network throughput with multi-channel selection capability while maintaining fairness among the SUs, in this paper, we propose a fair multi-channel assignment scheme (FMCA) for distributed cognitive radio networks. For the FMCA scheme, we design a new MAC framework for sensing and access contention resolution, which is integrated into the FMCA scheme. Channel-aggregation (CA) technique is used in each SU to enable the multi-channel selection ability. Considering both of the idle data channel utilization efficiency and the transmit power budget constrained CA ability of each SU, we analytically formulate a channel assignment problem according to the well-known Jain's fairness criterion. Our objective is to find a channel assignment with maximal fairness index for all SUs. The optimization problem is turned out to be a quadratic integer programming (QIP). According to the definition of Jain's fairness criterion, we design an algorithm to get the optimal solution of the QIP. With the optimal channel assignment solution, the FMCA scheme is realized in the channel assignment phase of the proposed MAC protocol. Extensive simulation results show that the proposed FMCA scheme gets a good tradeoff between throughput and fairness compared with the existing SA schemes.

**INDEX TERMS** Fair multi-channel assignment, channel-aggregation, cognitive radio, distributed cognitive radio networks, medium access control (MAC) protocol, fairness, throughput.

## I. INTRODUCTION

Cognitive radio (CR) technology has proven to be an effective way to enable dynamic spectrum access (DSA) to improve spectrum utilization efficiency in CR networks (CRN) [1]. Generally speaking, there are two kinds of nodes in CRN: licensed primary users (PUs) and unlicensed secondary users (SUs). SUs are allowed to share the licensed channels while not causing harmful interferences to PUs. To realize spectrum sharing in CRN, a key challenge is how to utilize the spectrum resources efficiently. To handle the challenge, designing an efficient spectrum assignment (SA) mechanism is a possible solution [2], [3]. Moreover, the task of SA is often assigned and realized by the media access control protocol (MAC) [4], [5].

According to [2], the general design process of a SA mechanism includes three steps: first, to select a criteria to define the target objectives; second, to formulate a SA problem that best fits to the target objective; third, to select the most suitable technique to solve the SA problem. There are many challenges in designing a SA mechanism [2], such as how to minimize interference between SUs and PUs [6]–[8], how to maximize spectrum utilization or throughput [9]–[17], and how to achieve fair spectrum distribution among SUs [18]–[25]. As one of the challenges, achieving fairness among SUs is very important [26]. Without considering fairness, some SUs may suffer from a fairness problem, especially when one SU can select mulitiple idle channels while others are left with no idle channels. For example, in [27], a fairness problem may happen between LTE-Advanced users and LTE users as LTE-Advanced users can grab more channels than LTE users within the same schedule process.

Taking the fairness problem as well as throughput into consideration, in this paper, we focus on designing a multi-channel multi-user SA mechanism in distributed CRNs (DCRNs). To save the hardware cost and power consumption, we assume each SU is Channel-Aggregation Diversity (CAD) technology [28] enabled. With CAD, each SU can use multiple channels simultaneously under a limited transmit power budget with only one software defined radio (SDR) [29]. Then, aiming at maximizing the spectrum efficiency with channel aggregation while maintaining the fairness among the SUs in a distributed manner, we propose a fair multi-channel assignment scheme (FMCA) for DCRNs. The main idea of our scheme is to enlarge the bandwidth of each CR link and to consider the Jain's fairness criteria while performing channel assignments for multiple CR links. For the FMCA scheme, considering the practical implementation issue, we design a new MAC framework for sensing and access contention resolution, which is integrated into the FMCA scheme. For simplicity, we assume each data channel has identical propagation characteristic and certain rate. Therefore, we can focus on the problem about how many data channels should be assigned to each SU. Motivated by [30], in the proposed MAC framework, spectrum sensing is decoupled from the SUs and done by dedicated sensors (DSs) when spectrum access is based on a slotted ALOHA protocol [31].

*Contributions*: With respect to previous metrics, the contributions of this work are: 1) we analytically formulate the fair multi-channel assignment problem as an optimization problem according to the Jain's fairness criterion, which is shown to be a quadratic integer programming problem (QIP); 2) To solve the problem, with the aid of the definition of Jain's fairness, we design an algorithm to find the optimal channel assignment scheme which guarantees the fairness performance of the SUs while improving the spectrum efficiency and throughput by channel aggregation; 3) we present a new MAC framework which enables the proposed fair multi-channel assignment scheme in a distributed manner.

Simulation results show that the proposed fair multi-channel assignment scheme gets a good tradeoff of throughput performance and fairness performance compared with the existing SA schemes and protocols.

The rest of the paper is organized as follows. Related works on spectrum assignment schemes and protocols are discussed in Section II. Section III describes the models and the problem formulation. The proposed MAC protocol is discussed in Section IV. Simulation results are presented in Section V. Conclusions are drawn in the last section.

## II. RELATED WORK

There are many schemes and MAC protocols conducted for SA issue in CRNs with different design criteria [2]–[5].

Throughput is one of the most common criteria for SA schemes in CRNs, which has attracted significant research efforts [9]–[17]. These works can be broadly classified into two categories according to the spectrum usage strategy [2]: single channel selection based [9]–[12] and multi-channel selection based [13]–[17]. In [9], basing on Q-learning technique, each SU selects the best available band in a distributed opportunistic spectrum access system. Both sensing and channel selection schemes are considered in [10], which exploit collaboration among SUs to detect PUs. With the collaboration among SUs, some SUs can be relieved from the sensing task and focus on the channel selection and transmition, thereby improving the spectrum utilization. By employing the advanced full-duplex (FD) transceiver for each SU, [11] proposes an FD cognitive MAC (FDC-MAC) protocol. With FDC-MAC protocol, the maximum throughput is achieved by optimizing sensing time and transmit power. The channel allocation problem for multi-channel cognitive vehicular networks is considered in [12], with the objective of system-wide throughput maximation.

To further improve the throughput performance with multi-channel selection, [13] proposes a distance-dependent MAC protocol (DDMAC) which aims at maximizing the CRN throughput. Wherein a probabilistic channel assignment mechanism is employed in the DDMAC, which exploits the dependence between the RF signal model and transmission distance. To locate and exploit unused spectrum opportunities effectively, [14] proposes the cross-layer aware resource allocation techniques and presents a two-phase heuristic to achieve the optimal spectrum and power allocation for the throuoghput maximization. In [15], a prioritized medium access control protocol for CRAHN, named PCR-MAC, is proposed to select the optimal data and backup channels from a list of available channels. In [16], a spatial spectrum-sharing strategy is proposed for massive multiple-input multiple-output (MIMO) CRN with two greedy CR scheduling algorithms to improve the spectral efficiency. Reference [17] decomposes the SA problem into two subproblems: a resource allocation at the physical (PHY) layer, and a throughput optimization at the network layer. The particle swarm optimization algorithm is used in the PHY layer while the linear programming is applied in the network layer to solve the above two subproblems.

However, the aforementioned works which merely aim to increase the throughput would inevitably suffer from the fairness problem may occur [2]. For example, in single channel selection schemes, each SU just select a channel to maximize its own throughput, then some SUs may achieve low throughput once all the good channels are occupied; in multi-channel selection schemes, as a SU can concurrently utilize multiple channels, some SUs may utilize too many idle data channels, and other SUs are left with no idle data channels [2].

To tackle this, many fair SA schemes have been proposed CRN [18]–[25]. In [18]–[20], the fairness problem is solved in a centralized manner where a central unit or a base station takes the full responsibility of fair channel assignment. However, these centralized works may have limitations on scalability and computational complexity. In comparison, solving the fairness problem in a distributed manner may be more attractive in some cases. In [21], a fair multiple access scheme is proposed to enable the incoming SUs to access the idle channels with the fair opportunities as the working SUs. However, no fairness criteria is considered in [21]. Max-min fairness criterion is considered in [22] and [23]. Reference [22] proposes a distributed MAC protocol with a greedy channel assignment algorithm under the max-min fairness criterion. In [23], based on particle filtering, max-min fairness is considered to allocate the channels among the SUs in a distributed manner. To achieve better fairness, [24] introduces a proportionally fair based global objective function to maximize the total network throughput while ensuring fairness among users. However, all of [22]–[24] only consider single channel selection. To further improve the throughput efficiency, in [25], each SU is equipped with multi-interface to enable multi-channel selection. The fairness among the SUs is achieved by a contention-free distributed scheduling approach where each SU gets a fair number of licensed channels to sense and access. However, as the licensed channels are scheduled before sensing, these channels may be ended up as busy channels due to the PU activities, which may still cause unfairness among the SUs.

With respect to previous works, there are few works consider the fairness criterion in multi-channel selection based channel assignment in DCRNs. To fill the gap, we design a fair multi-channel assignment scheme with MAC framework for DCRNs, which optimizes the Jain's fairness criterion while maintaining a good throughput performance.

## III. MODELS AND PROBLEM FORMULATION

### A. SYSTEM MODEL

We consider a single hop DCRN with $N_{su}$ SUs, dedicated sensors (DSs) and a primary user network. DSs are dedicated for spectrum sensing [30], which decouple the sensing process from the SUs. Therefore, in this network, SUs can focus on realizing dynamic spectrum access. Considering that, the DSs can be replaced by a white space database as [32], which shows the flexibility of the DCRN. There is a dedicated common control channel (DCCC) [30], [33], [34] for SUs to exchange the control information which is always available to all the SUs without any interference from PU. Similar to [28], in order to protect the PUs, all SUs are assumed to be synchronized and have the same time slot division with PUs. Each SU has two transceivers: one for data transmission (i.e. the data transceiver), and another is dedicated to DCCC (i.e. the control transceiver). It is further assumed that the data transceiver is CAD enabled [28], which allows each SU to use multiple channels simultaneously under the limited transmit power. Considering the practical constraint, we assume the upper-bounded transmit power for each SU is $P_{max}$. We also assume that there are $N_{ch}$ non-overlap licensed data channels in the PU network and each data channel has an identical band width $W$. Moreover, we assume that the guard band between adjacent data channels is very small and can be neglected [35], and all the data channels have identical propagation characteristics [30]. Considering the PU activities, like [36], we assume that each of the $N_{ch}$ data channels is modeled as a 2-state Markov model with IDLE state and BUSY state.

According to [37], we assume that each idle channel $i$ can provide a fixed data rate $D_i$:

$$D_i = \begin{cases} C \text{ Mbps}, & \textit{if } \textit{SINR}^{(i)} \geq \mu, \\ 0, & \textit{otherwise}. \end{cases} \tag{1}$$

Then, let $P_{min}$ denote the minimum power required for data transmission on each channel, which can meet the signal to interference plus noise ratio (*SINR*) requirement. According to (1), $P_{min}$ can be calculated before transmission. Therefore, let $P_{ij}$ denote the transmit power of SU $j$ on channel $i$, if $P_{ij} \geq P_{min}$, the rate of channel $i$ is $C$, else the rate of channel $i$ is 0. Like [30], we assume the licensed data channels can be accessed in an overlay manner by the SUs if the data channels are sensed idle, i.e. each idle channel can be used by at most one SU. To protect the PU from harmful interference caused by SUs, periodically spectrum sensing is executed by DSs. Considering that, the notations used in the paper can be seen in Table I.

### B. PROBLEM STATEMENT AND DESIGN CONSTRAINTS

We consider a DCRN with a synchronous random access mechanism which is based on slotted ALOHA in the contention phase over the DCCC. The contention phase is further divided into two sub-phases: request to send (RTS) sub-phase and clear to send (CTS) sub-phase. Both of the two contention sub-phases are consisted by $L$ mini-slots which are provided for the SUs to compete for accessing the PU channels. During the contention phase, all needed information for conducting the channel assignment will be exchanged over the DCCC. With the needed information, the proposed channel assignment mechanism aims at maximizing the fairness among the SUs while maintaining the best idle channel utilization efficiency. To realize the proposed channel assignment mechanism, the contending SUs must meet the following constraints:

1. **Maximum channel reservation**: For a given SU transmission, the total data channels which can be grabbed in a MAC cycle is limited to $M$ ($M = \lfloor \frac{P_{max}}{P_{min}} \rfloor$).

2. **User data rate constraint**: Each SU $j$ has a rate demand $R_d(j) = R_jC$, where $R_j$ is the number of required data channels ($R_j \leq M$). If the demand $R_j$ cannot be satisfied, the demand of SU $j$ transfer to best-effort and grab the channels which are available.

3. **Contention frequency**: In each contention phase, a specific SU is allowed to contend for only one mini-slot. Therefore, the long term fairness of random access can be guaranteed.

4. **Exclusive data channel occupancy**: For a given idle data channel, if it is grabbed by a SU in a MAC cycle, it cannot be assigned to other SUs in the same MAC cycle.

### C. PROBLEM FORMULATION

In this paper, the main objective is to maximize the fairness among the SUs in each MAC cycle while maintaining the best idle channel utilization efficiency as well as the system throughput. The key idea is to choose an appropriate number of data channels for each SU. Also, the control overhead for realizing the spectrum assignment decision should be considered. If multiple solutions exist, we seek the one which is easy to broadcast. Let $S$ denote the set of contending SUs, where $S = \{SU_1, SU_2, \ldots, SU_{N_{SU}}\}$.

Let $N_{idle}$, $R$ and $X$ denote the number of sensed idle data channel, the set of the numbers of requested idle channels for the contending SUs, and the set of the numbers of assigned idle channels for the contending SUs in a MAC cycle, respectively. We have $R=\{R_1, \ldots, R_{N_{su}}\}$, $X=\{X_1, \ldots, X_{N_{su}}\}$. Considering that, for any given $SU_j$ ($SU_j \in S$) which joins the contention phase, if the mini-slot selected by $SU_j$ is collided (i.e. two or more SUs send data on the selected mini-slot), the $R_j$ cannot be heard through the DCCC. In this case, we set $R_j = 0$. Then, let $R_{sum}$ be the total number of successful requested idle data channels, we have $R_{sum} = \sum_j R_j$. Since the total number of idle data channels assigned to the SUs can be no more than $N_{idle}$ and $R_{sum}$, we define $G$=min$\{N_{idle}, R_{sum}\}$. Considering Jain's fairness criterion [38] and the idle channel utilizaiton, the channel assignment problem can be formulated as follows:

$$\max_{X} \ F(X) = \frac{(\sum_j X_j \times C)^2}{N_{su} \sum_j (X_j \times C)^2}$$
$$s.t.\ C1: 0 \leq X_j \leq R_j \quad \forall j$$
$$C2: \sum_j X_j = G \qquad (2)$$

To any given $N_{idle}$ and $R_{sum}$, $G$ is a constant. Therefore, using C2, (2) can be simplified as:

$$\max_{X} \ F(X) = \frac{(G \times C)^2}{N_{su} \sum_j (X_j \times C)^2}$$
$$s.t.\ C1: 0 \leq X_j \leq R_j \quad \forall j$$
$$C2: \sum_j X_j = G \qquad (3)$$

Since $\frac{(G\times C)^2}{N_{su}\times C^2}$ is a constant, (3) transforms to the following problem:

$$\min_{X} \quad f(X) = \sum_j X_j^2$$
$$s.t.\ C1: 0 \leq X_j \leq R_j \quad \forall j$$
$$C2: \sum_j X_j = G \qquad (4)$$

### D. CHANNEL ASSIGNEMNT ALGORITHM

The optimization problem in (4) is a quadratic integer programming (QIP) [39]. As our aim is maintaining the best idle channel utilization efficiency at first, we analyze the problem in the following two cases.

*Case 1 ($R_{sum} \leq N_{idle}$):* In this case, we have $G = R_{sum}$. According to C1 and C2 in (4), we have $X_j = R_j$, $\forall j \in \{1, \ldots, N_{su}\}$, which means that there are plenty of idle data channels for all SUs.

*Case 2 ($R_{sum} > N_{idle}$):* We have $G = N_{idle} < R_{sum}$. In this case, the idle data channels are not enough for all the contending SUs. Then, we try to solve the channel assignment problem in (4). Generally speaking, the solution of a general QIP problem is NP-hard. Fortunately, thanks to the nature of Jain's Fairness criterion, we are able to design an algorithm to solve the QIP in (4). The details of the proposed algorithm are shown in **Algorithm 1**. The main idea is to separate the channel assignment task into multiple rounds and make this process as fair as possible for each round. In each channel assignment round of **Algorithm 1**, each SU can be assigned at most one idle data channel. As there are $N_{su}$ SUs joining the channel assignment process and each SU can reserve at most $M$ data channels, the complexity of **Algorithm 1** is $O(N_{su}M)$. The channel assignment of the **Algorithm 1** is one of the optimal solutions of the QIP in (4), which is proved in **Theorem 1** of the Appendix. Considering that, $R_a$ and $I_a$ are channel assignment parameters which will be discussed in details in Section IV.B.

## IV. MEDIUM ACCESS CONTROL PROTOCOL

### A. PROTOCOL OVERVIEW

The time structure of the proposed MAC framework is shown in Fig. 1, where $N_{ch}$ represents the number of PU channels. If the PU channels are idle, they can be used by SUs opportunistically. The time on each channel is divided into data slots ($T_{slot}$), and each slot on the DCCC can be further divided into four phases: starting ($T_{start}$), contention ($T_{ct}$), channel assignment ($T_{as}$) and channel grabbing ($T_{gb}$). To protect PUs, the data transmission phase is carried out after the starting phase on the idle PU channels. Therefore, time duration of transmission phase ($T_{tr}$) equals to $T_{slot} - T_{start}$. Furthermore, $T_{ct}$ is further divided into two sub-phases: RTS sub-phase and CTS sub-phase, both of which are further divided into $L$ mini-slots. The two contention sub-phases are used by the SUs for access contention resolution. Meanwhile, $T_{gb}$ is further divided into $L$ mini-slots which are used by the SUs for sending acknowledgement frame (ACK) and grabbing idle

**Algorithm 1** Fair Multi-Channel Assignment Algorithm

**Input**: $R = \{R_1, \ldots, R_{N_{su}}\}$, $I = \{I_1, \ldots, I_{N_{su}}\}$, $N_{idle}$
**Output**: $X = \{X_1, \ldots, X_{N_{su}}\}$, $R_a$, $I_a$
**Initialization**
  • Set channel assignment index $l = 1$.
  • Let $X = \{X_1, \ldots, X_{N_{su}}\}$ be the channel assignment for all winning SUs, where $X_l = 0, \forall l \in [1, \ldots, N_{su}]$.
**if** $N_{idle} = 0$ **then**
  Return "no feasible assignment found ($X = \varnothing, R_a = \varnothing, I_a = \varnothing$.)"
**else**
  **while** $N_{idle} > 0$ **do**
    **if** $R_l - X_l = 0$ **then**
      $l = l + 1$;
      **if** $l = N_{su} + 1$ **then**
        $l = 1$;
      **end if**
    **else**
      $X_l = X_l + 1, N_{idle} = N_{idle} - 1$;
      **if** $N_{idle} = 0$ or $\sum_{i=1}^{N_{su}} R_i - \sum_{i=1}^{N_{su}} X_i = 0$ **then**
        $R_a = X_l, I_a = I_l$; **Break**;
      **else**
        $l = l + 1$;
        **if** $l = N_{su} + 1$ **then**
          $l = 1$;
        **end if**
      **end if**
    **end if**
  **end while**
  Return $X, R_a, I_a$;
**end if**

PU channels. Each of the mini-slots of $T_{ct}$ and $T_{gb}$ has fixed duration $T_{ms}$.

### B. OPERATION DETAILS

Operation details of the five phases of the proposed MAC protocol are introduced as follows.

- **Starting Phase**. Starting Phase is designed for network synchronization and sensing results broadcasting. Similar to [33], two types of SUs are defined for the DCRN: the manager SU (MSU) and normal SU (NSU). There is at most one MSU in a DCRN. This MSU is responsible for sending synchronized signal (SYNC) during the starting phase on the DCCC and sending channel assignment parameters during the channel assignment phase on the DCCC which will be discussed later in this Section. Then, all NSUs in the DCRN will synchronize itself by listening to the SYNC on the DCCC. Taking a newly joining SU for example, when an additional SU wants to join the network, it listens to the Starting Phase on the DCCC firstly to get the SYNC to synchronize. If no SYNC is heard for $z$ consecutive timeslots, it considers itself as the MSU in the network and starts to send a SYNC signal after a random waiting period; if SYNC is heard, it considers itself to be a NSU and prepares for the following phases of the MAC protocol. As the SYNC is sent on the DCCC, it can be heard by the DSs. The DSs consider the SYNC as a reminding flag and send the sensing results in a fixed time duration after the SYNC is heard. After getting the sensing results, both MSU and NSUs move to the next phase.
- **Contention Phase**. Two consecutive sub-phases: RTS and CTS form the contention phase. The contention phase is just like a frame slotted ALOHA process. At first, each SU randomly picks up one of the $L$ mini-slots in the RTS sub-phase and transmits a RTS request to the intended receiver. For a given mini-slot in the RTS sub-phase, there are only three possible outcomes: idle, successful transmission, and collision. The mini-slot is idle if no SU transmits a RTS request in it. A successful transmission means that only one SU transmits a RTS request in the chosen mini-slot. If two or more SUs transmit in the same mini-slot, the intended receiver suffers from collision, so it is unable to decode the RTS requests. Then, according to the outcomes of the RTS sub-phase, the intended receivers will response in the CTS sub-phase. For example, if a mini-slot in the RTS window is a successful transmission, the intended receiver will send a CTS message in the same mini-slot of the CTS sub-phase. Otherwise, no CTS message will be replied if the mini-slot in the RTS sub-phase is idle or a collision. After receiving the CTS request from the intended receiver, the transmitter responds an ACK frame in the same mini-slot of the channel grabbing phase (will be discussed later in the section) after waiting for a fixed duration of channel assignment phase. It should be noticed that to realize fair channel assignment, to any given $SU_j$ ($SU_j \in S$), we set $MS_j$ to save the number of the chosen mini-slot for every data slot. If the chosen mini-slot is collided, the $SU_j$ will set $MS_j = 0$.

  To realize the CAD technology, we modify the frame structure of the typical RTS frame used in IEEE 802.11 [40] by adding a multi-channel request parameter $R$ ($1 \leq R \leq M$) in it. For example, if $SU_j$ wants to reserve 3 data channels in a timeslot, $R_j$ will be set as $R_j = 3$.
- **Channel Assignment Phase**. Channel assignment parameters will be sent by the MSU in this phase. The channel assignment parameters include two elements: the index of the multi-channel assignment mini-slot $I_a$, the multi-channel assignment parameter $R_a$. Both of the two parameters are updated every time-slot by MSU according to **Algorithm 1**. Then, upon the channel assignment parameters, $SU_j$ will set the multi-channel grabbing parameter $X_j$ according to **Algorithm 2** and then move to the channel grabbing phase.

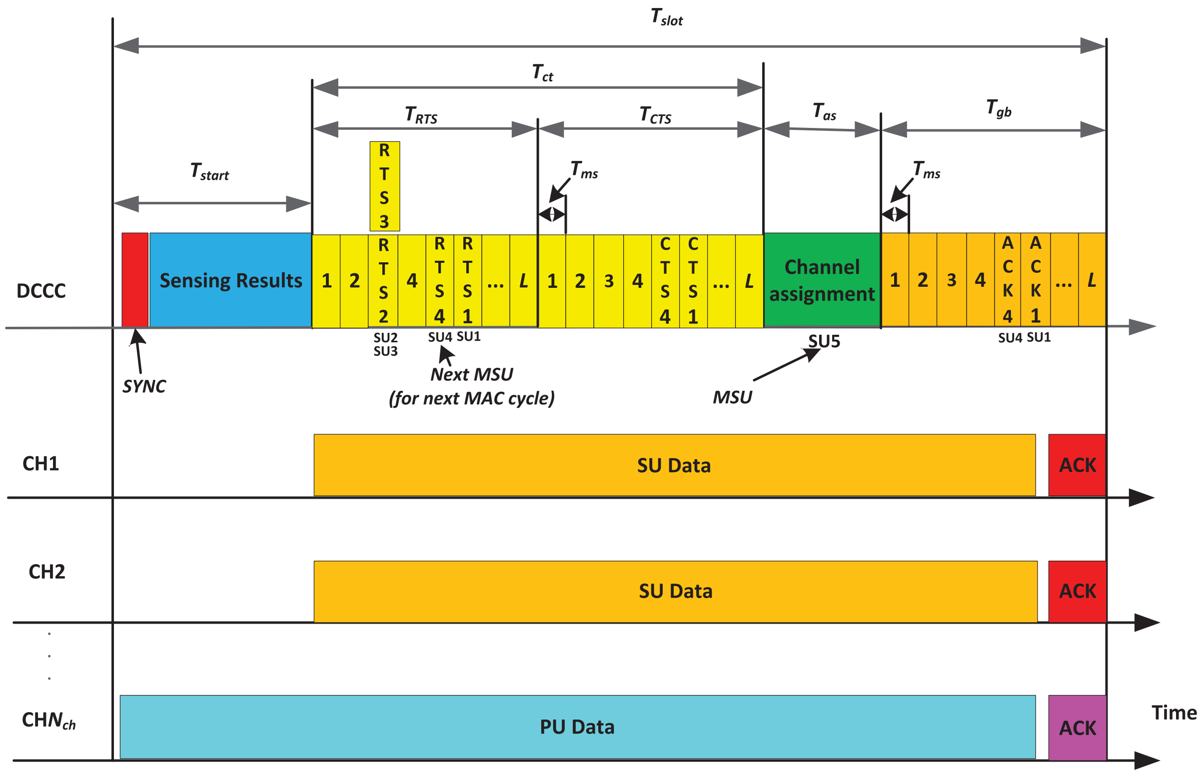


**FIGURE 1.** Timing structure of the proposed MAC.

**Algorithm 2** Distributed Channel Grabbing Algorithm

**Input**: $MS = \{MS_1, \ldots, MS_{N_{su}}\}$, $R = \{R_1, \ldots, R_{N_{su}}\}$, $R_a$, $I_a$
**Output**: $X = \{X_1, \ldots, X_{N_{su}}\}$
**for** $j = 1 : N_{su}$ **do**
  **if** $R_j < R_a$ **then**
    $X_j = R_j$
  **else**
    **if** $MS_j \leq I_a$ **then**
      $X_j = R_a$
    **else**
      $X_j = R_a - 1$
    **end if**
  **end if**
**end for**

- **Channel Grabbing Phase**. Upon the $X_j$ which is formulated during the update phase, the successful $SU_j$ will send an ACK message in the same mini-slot in the Channel Grabbing Phase as it has selected in the RTS sub-phase. The ACK contains the indexes of $X_j$ data channels which will be used for data transmission in the next time-slot. As the mini-slots of the Channel Grabbing Phase are running in a sequential manner, one SU will not reserve the data channel which has already been reserved in the former mini-slots by others. Thus, the interference among the SUs can be avoided.
- **Data Transmission Phase**. As mentioned before, each SU has the data transceiver which is dedicated for data transmission. Hence, the data transmission phase can be run simultaneously with the other phases. To protect PUs, both the transmitter and intended receiver will listen to the sensing results firstly. After that, data will be transmitted on the reserved data channels which are still being idle in the current time-slot.

### C. PERFORMANCE ANALYSIS

As mentioned before, there are $N_{su}$ SUs, $N_{ch}$ PU data channels in the DCRN, and each PU data channel state is characterized as a 2-state Markov model with IDLE state and BUSY state [34]. Therefore, in any given slot, each PU data channel is busy with probability $\rho$. Then, the average number of idle data channels $N_{idle}$ can be expressed as:

$$N_{idle} = N_{ch} \times (1 - \rho) \tag{5}$$

There are $L$ mini-slots in RTS sub-phase, CTS sub-phase, and Channel grabbing phase, respectively. To analyze the saturation throughput, it is assumed that all SUs have data to transmit in every MAC slot. Each SU uses slotted ALOHA scheme to pick one out of the $L$ mini-slots randomly, which can be seen as a $N_{su}$ Bernoulli experiments [41].

**TABLE 1. Notations used in the paper.**

| Symbol | Explanations |
|---|---|
| $N_{su}$ | Number of SUs in the DCRN |
| $N_s$ | Average number of successful mini-slots of the contention phase |
| $N_{sg}$ | Average number of SUs which successfully grab at least one licensed data channel |
| $N_{ch}$ | Total number of licensed data channels |
| $N_{idle}$ | Number of idle licensed data channels |
| $M$ | Maximum number of licensed channels can be aggregated by one SU in a MAC slot |
| $P_{max}$ | The limited transmit power for each SU |
| $P_{min}$ | The minimum transmit power for data transmission on one licensed data channel |
| $R_j$ | Number of required data channels of the $j$th SU in a MAC slot |
| $R_{sum}$ | Total number of successfully requested idle licensed data channels |
| $X_j$ | Number of actually grabbed data channels of the $j$th SU in a MAC slot |
| $R_a$ | Multi-channel assignment parameter which is updated in **Algorithm 1** |
| $I_a$ | Index of the multi-channel assignment mini-slot, which is updated in **Algorithm 1** |
| $P_s$ | Probability of a successful RTS contention in the contention phase |
| $P_{sg}$ | Probability for a SU to successfully grab a licensed data channel in a MAC slot |
| $P_b$ | Probability for a SU to be blocked during the channel grabbing phase |
| $T_{slot}$ | Time duration of a MAC frame slot |
| $T_{start}$ | Time duration of starting phase |
| $T_{ct}$ | Time duration of contention phase |
| $T_{RTS}$ | Time duration of RTS sub-phase for the contention phase |
| $T_{CTS}$ | Time duration of CTS sub-phase for the contention phase |
| $T_{as}$ | Time duration of channel assignment phase |
| $T_{gb}$ | Time duration of channel grabbing phase |
| $T_{tr}$ | Time duration of transmission phase |
| $T_{ms}$ | Time duration of a mini-slot |
| $L$ | Number of mini-slots in the $T_{RTS}, T_{CTS}$, and $T_{gb}$ |
| $C$ | Channel rate for each licensed data channel |
| $\rho$ | Traffic load of the licensed data channels |
| $\beta$ | Probability for a licensed data channel remains idle in the current MAC slot |

So, the expected RTS success probability is :

$$P_s = \frac{N_{su}}{L} \times (1 - \frac{1}{L})^{N_{su}-1} \tag{6}$$

Then, the expected number of successful mini-slots $N_s$ can be given as:

$$N_s = P_s \times L \tag{7}$$

Since the number of idle data channels is limited, one successful SU can grab data channels only when there are still idle data channels remaining. Defining the expected number of SUs which can successfully grab data channel as $N_{sg}$, we have:

$$N_{sg} = \begin{cases} N_s, & N_s \leq N_{idle}, \\ N_{idle}, & otherwise. \end{cases} \tag{8}$$

Then, we define the probability for a SU to grab at least one idle channel during the channel grabbing phase as the successful channel grabbing probability $P_{sg}$:

$$P_{sg} = \frac{N_{sg}}{N_{su}} \tag{9}$$

Similar to [30], we define the blocking probability $P_b$ as:

$$P_b = \frac{N_s - N_{sg}}{N_{su}} \tag{10}$$

After running the channel assignment process in the last time-slot, we have the number of reserved idle channels $X_j$ of $SU_j$ in the current time-slot. Similar to [25], $SU_j$ can transmit data only when the reserved idle channels are still idle in the current time-slot. Therefore, the average throughput for the $SU_j$ is:

$$Th_j = \begin{cases} \sum_{i=1}^{X_j} i \cdot B(X_j, i; \beta) \cdot \frac{T_{tr}}{T_{slot}} \cdot C, & X_j \geq 1, \\ 0, & otherwise. \end{cases} \tag{11}$$

where $B(X_j, i; \beta) = \binom{X_j}{i} \beta^i (1-\beta)^{X_j - i}$, $\beta$ is the probability of a data channel to remain idle in the current time-slot, and $C$ is the channel rate which is defined in (1).

Then, the total throughput of the network of a given time-slot is:

$$Th_{tot} = \sum_{j=1}^{N_{su}} Th_j \tag{12}$$

Finally, according to [38], we define the fairness index $F$ of a given time-slot as:

$$F = \frac{(\sum_{j=1}^{N_{su}} Th_j)^2}{N_{su} \sum_{j=1}^{N_{su}} Th_j{}^2} \tag{13}$$

## V. NUMERICAL RESULTS

Numerical results are given in this section to evaluate the proposed FMCA scheme and MAC framework. To make fair comparison, we embed two existing SA schemes into the proposed contention based MAC framework: distributed single channel assignment scheme (SC) [24] and Greedy multi-channel selection scheme (Greedy) [42]. In SC, each SU can grab only one channel in a MAC slot. In Greedy, each SU aims at selecting the best data channels without considering other SUs. Moreover, a state-of-the-art multi-channel assignment scheme with contention-free MAC framework [25], named Distributed scheduling scheme (DS), is also considered in the performance comparison. In DS, PU channels are fairly scheduled to the SUs according to the number of active SUs before sensing, which save the control overhead compared with the contention based channel access. To get a completed comparison, four performance metrics are considered: network throughput, fairness index, successful channel grabbing probability, blocking probability.

MATLAB is used to build the simulator. Simulation settings are given as follows: $N_{ch} = 40$, $T_{slot} = 1$s, $T_{tr} = 0.9T_{slot}$, $L = 100$, $M = 5$, $C = 1$ Mb/s. The simulation parameters are listed in Table 2 for clarity. We consider there are $N_{su}$ SUs in the DCRN and each $SU_j$ requires $R_j$ data channels in one timeslot. Then, we study the performance of the proposed protocol as function of SU data rate requirement $R$ (fixed and variable), number of contending SUs $N_{su}$,

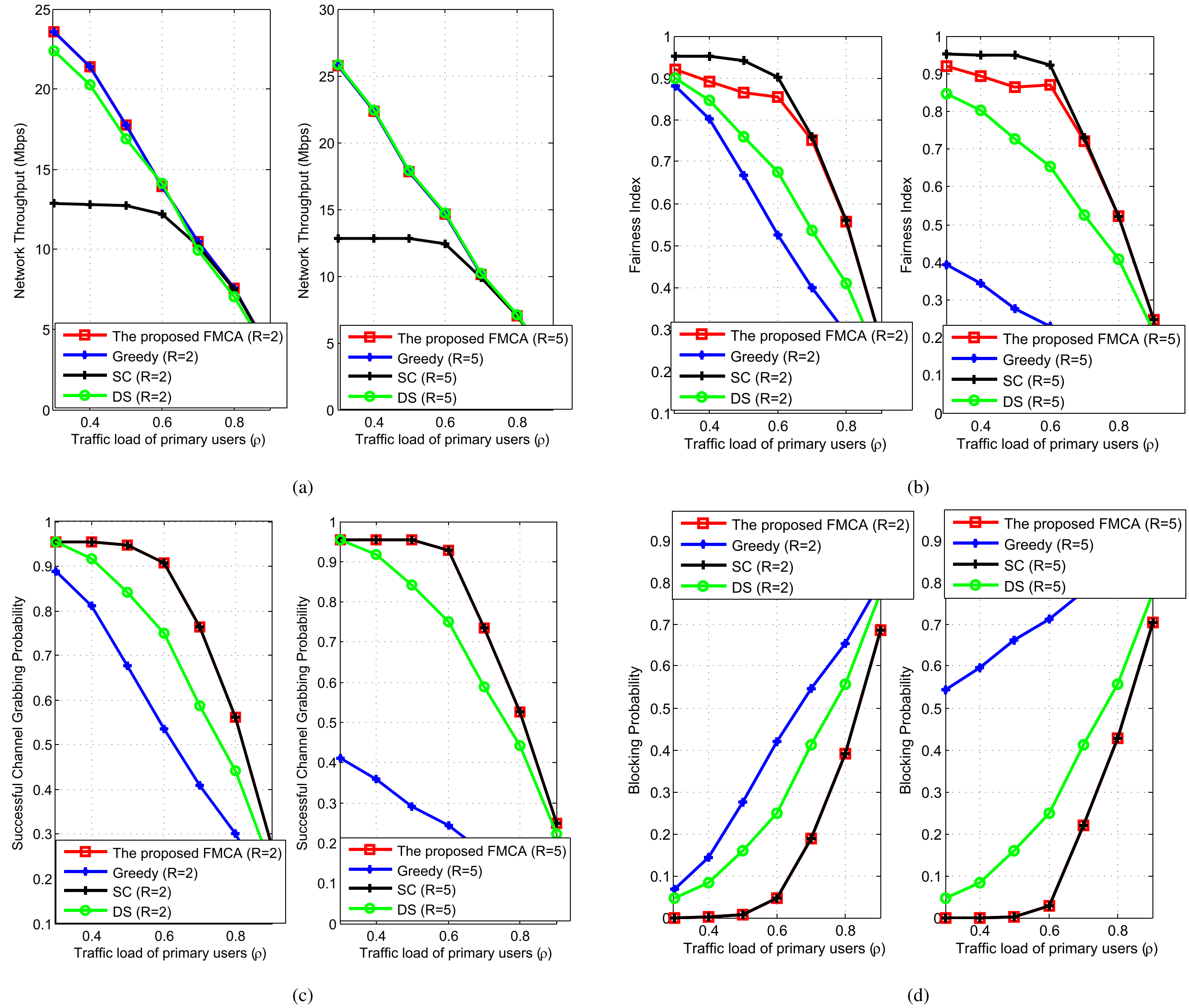


**FIGURE 2.** **Performance comparison for various $R$ and $\rho$ with $N_{su} = 15$. (a) Network throughput. (b) Jain's Fairness Index. (c) Successful channel grabbing probability. (d) Blocking probability.**

**TABLE 2.** **Simulation parameters.**

| Parameter | Value |
|---|---|
| $N_{ch}$ | 40 |
| $T_{slot}$ | 1s |
| $T_{start}$ | 100ms |
| $T_{tr}$ | 900ms |
| $L$ | 300 |
| $M$ | 5 |
| $C$ | 1 Mb/s |

and PU traffic load $\rho$. Each figure is obtained after running 10000 MAC cycles for each set of parameter values. The numerical results for each scene are presented as follows.

## A. SCENE 1: FIXED R

For simplicity, in both of the two cases in Scene 1, all the SUs are assumed to have the same rate requirement, i.e. $R_j = R$, $\forall j \in \{1, \ldots, N_{su}\}$.

### 1) SCENE 1a: FIXED $R$ AND FIXED $N_{su}$ WITH VARIOUS $\rho$

Fig. 2 shows the performance comparison as a function of $\rho$ for different $R$ with $N_{su} = 15$. Fig. 2(a) reveals that multi-channel selection scheme can greatly improve the network throughput performance compared with single channel selection scheme. We can see that the proposed FMCA scheme achieves the same throughput performance as the greedy scheme with different $R$. This is due to that the proposed protocol maintains the best idle channel utilization efficiency to form the fair channel assignment problem, which has been mentioned before in Section III. Moreover, the proposed FMCA gets a higher throughput than DS when $R = 2$. This is because in DS, some SUs may be scheduled more than 2 idle channels while the extra idle channels are wasted in this case. Besides, it is observed in Fig. 2(a) that better network throughput performance can be achieved as $R$ increases, especially when $\alpha$ is low. This is because each SU can grab

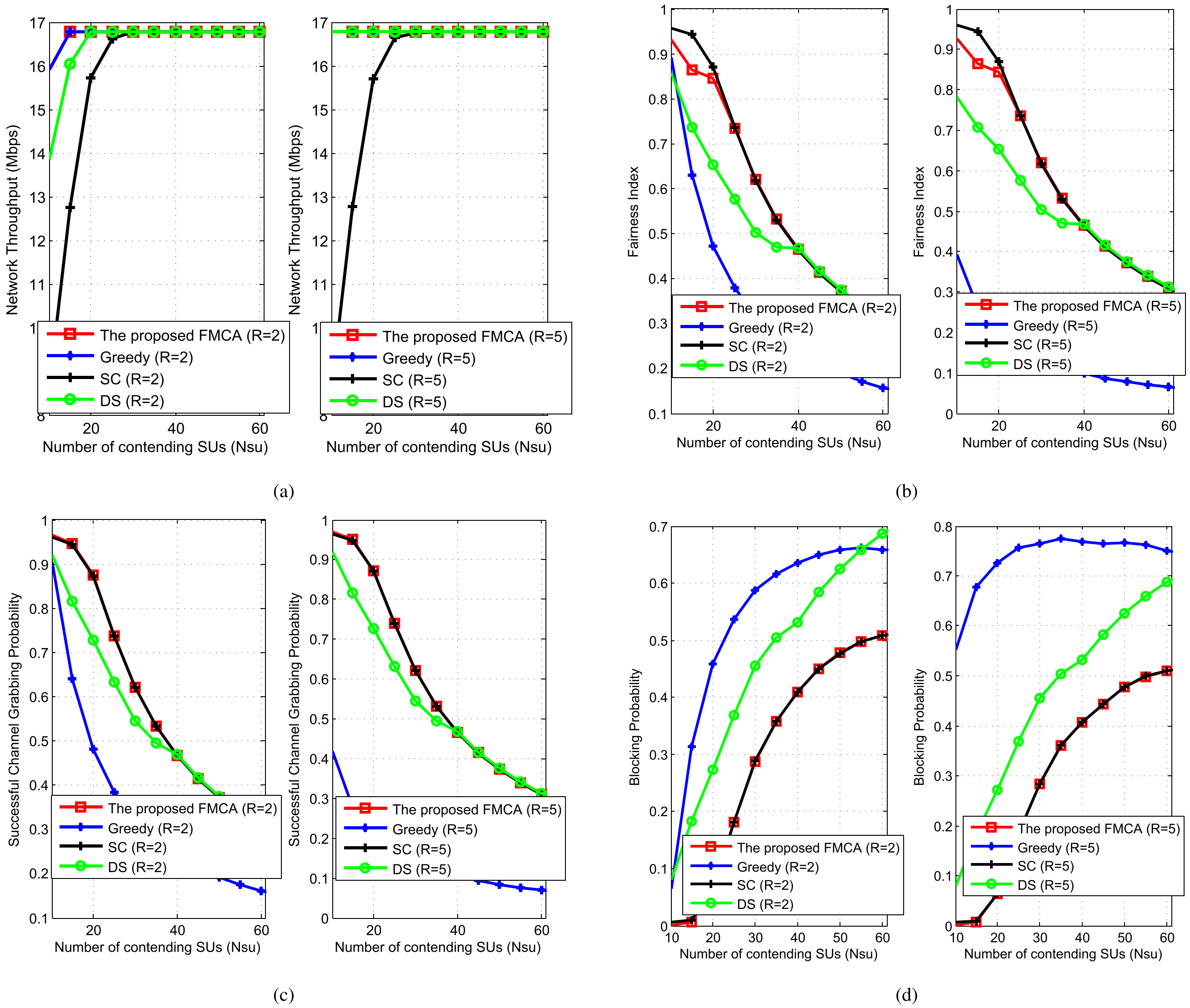


**FIGURE 3. Performance comparison for various $R$ and $N_{su}$ with $\rho = 0.5$. (a) Network throughput. (b) Jain's Fairness Index. (c) Successful channel grabbing probability. (d) Blocking probability.**

more idle channels with a higher $R$. Fig. 2(b) shows the influence of multi-channel selection on the Jain's fairness index. As expected, the proposed FMCA scheme gets a good fairness performance which is close to the SC scheme, while outperforms the greedy scheme and the DS scheme. Furthermore, we can see the fairness index of the proposed protocol only decreases slightly when $R$ is changed from 2 to 5, which shows the robustness of the proposed scheme. To clarify how the proposed protocol maintains the fairness performance, we further provide two MAC metrics in Fig. 2(c) and Fig. 2(d). From Fig. 2(c), we notice that the proposed FMCA scheme has the same channel access probability as the SC scheme which is higher than that of the DS scheme and greedy scheme. This is due to the fairness channel assignment scheme that the winners have the fair opportunities to access the idle data channels, no matter how many data channels they have requested initially. Notice that, when $\rho$ is low, DS gets a high successful channel grabbing probability. This is becasue of the advantage of contention-free channel scheduling when there are plenty of idle channels. However, when $\rho$ is high, as the licensed channels are scheduled before sensing in DS, the scheduled channels may be ended up as busy channels, thus causing the decrease of the successful channel grabbing probability. For the blocking probability, upon the proposed FMCA scheme, very few winners will be blocked during the channel grabbing phase, which can be seen in Fig. 2(d). Considering that, in DS, all the $N_{su}$ SUs are scheduled with licensed channels before sensing. Therefore, according to (10), we set $N_s = N_{su}$ for DS in the simulation.

### 2) SCENE 1b: FIXED $R$ AND FIXED $\rho$ WITH VARIOUS $N_{su}$

In Fig. 3, we plot the performance comparison for $\rho = 0.5$. From Fig. 3(a), it can be noticed that the proposed FMCA

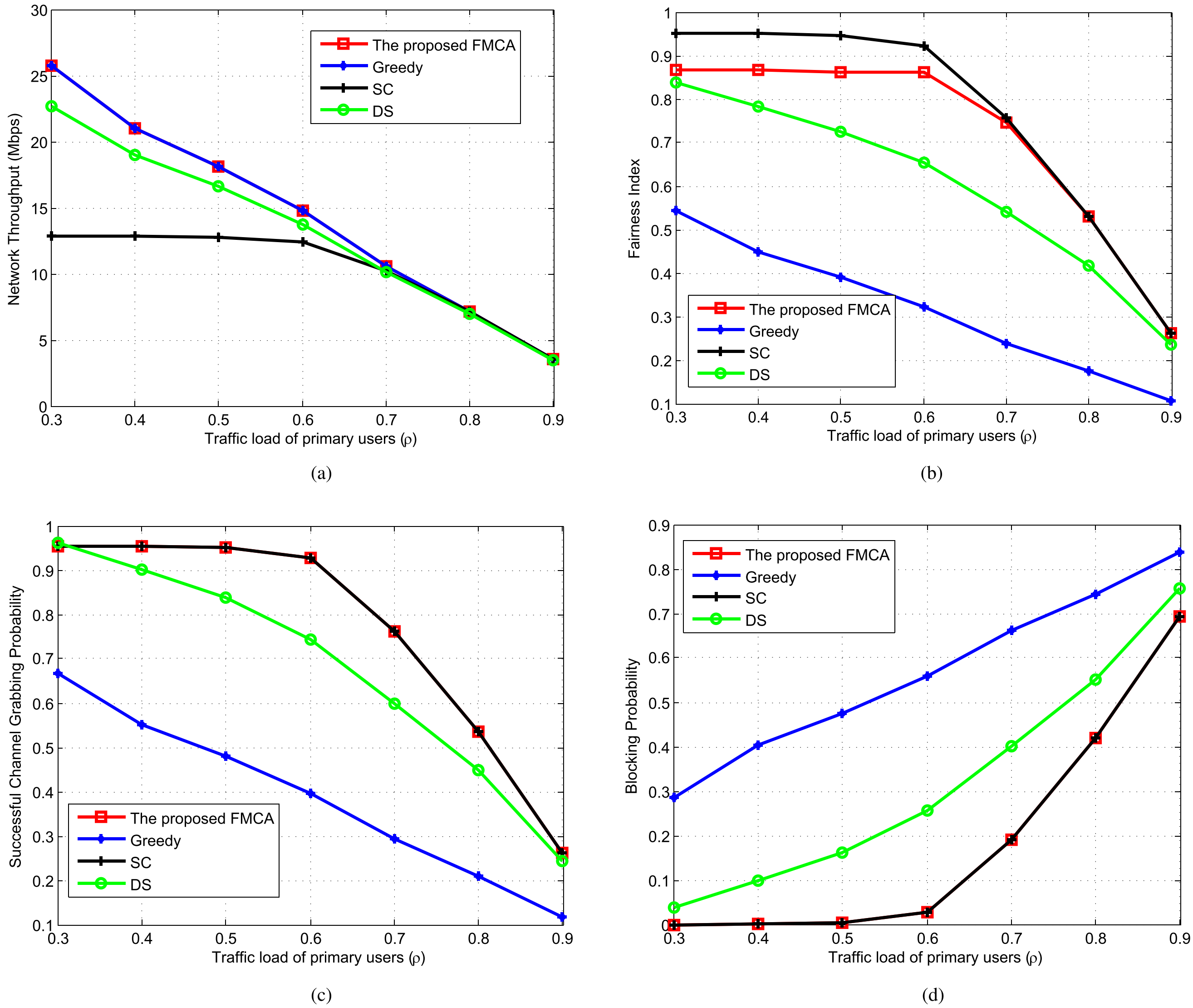


**FIGURE 4. Performance comparison for various $\rho$ with $N_{su} = 15$ and $R$ ∼Uniform[1,5]. (a) Network throughput. (b) Jain's Fairness Index. (c) Successful channel grabbing probability. (d) Blocking probability.**

scheme gets the best network throughput as the Greedy scheme do. Fig. 3(b) shows that the fairness index decreases as $N_{su}$ increases, irrespective of $R$, which is consistent with the previous analysis. Due to the limited spectrum resource, the fairness problem will become serious when there are too many contending SUs. Nevertheless, the proposed protocol still gets a good fairness performance which is close to that of the SC and better than that of DS and SC. Moreover, from Fig. 3(a) and Fig. 3(b), we can see that, compared with the other schemes, the proposed FMCA scheme gets a good tradeoff between network throughput and fairness with a dynamic range of $N_{su}$. Apart from that, the successful channel grabbing probability and blocking probability which are plotted in Fig. 3(c) and Fig. 3(d). FMCA gets the same successful channel grabbing probability and blocking probability as the SC scheme which is much better than the other two schemes.

### B. SCENE 2: VARIOUS R

Considering the practical situation of DCRN, each SU has a unique rate requirement. Therefore, in Scene 2, we study the performance of the proposed FMCA scheme with various $R$: for any given $SU_j$, $R$ is uniformly distributed in the interval [1,5] ($R$ ∼Uniform[1,5]).

#### 1) SCENE 2a: VARIOUS $R$ AND FIXED $N_{su}$ WITH VARIOUS $\rho$

Fig. 4 shows the performance curves of the metrics as Fig. 2. From Fig. 4(a) and Fig. 4(b), we can see that the proposed FMCA still gets the best throughput performance and second best fairness index, which verifies the effectiveness of the proposed FMCA scheme under more practical situation. According to Fig. 4(c) and Fig. 4(d), it can be seen that the channel access probability and blocking probability of the proposed protocol are still as good as the SC

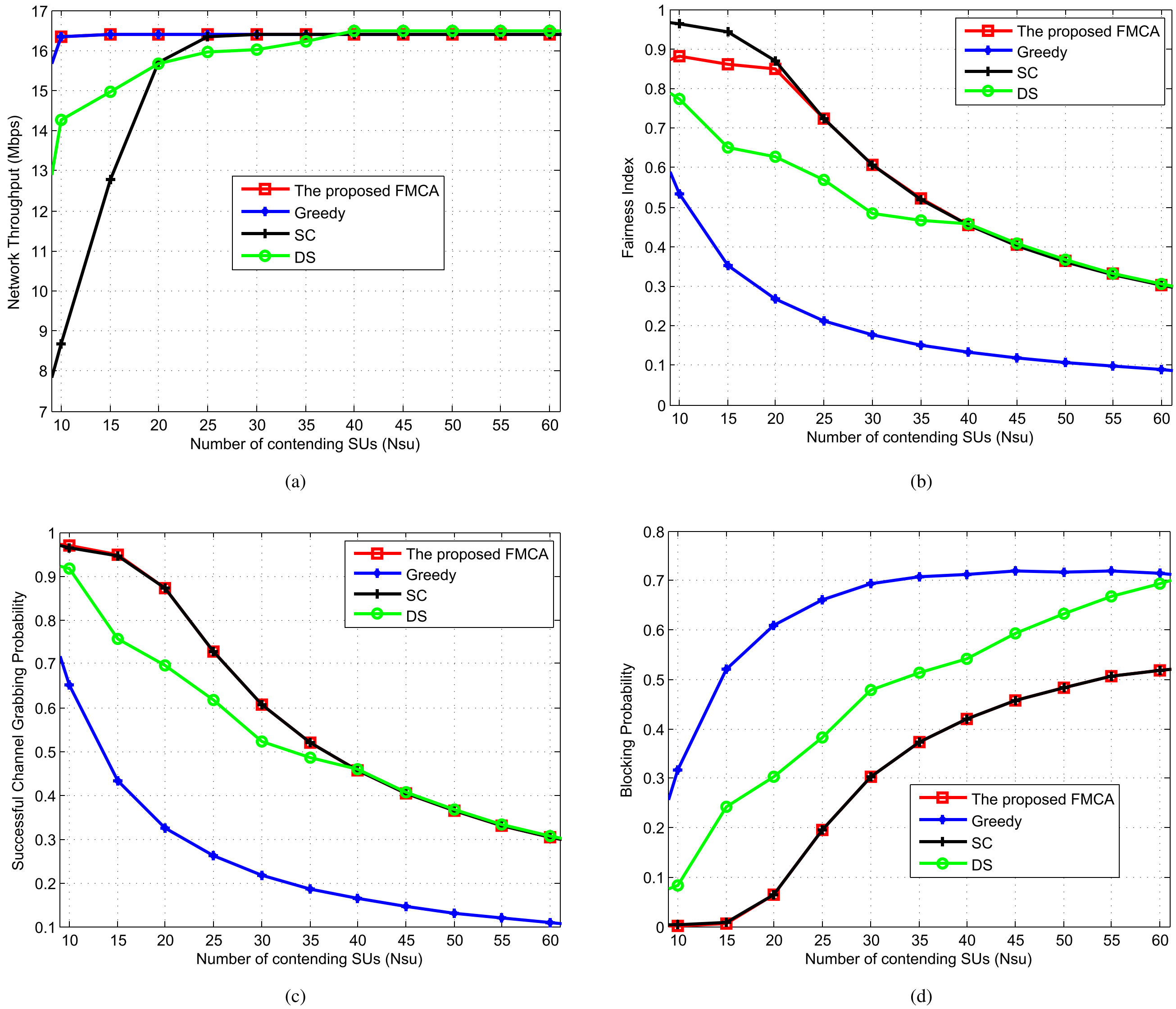


**FIGURE 5. Performance comparison for various $N_{su}$ with $\rho = 0.5$ and $R$ ~Uniform[1,5]. (a) Network throughput. (b) Jain's Fairness Index. (c) Successful channel grabbing probability. (d) Blocking probability.**

scheme, which means that SUs with different rate requirements still have a fair opportunity to access the idle data channels.

### 2) SCENE 2b: VARIOUS $R$ AND FIXED $\rho$ WITH VARIOUS $N_{SU}$

Fig. 5 evaluates the four metrics in Fig. 3 under a more practical situation. Fig. 5(a) and Fig. 5(b) show that the proposed FMCA gets similar throughput performance and fairness performance as those in Fig. 3(a) and Fig. 3(b). Hence, the influence of various $R$ to the proposed FMCA is limited, which proves the robustness of the proposed FMCA. Moreover, for different values of $N_{su}$ and random rate demands of different SUs, Fig. 5(c) and Fig. 5(d) reveal that all these SUs still have a fair opportunity to access the idle channels without being blocked, which further demonstrates the effectiveness of the proposed FMCA scheme.

## VI. CONCLUSION

In this paper, we have proposed a fair multi-channel assignment scheme (FMCA) for DCRNs. For the practical implementatnion of the FMCA scheme, we have designed a new MAC framework for sensing and access contention resolution, which is integrated into the FMCA scheme. In order to optimize the performance of FMCA scheme and MAC framework, we have developed an optimization problem according to the Jain's fairness criterion. Then, we have designed an algorithm to find the optimal channel assignment solution which guarantees the fairness performance of the SUs while maintaining the best network throughput. Simulation results verify the effectiveness of the proposed FMCA scheme which gets a good tradeoff between throughput and fairness compared with other three existing SA schemes. To the best of our knowledge, our proposed algorithm is the first that takes the Jain's fairness criterion into account to make the multi-channel assignment decision. Finally, considering more practical assumptions about the data channel quality, such as fading and shadowing, further investigation of this problem is left for future work.

## APPENDIX

*Theorem 1:* The channel assignment of the Algorithm 1 is one of the optimal solution of the QIP in (4).

*Proof:* As mentioned in Section III.D Case 2, we have $R_{sum} > N_{idle}$, which means that there is at least one $SU_j$ with $X_j < R_j$. According to **Algorithm 1**, we assume there are $k$ rounds channel assignment. Then, we divide the SUs into two groups:

Group $I$: SUs which do not attend the $k$th round channel assignment. To any $i \in I$, we have $X_i = R_j$.

Group $J$: SUs which attend the $k$th round channel assignment. Moreover, we have $J = J_0 + J_1$ where $J_0 = \{j|j \in J, X_j = k-1\}$, $J_1 = \{j|j \in J, X_j = k\}$.

We define the set of channel assignment of **Algorithm 1** as $X = \{X_{w_1}, \ldots, X_{w_K}\}$ and the theoretical optimal fair channel assignment of (4) as $X_{opt} = \{X_{opt1}, \ldots, X_{optK}\}$. According to (4), we have $\sum_{m=1}^{K} X_{optm} = \sum_{i\in I} X_{opti} + \sum_{j\in J} X_{optj} = N_{idle}$. Moreover, we define $\hat{J}_0 = \{j|j \in J, X_{optj} = k-1\}$, $\hat{J}_1 = \{j|j \in J, X_{optj} = k\}$. The **Theorem 1** turn out to be the following two propositions:

*Proposition 1:* To any $i \in I$, $X_i = X_{opti}$.

*Proof:* Define $I = I_0 + I_1$, where $I_0 = \{i|i \in I, X_i \neq X_{opti}$, $I_1 = I - I_0 = \{SU_i|i \in I, X_i = X_{opti}\}$. Then **Proposition 1** turns out to be proving $I_0 = \varnothing$.

Proof by contradiction, we assume $I_0 \neq \varnothing$, which means there is at least one $i_0 \in I_0$ makes $X_{i_0} \neq X_{opti_0}$. According to the definition of $I$, we have $X_{i_0} = R_{i_0}$. Then, we have:

$X_{opti_0} < R_{i_0} \Leftrightarrow \sum_{i\in I_0} X_{opti} < \sum_{i\in I_0} X_i \Rightarrow \sum_{j\in J} X_{optj} > N_{idle} - \sum_{i\in I_0} X_i - \sum_{i\in I_1} X_{opti} \Rightarrow$ there is at least one $j_0$ makes $X_{optj_0} \geq X_{i_0} + 1 \geq X_{opti_0} + 2$. Therefore, we have:

$$X_{optj_0} \geq X_{opti_0} + 2 \tag{14}$$

According to (14), we try this channel reassignment: $\hat{X}_{optj_0} = X_{optj_0} - 1$, $\hat{X}_{opti_0} = X_{opti_0} + 1$, we have $\hat{X}^2_{optj_0} + \hat{X}^2_{opti_0} - X^2_{optj_0} - X^2_{opti_0} < 0$. With $\hat{X}_{optj_0}$ and $\hat{X}_{opti_0}$, a smaller $f(X)$ can be drawn in (5) compared to $X_{optj_0}$ and $X_{opti_0}$. Therefore, $X_{opti_0}$ is not a theoretical optimal fair channel assignment and there is no $i_0 \in I_0$ makes $X_{i_0} \neq X_{opti_0}$. Then, we have $I_0 = \varnothing$ and $I = I_1$, **Proposition 1** is proven.

*Proposition 2:* To $J_0 = \{j|j \in J, X_j = k-1\}$, $J_1 = \{j|j \in J, X_j = k\}$, $\hat{J}_0 = \{j|j \in J, X_{optj} = k-1\}$, and $\hat{J}_1 = \{j|j \in J, X_{optj} = k\}$, $|\hat{J}_0| = |J_0|$, $|\hat{J}_1| = |J_1|$.

For simplicity, we can transfer **Proposition 2** into the following inequality: to any $j \in J$, $k-1 \leq X_{optj} \leq k$.

*Proof:* Firstly, we try to find the lower bound of $X_{optj}$. Proof by contradiction, we assume there is a $j_0 \in J$ makes $X_{optj_0} \leq k-2$ and a $j_1 \in J$ makes $X_{optj_1} \geq k+1$. It's easy to proof, there is at least one $j_2 \in J$ makes $X_{optj_2} = k$. Then, we have:

$$X_{optj_0} \leq X_{optj_2} - 2 \tag{15}$$

According to (15), using the same channel reassignment method as (14), we know that $X_{optj_0}$ is not a theoretical optimal fair channel assignment. Then, we have: to any $j \in J$, $X_{optj} \geq k-1$.

Secondly, we try to find the upper bound of $X_{optj}$. According to **Proposition 1**, we have:

$$\sum_{j\in J} X_j = N_{idle} - \sum_{i\in I} X_{opti} = \sum_{j\in J} X_{optj} \tag{16}$$

Then, there is at least one $j_3 \in J$ makes $X_{optj_3} \leq k-1$. Otherwise, $\sum_{j\in J} X_{optj} > (|J_0| + |J_1|) \times k \geq \sum_{j\in J} X_j$, which is contradicted to (16). Then, we have:

$$X_{optj_3} < X_{optj_1} - 2 \tag{17}$$

According to (17), similar to (14) and (15), we know that $X_{optj_1}$ is not a theoretical optimal fair channel assignment. Then, we have: to any $j \in J$, $X_{optj} \leq k$.

To sum up, to any $j \in J$, $k-1 \leq X_{optj} \leq k$. As $\sum_{j\in J} X_j = \sum_{j\in J} X_{optj} = |J_0|(k-1) + |J_1|k = |\hat{J}_0|(k-1) + |\hat{J}_1|k$, we have: $|\hat{J}_0| = |J_0|$, $|\hat{J}_1| = |J_1|$. **Proposition 2** is proven.

According to the proof of **Proposition 1** and **Proposition 2**, **Theorem 1** is proven.

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## REFERENCES

[1] K. G. Shin, H. Kim, A. W. Min, and A. Kumar, "Cognitive radios for dynamic spectrum access: From concept to reality," *IEEE Wireless Commun.*, vol. 17, no. 6, pp. 64–74, Dec. 2010.

[2] E. Z. Tragos, S. Zeadally, A. G. Fragkiadakis, and V. A. Siris, "Spectrum assignment in cognitive radio networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1108–1135, 3rd Quart., 2013.

[3] E. Ahmed, A. Gani, S. Abolfazli, L. J. Yao, and S. U. Khan, "Channel assignment algorithms in cognitive radio networks: Taxonomy, open issues, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 795–823, 1st Quart., 2016.

[4] A. De Domenico, E. Strinati, and M.-G. Di Benedetto, "A survey on MAC strategies for cognitive radio networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 1, pp. 21–44, 1st Quart., 2012.

[5] L. Gavrilovska, D. Denkovski, V. Rakovic, and M. Angjelichinoski, "Medium access control protocols in cognitive radio networks: Overview and general classification," *IEEE Commun. Surveys Tuts*, vol. 16, no. 4, pp. 2092–2124, 4th Quart., 2014.

[6] D. R. Joshi, D. C. Popescu, and O. A. Dobre, "Joint Spectral shaping and power control in spectrum overlay cognitive radio systems," *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2396–2401, Sep. 2012.

[7] H. Wang, J. Ren, and T. Li, "Resource allocation with load balancing for cognitive radio networks," in *Proc. IEEE GLOBECOM*, Dec. 2010, pp. 1–5.

[8] W. Wang, K. G. Shin, and W. Wang, "Joint spectrum allocation and power control for multihop cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 7, pp. 1042–1055, Jul. 2011.

[9] M. Noroozoliaee, B. Hamdaoui, and K. Tumer, "Efficient objective functions for coordinated learning in large-scale distributed OSA systems," *IEEE Trans. Mobile Comput.*, vol. 12, no. 5, pp. 931–944, May 2013.

[10] M. I. B. Shahid, J. Kamruzzaman, and M. R. Hassan, "Modeling multiuser spectrum allocation for cognitive radio networks," *Comput. Electr. Eng.*, vol. 52, pp. 266–283, May 2016.

[11] L. T. Tan and L. B. Le, "Design and optimal configuration of full-duplex MAC protocol for cognitive radio networks considering self-interference," *IEEE Access*, vol. 3, pp. 2715–2729, 2015.

[12] Y. Han, E. Ekici, H. Kremo, and O. Altintas, "Throughput-efficient channel allocation algorithms in multi-channel cognitive vehicular networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, pp. 757–770, Feb. 2017.

[13] H. A. B. Salameh, M. Krunz, and O. Younis, "Cooperative adaptive spectrum sharing in cognitive radio networks," *IEEE/ACM Trans. Netw.*, vol. 18, no. 4, pp. 1181–1194, Aug. 2010.

[14] M. B. Ghorbel, B. Hamdaoui, R. Hamdi, M. Guizani, and M. NoroozOliaee, "Distributed dynamic spectrum access with adaptive power allocation: Energy efficiency and cross-layer awareness," in *Proc. IEEE INFOCOM*, Apr. 2014, pp. 694–699.

[15] R. Hossain, R. H. Rijul, M. A. Razzaque, and A. M. J. Sarkar, "Prioritized medium access control in cognitive radio ad hoc networks: Protocol and analysis," *Wireless Pers. Commun.*, vol. 79, no. 3, pp. 2383–2408, 2014.

[16] H. Xie, B. Wang, F. Gao, and S. Jin, "A full-space spectrum-sharing strategy for massive MIMO cognitive radio," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2537–2549, Oct. 2016.

[17] J. Chen, S. Ping, J. Jia, Y. Deng, M. Dohler, and H. Aghvami, "Cross-layer optimization for spectrum aggregation-based cognitive radio ad-hoc networks," in *Proc. IEEE GLOBECOM*, Dec. 2017, pp. 1–6.

[18] L. B. Le and E. Hossain, "Resource allocation for spectrum underlay in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5306–5315, Dec. 2008.

[19] T. Zhang, B. Wang, and Z. Wu, "Spectrum assignment in infrastructure based cognitive radio networks," in *Proc. NAECON*, 2009, pp. 69–74.

[20] D. A. López, C. A. Rojas, D. F. Zapata, and E. R. Trujillo, "Designing a MAC algorithm for equitable spectrum allocation in cognitive radio wireless networks," *Wireless Pers. Commun.*, vol. 98, no. 1, pp. 363–394, 2018.

[21] Z. Ma, Z. Cao, and W. Chen, "A fair opportunistic spectrum access (FOSA) scheme in distributed cognitive radio networks," in *Proc. IEEE ICC*, May 2008, pp. 4054–4058.

[22] L. T. Tan and L. B. Le, "Channel assignment with access contention resolution for cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 61, no. 6, pp. 2808–2823, Jul. 2012.

[23] M. B. Ghorbel, B. Khalfi, B. Hamdaoui, and M. Guizani, "Resources allocation for large-scale dynamic spectrum access system using particle filtering," in *Proc. IEEE GLOBECOM*, Dec. 2014, pp. 219–224.

[24] B. Khalfi, M. B. Ghorbel, B. Hamdaoui, and M. Guizani, "Distributed fair spectrum assignment for large-scale wireless DSA networks," in *Proc. Int. Conf. Cognit. Radio Oriented Wireless Netw.*, 2015, pp. 631–642.

[25] G. S. Uyanik and S. Oktug, "Cognitive channel selection and scheduling for multi-channel dynamic spectrum access networks considering QoS levels," *Ad Hoc Netw.*, vol. 62, pp. 22–34, Jul. 2017.

[26] H. Shi, R. V. Prasad, E. Onur, and I. G. M. M. Niemegeers, "Fairness in wireless networks: Issues, measures and challenges," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 5–24, 1st Quart., 2014.

[27] H. Lee, S. Vahid, and K. Moessner, "A survey of radio resource management for spectrum aggregation in LTE-advanced," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 745–760, 2nd Quart., 2014.

[28] P. Ren, Y. Wang, and Q. Du, "CAD-MAC: A channel-aggregation diversity based MAC protocol for spectrum and energy efficient cognitive ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 2, pp. 237–250, Feb. 2014.

[29] F. K. Jondral, "Software-defined radio—Basics and evolution to cognitive radio," *EURASIP J. Wireless Commun. Netw.*, vol. 2005, no. 3, p. 652784, Dec. 2005.

[30] S. Debroy, S. De, and M. Chatterjee, "Contention based multichannel MAC protocol for distributed cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 12, pp. 2749–2762, Dec. 2014.

[31] N. Abramson, "THE ALOHA SYSTEM: Another alternative for computer communications," in *Proc. Fall Joint Comput. Conf.*, 1970, pp. 281–285.

[32] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, "SenseLess: A database-driven white spaces network," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 189–203, Feb. 2012.

[33] S. Kown, B. Kim, and B.-H. Roh, "Preemptive opportunistic MAC protocol in distributed cognitive radio networks," *IEEE Commun. Lett.*, vol. 18, no. 7, pp. 1155–1158, Jul. 2014.

[34] S. Pandit and G. Singh, "Backoff algorithm in cognitive radio MAC protocol for throughput enhancement," *IEEE Trans. Veh. Technol.*, vol. 64, no. 5, pp. 1991–2000, May 2015.

[35] Y. Li, L. Zhao, C. Wang, A. Daneshmand, and Q. Hu, "Aggregation-based spectrum allocation algorithm in cognitive radio networks," in *Proc. IEEE NOMS*, Apr. 2012, pp. 506–509.

[36] H. Su and X. Zhang, "Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 118–129, Jan. 2008.

[37] H. A. B. Salameh, M. Krunz, and D. Manzi, "Spectrum bonding and aggregation with guard-band awareness in cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 3, pp. 569–581, Mar. 2014.

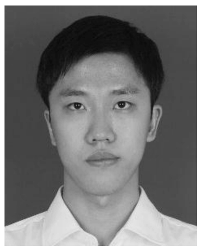
[38] R. K. Jain, D.-M. Chiu, and W. R. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared systems," Digit. Equipment Corp., Maynard, MA, USA, Tech. Rep. DEC-TR-301, Sep. 1984.

[39] O. V. Volkovich, V. A. Roshchin, and I. V. Sergienko, "Models and methods of solution of quadratic integer programming problems," *Cybernetics*, vol. 23, no. 3, pp. 289–305, 1987.

[40] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,* IEEE Standards 802.11-2012, Mar. 2012.

[41] W.-T. Chen, "An accurate tag estimate method for improving the performance of an RFID anticollision algorithm based on dynamic frame length ALOHA," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 1, pp. 9–15, Jan. 2009.

[42] H. B. Salameh, M. Krunz, and O. Younis, "MAC protocol for opportunistic cognitive radio networks with soft guarantees," *IEEE Trans. Mobile Comput.*, vol. 8, no. 10, pp. 1339–1352, Oct. 2009.



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