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A QoS-Aware Framework for Available Spectrum Characterization and Decision in Cognitive Radio Networks

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***Abstract*—The growing problem of spectrum scarcity and the inefficient spectrum utilization in the licensed bands, are addressed by the emerging Cognitive Radio (CR) paradigm. It is seen that the choice of the spectrum bands, called as *spectrum decision*, must be organized carefully by considering the challenges in the spectrum availability over time, the short term fluctuations in the availability, and the heterogeneous Quality of Service (QoS) requirements of the cognitive radio users. Taking into account these challenges, the main contribution of this paper is to design a QoS-aware spectrum decision framework that achieves higher throughput and fairness in CR networks. The available spectrum fluctuations are characterized by using queueing theoretic models and are parametrized by a novel QoS parameter called *opportunity index*, Ψ. The heterogeneous QoS requirements of CR users are classified by defining another novel QoS parameter called *request index*, κ. An admission control algorithm is designed to stabilize the heterogeneous QoS requirements according to Ψ and κ. A spectrum decision algorithm is developed to select most appropriate spectrum bands considering the stabilized QoS requirements and the characterized spectrum. Moreover, by using a novel spectrum mobility algorithm the available spectrum is continuously monitored for dynamic variations in the CR network. The simulations demonstrate that our QoS-aware spectrum characterization and decision framework maximizes the total throughput while maintaining the fairness.**

***Index Terms*—Cognitive radio networks, Spectrum decision, Spectrum characterization, QoS requirements, Admission control**

I. INTRODUCTION

Cognitive Radio (CR) networking has the capability to allow opportunistic use of the spectrum bands that are assigned to the primary users (PUs). Considering the PU activity, the CR users decide on the best available spectrum bands for their transmissions. This is part of the *spectrum decision* function. The spectrum decision framework must be aware of the available spectrum fluctuations, as well as the heterogeneous Quality of Service (QoS) requirements of the CR network [1].

In CR networks, the spectrum decision function must consider the fluctuations due to the following reasons: CR users can transmit data only if they can accurately detect the vacant (available) spectrum bands. However, the detection process must account for possible errors caused by the physical channel conditions and the fluctuations of the available spectrum. These fluctuations are caused by dynamic primary user (PU) activity [1]. More specifically, the spectrum usage of PUs can show significant short-term variations, and the CR users must be aware of them. Therefore, available spectrum characterization schemes should consider both the time-varying RF environment and the spiky traffic characteristics of the PU activity [2].

Besides the characterization of the available spectrum fluctuations, the spectrum decision mechanisms should also be aware of the heterogeneous QoS requirements of the CR users, like throughput and delay [1], [3]. In realistic scenarios, the QoS requirements of CR users can be classified into several heterogeneous application types, such as *Constant Bit Rate (CBR) traffic*, *video-conference*, *VoIP sessions and simple best effort (BE) communications*. Moreover, the QoS-aware spectrum decision schemes must also consider the trade-off between overall fairness among the CR users and the possible spectrum utilization.

In recent studies, the spectrum decision problem is addressed. In [3], an optimum spectrum decision framework is proposed by considering the basic QoS-specific CR user applications which are real-time and best effort (BE). In [3] novel optimization schemes are defined for spectrum decision to maintain the specific QoS requirements such as capacity and delay for CR users. In [4], a spectrum allocation paradigm is proposed only for the devices with constrained communication resources, as seen in sensor and ad hoc networks. The trade-off between fairness and utilization is pointed out in [4] for basic CR user applications. The studies in [5], [6] give optimization solutions for overall throughput and fairness using collaboration of CR users with basic QoS classifications but without a specific spectrum characterization.

Overall, these aforementioned studies assume Poisson modeling to characterize the available spectrum and PU activities.

However, the short-term fluctuations and spiky characteristics of the available spectrum should also be captured to achieve higher throughput [2]. Recent studies consider some basic CR user applications without clear distinction of their traffic types. In order to analyze the effects of heterogeneous applications on the overall performance of the CR network fairness, we also need to consider different CR user types [1]. With these motivations in mind, we propose a novel QoS-aware spectrum decision framework with the following contributions:

- A novel QoS parameter called *the Opportunity Index*, Ψ, is developed to characterize the available spectrum, considering the short-term fluctuations in the PU activity.
- The heterogeneous QoS requirements of CR users are categorized into four different groups by implementing four different queuing disciplines. Here, *the Request Index* κ is derived, which is able to capture the dynamic QoS requirements of CR users, i.e., the throughput and delay requirements.
- An admission control algorithm is designed to balance the available spectrum and the QoS requirements of CR users.
- Having the stabilized QoS requirements and the characterized spectrum as input, a spectrum decision algorithm is introduced, considering the overall fairness and throughput.
- Moreover, the spectrum mobility algorithm monitors the dynamic characteristics of the available spectrum and provides feedbacks to the spectrum decision algorithm for CR users to evacuate the spectrum when a PU comes back.

The remainder of the paper is organized as follows. In Section II, we introduce the system architecture and the proposed framework. The proposed framework modules are also explained in this section. In Section III, the performance of the proposed framework is evaluated in terms of the total throughput and fairness. We finalize the paper by summarizing the achievements in Section IV.

II. THE NETWORK ARCHITECTURE AND THE PROPOSED FRAMEWORK

A. Network Architecture

We consider an infrastructure-based CR network integrated in a licensed PU network, which operates on multiple spectrum bands. The CR network has a centralized network entity such as a base station (BS) and associated CR users. The BS has the control over all CR users within its transmission range. CR users are equipped with multiple software-defined radio (SDR) transceivers in order to monitor all spectrum bands [3]. The monitored information is gathered by BS to characterize the available spectrum at each band. Moreover, BS also collects the heterogeneous QoS requirements of CR users since they communicate with each other using the BS. Based on the state of the monitored spectrum and QoS requirements, BS decides on the appropriate spectrum bands for all CR users by the proposed framework.

B. Proposed Framework

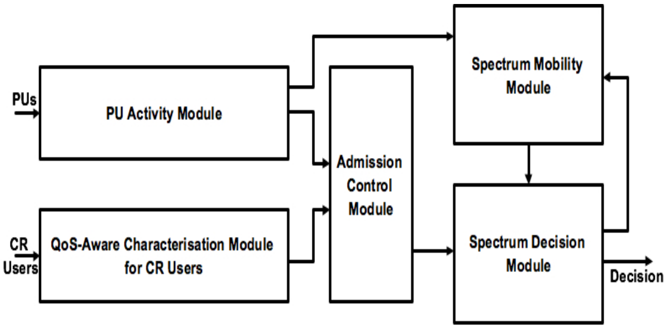


Fig. 1. The Proposed Framework

The proposed framework is implemented in the BS and it has five modules as shown in Fig.1. The PU Activity Module models each spectrum band by a separately. Then, it defines *the Opportunity Index*, Ψ, for each spectrum band. The QoS-Aware Characterization Module for CR users characterizes the heterogeneous CR users according to their QoS requirements by introducing a novel QoS parameter called *the Request Index*, κ. By using Ψ and κ, The Admission Control Module stabilizes the QoS requirements of the CR users according to the available spectrum. More specifically, the Admission Control Module checks the QoS requirements of the new CR users and accepts the newcomers only if their QoS requirements do not cause any QoS degradation for the existing CR users in the network. The Spectrum Decision Module runs its decision algorithm to assign the most appropriate spectrum bands to all CR users. The Spectrum Mobility Module continuously monitors spectrum for any dynamic changes. If there is a change, it means that there are PUs appearing in the spectrum bands. Then, the Spectrum Mobility warns the Spectrum Decision Module to modify the decisions accordingly.

1) The PU Activity Module: In this module, each spectrum band is modeled and analyzed by a separate queue-server mechanism. It analyzes each queue-server mechanism and defines *the opportunity index*, Ψ_m, for the m^{th} spectrum band. Actually, Ψ_m is the ratio between the spectrum availability, S_m, of CR users and the maximum usage, M_m, of PUs. This parameter shows the amount of available spectrum that CR users can exploit in the m^{th} spectrum band. It is defined as:

$$\Psi_m = \frac{S_m}{M_m}, \qquad \forall\ m \in [1, 2, .., \iota] \tag{1}$$

where ι is the total number of spectrum bands.

2) The QoS-Aware Characterization Module for CR Users: This module characterizes the heterogenous CR users according to their QoS requirements by defining a novel QoS parameter, *the Request Index*, κ_n. We define κ_n for CR users of type *n*, willing to use the m^{th} spectrum band, as the ratio between the instantaneous spectrum request of CR users R_n and the maximum request of CR users R_{max}.

$$\kappa_n = \frac{R_n}{R_{max}}, \qquad \forall\ n \in [1, 2, 3, 4]. \tag{2}$$

In this module, the CR users are classified into four different types and each CR User type is modeled with a different queuing discipline. The four different CR User types and their queuing disciplines are explained as follows.

- *Type 1 CR Users—E1/T1 Type Applications*: Type 1 CR users are E1/T1 applications based on Constant Bit Rate (CBR) traffic. More specifically, the traffic of type 1 CR users has deterministic behavior. They have the *highest* priority, i.e., they can occupy spectrum bands before all other CR user types. We model Type-1 CR users by a D/G/1 queueing system [7].
- *Type 2 CR Users—Video Conference Users*: They have the *second highest* priority, i.e., they can occupy spectrum band after serving Type 1 CR users and before Type 3 and 4 CR users. We model Type 2 CR users by a G/G/1 queuing system [8].
- *Type 3 CR Users— Voice Over IP (VoIP) Users*: They have the *third highest* priority, i.e., they can occupy spectrum band after Type 1, 2 CR users and before type 4 CR users. The VoIP traffic is modeled using a 2 State-Markov Modulated Poisson Process *MMPP* [9]. The two states of MMPP are BUSY and IDLE periods of a VoIP call. The BUSY period is the talk duration of the VoIP call, whereas the IDLE period is the silent period. Therefore, We model Type 3 CR users by a MMPP/G/1 queuing system [9].
- *Type 4 CR Users— Best Effort (BE) Users*: They have the *lowest* priority, i.e., they can occupy spectrum band after Type 1, 2 and 3 CR users. Type 4 CR users can be modeled by using an M/G/1 queueing system.

Moreover, we define some priorities, ϵ_n, for each type of user in order to have an accurate classification among different CR user types. These priorities are specified according to the QoS requirements of CR user applications. Therefore, defining priorities for different CR user types provides more QoS-awareness to our framework. The priorities are also important to achieve higher throughput for each CR user type. More precisely, CR users with higher priority indexes use the spectrum more aggressively than the CR users with lower priority. We define that Type-1 E1/T1 type CR users have highest priorities with $\epsilon_1 = 0.4$, Type-2 video-conference users have second highest priorities with $\epsilon_2 = 0.3$, Type-3 VoIP users have the third-highest priorities with $\epsilon_3 = 0.2$ and Type-4 BE users have lowest priorities with $\epsilon_4 = 0.1$.

3) The Admission Control Module: The Admission Control Module, seen in Fig.1, is responsible for stabilizing the QoS requests of new CR users. This is necessary to achieve higher throughput and fairness. More specifically, when new CR users arrive, they should not affect the QoS of existing CR users. New CR users should also be evaluated how much of their QoS requirements can be satisfied according to the available spectrum bands in order to provide higher throughput. Therefore, newcomers should be accepted to the system only if their QoS requirements do not degrade in the service quality of existing CR users.

The admission control module receives the QoS requirements of new CR users from the QoS-aware characterization module and the available spectrum information (i.e. the opportunity index Ψ) from the PU activity module. Then, the admission control module runs the Algorithm 1.

Algorithm 1 : Admission Control

```
Require: $\Psi_m \bigwedge \kappa_n \bigwedge \delta_n^{(m)}, \quad \forall m \in [1,2,..,\iota], n \in [1,2,3,4]$
$Total\_Opp \Leftarrow \sum_{m=1}^{\iota} \Psi_m$
$\epsilon_n \Leftarrow 1, \quad \forall n \in [1,2,3,4]$
$Total\_Req \Leftarrow \sum_n^4 \epsilon_n \kappa_n$
while $(Total\_Opp \le Total\_Req) \&\& (\delta_n^{(m)})$ do
    if $\epsilon_4 == 1$ then
        $\epsilon_4 \Leftarrow 0.1$
        $Total\_Req \Leftarrow \sum_n^4 \epsilon_n \kappa_n$
    else if $\epsilon_3 == 1$ then
        $\epsilon_3 \Leftarrow 0.2$
        $Total\_Req \Leftarrow \sum_n^4 \epsilon_n \kappa_n$
    else if $\epsilon_2 == 1$ then
        $\epsilon_2 \Leftarrow 0.3$
        $Total\_Req \Leftarrow \sum_n^4 \epsilon_n \kappa_n$
    else if $\epsilon_1 == 1$ then
        $\epsilon_1 \Leftarrow 0.4$
        $Total\_Req \Leftarrow \sum_n^4 \epsilon_n \kappa_n$
    else
        $Total\_Req \Leftarrow Total\_Opp$
    end if
end while
return $\kappa_n \Leftarrow Total\_Req$
```

The Admission Control Algorithm adjusts the QoS requirements of the new CR users considering the spectrum requests and available spectrum. New CR users are admitted to the system in a way that they don't cause any overload in the system resources.

4) The Spectrum Decision Module: The spectrum decision module seen in Fig.1 selects the most appropriate spectrum bands for CR users. This module runs the Spectrum Decision Algorithm as shown in Algorithm 2.

Following the necessary checks, the currently available spectrum is assigned to the CR users. For each CR user, this algorithm is repeated to allocate the most appropriate channel according to the QoS requirements of the CR user. Here, the assigned spectrum index $\delta_n^{(m)}$ of a type-n CR user in the m^{th} spectrum band is defined as follows:

$$\delta_n^{(m)} = \begin{cases} \kappa_n, & \text{if Perfect Decision} \\ \epsilon_n \kappa_n, & \text{if Smooth Decision} \\ \epsilon_n \Psi_m, & \text{if Aggressive Decision} \end{cases} \tag{3}$$

$$\forall n \in [1,2,3,4], \ m \in [1,2,..,\iota]$$

where κ_n is the request index of the type *n* CR users, Ψ_m is the opportunity index of the m^{th} spectrum band, ϵ_n is the priority index of type *n* CR users and ι is the total number of spectrum bands.

5) The Spectrum Mobility Module: This module as shown in Fig.1, continuously monitors the changes in the available

Algorithm 2 : Spectrum Decision

```
Require: $\Psi_m \bigwedge \kappa_n, \quad \forall m \in [1, 2, .., \iota], n \in [1, 2, 3, 4]$
for $m = 1$ $to$ $\iota$ do
    while $n \leq 4$ do
        if $\Psi_m > \kappa_n$ then
            $\delta_n^m \Leftarrow \kappa_n$ {Perfect Decision}
            $\Psi_m \Leftarrow \Psi_m - \delta_n^{(m)}$
            $n \Leftarrow n + 1$
        else if $\Psi_m > \epsilon_n \kappa_n$ then
            $\delta_n^m \Leftarrow \epsilon_n \kappa_n$ {Smooth Decision}
            $\Psi_m \Leftarrow \Psi_m - \delta_n^{(m)}$
            $n \Leftarrow n + 1$
        else
            $\delta_n^m \Leftarrow \epsilon_n \Psi_m$ {Aggressive Decision}
            $\Psi_m \Leftarrow \Psi_m - \delta_n^{(m)}$
            $n \Leftarrow n + 1$
        end if
    end while
end for
return $Fairness\ F\ and\ Throughput\ T$
```

spectrum. A change means that there is PU appearing in the spectrum band. Accordingly, the spectrum mobility module updates the results of the spectrum decision module.

When PU appears in the m^{th} spectrum band, the opportunity index Ψ_m starts decreasing. This is because there will be less opportunities for CR users to exploit that spectrum band when PUs appear. Moreover, the moment when the opportunity index Ψ_m becomes smaller than the assigned spectrum index $\delta_n^{(m)}$ in the m^{th} spectrum band, the CR users should evacuate that band. In that moment, the PUs start occupying the spectrum band and CR users should not affect the PU transmissions. Accordingly we define the so-called *Mobility Condition*:

$$\Psi_m < \sum_{n=1}^{4} \delta_n^{(m)}, \qquad \forall\ m \in [1, 2, .., \iota]. \tag{4}$$

This condition holds when the available spectrum band becomes less than the assigned spectrum due to the PU appearance. Using Eq. (4), we design a spectrum mobility algorithm as given in Algorithm 3. This algorithm updates the decisions made by the spectrum decision module when the condition, given in Eq. (4) holds, i.e., when PUs appear in the spectrum band.

The spectrum mobility algorithm updates the decisions made by the spectrum decision algorithm by considering the changes in the assigned spectrum indices $\delta_n^{(m)}$ of CR users based on the PU appearance.

III. PERFORMANCE EVALUATION

A. Simulation Environment

We implement all the system modules and the algorithms in MATLAB environment. We use a centralized CR network topology with one CR Base Station and 100 CR users [3].

Algorithm 3 : Spectrum Mobility

```
Require: $\Psi_m \bigwedge \delta_n^{(m)}, \quad \forall\ m \in [1, 2, .., \iota], n \in [1, 2, 3, 4]$
while $m \leq \iota$ do
    if $\Psi_m < \sum_{n=1}^{4} \delta_n^{(m)}$ then
        $\delta_n^m \Leftarrow 0$
        $m \Leftarrow m + 1$
    else
        $m \Leftarrow m + 1$
    end if
end while
return $\delta_n^{(m)}$
```

We assume 20 licensed spectrum bands ($\iota = 20$) as in [3]. These spectrum bands are 4 VHF/UHF TV bands with 6MHz bandwidth, 4 AMPS with 30 kHz bandwidth, 4 GSM with 200 kHz bandwidth, 4 CDMA with 1.25 MHz bandwidth and 4 WCDMA with 5 MHz bandwidth [3]. Moreover, we consider that the CR users are randomly distributed over a network coverage of 250 m [10]. The CR users are equipped with software defined radios (SDR) transceivers in order to select the appropriate spectrum band over a wide frequency range [3]. There are 4 different types of CR users (n=4). The 100 CR users are randomly distributed among four CR User types [3].

We compare our framework in terms of throughput and fairness with two other approaches (Approach 1 and Approach 2).

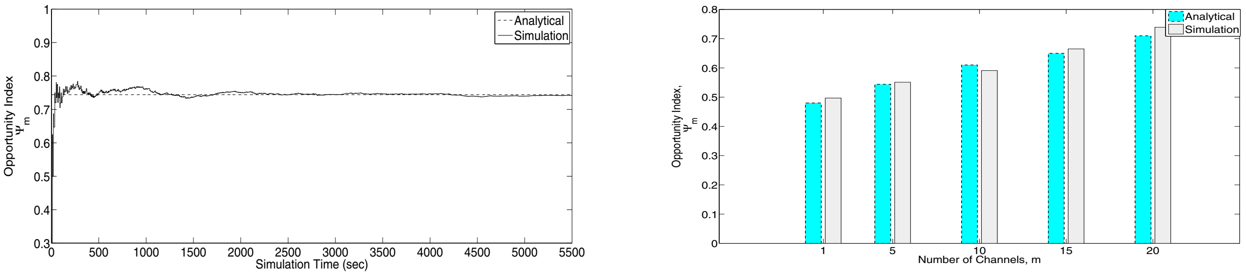
- *Approach 1–Traditional WFQ:* We implement a spectrum decision mechanism based on the traditional weighted fair queueing (WFQ) discipline [11]. In WFQ, each CR user type is served considering some static weight which is related to the specific QoS requirements.
- *Approach 2–WFQ with PU avoidance:* We implement the same WFQ based spectrum decision mechanism with Approach 1. Moreover, in this approach, we also implement the dynamic PU avoidance provided by our spectrum mobility module. Therefore, the CR users may utilize the available spectrum more efficiently using our spectrum mobility module.

The proposed framework is shown as *Approach 3*.

B. The Verification of the Opportunity Index

The proposed opportunity index Ψ_m is verified by simulation results as shown in Fig. 2(a). As shown, the simulation and the analytical results of the opportunity index are overlapping with time, which indicates that the proposed Ψ_m characterizes the available spectrum accurately.

In Fig.2(b), we show the verification of Ψ_m for different number of channels ($m = 20$). As seen, the analytical and the simulation results are similar. Moreover, Ψ_m increases with the number of channels *m*. This implies that when there are more channels, more transmission opportunities will be achieved for CR users.



(a)

(b)

Fig. 2. The Verification of The Opportunity Index Ψ_m in (a) Simulation Time and (b) in Multi-Channel Environment

C. Total Throughput

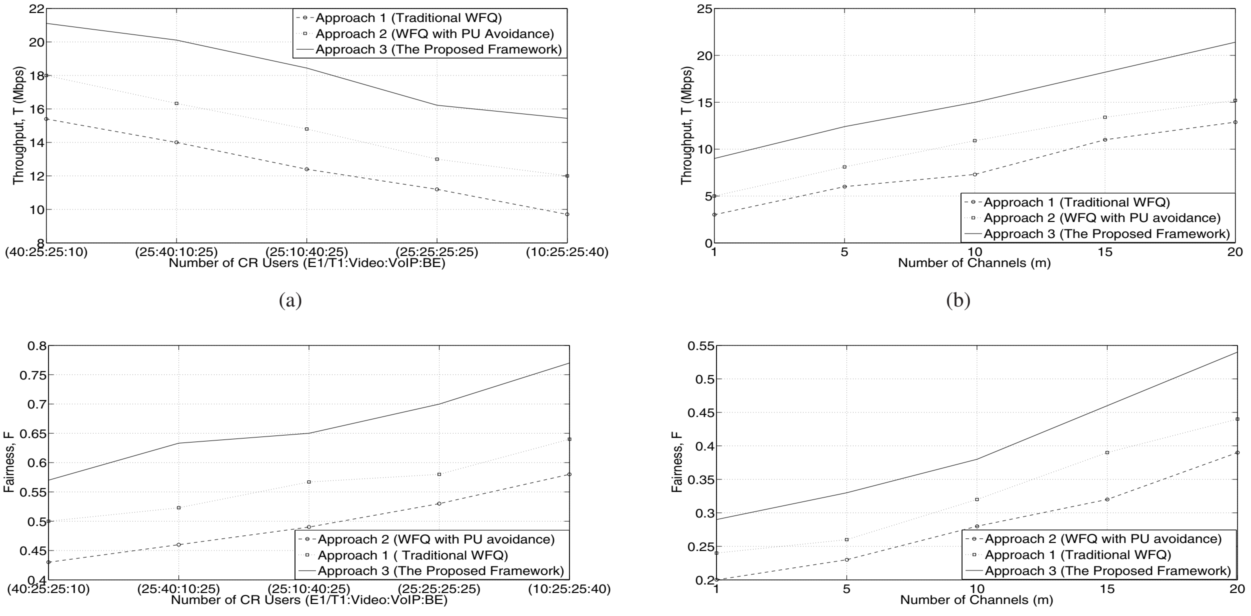
In Fig.3(a), the throughput is maximized in all three approaches when the number of Type-1 CR users (E1/T1) is greater than the others, represented by 40:25:25:10. This is due to the priority of Type-1 CR users being higher than the other traffic types. On the other hand, in Fig.3(a), we show that the throughput decreases when the number of CR users with smaller priorities increases. When the system has more CR users with smaller priorities, the available spectrum is decided by *the aggressive decision* part of the spectrum decision algorithm, given in Algorithm 2. Since the QoS requirements are not strictly considered in the aggressive decision, the total throughput decreases. In Fig.3(a), the total throughput in Approach 2 is higher than Approach 1 because the CR users may utilize the available spectrum more efficiently using the proposed spectrum mobility module which does not exist in Approach 1. Moreover, as shown in Fig.3(a), the throughput of the proposed algorithm (Approach 3) is higher than Approaches 1 and 2. Approach 3 has an admission control module in order to stabilize the QoS requirements of the new CR users according to the QoS of the existing CR users. This module admits the new CR users only if they do not cause any QoS degradation to the existing CR users. The accepted CR users employed the available spectrum bands based on three different decision procedures (perfect, smooth and aggressive). This technique leads to a dynamic spectrum decision mechanism for the new CR users since they can be assigned to more appropriate spectrum bands according to their QoS requirements. Consequently, in Approach 3 the decisions are taken more dynamically and accurately leading to an increase in the throughput compared to Approach 1 and Approach 2.

In Fig.3(b), we show the total throughput varying the number of channels *m*. For increasing number of channels the available spectrum for CR users also increases. Thus, there are more available spectrum bands to utilize leading to an increase in the throughput. More specifically, as we see in Fig.3(b), the throughput obtained by our framework (Approach 3) is almost 21 Mbps for 20-channel environment (m=20) whereas it is around 12 Mbps when m is equal to 5. Moreover, our framework achieves the highest throughput, since it stabilizes the QoS requirements of new CR users according to the admission control algorithm. Besides, the dynamic changes in the available spectrum can be captured better than the other two approaches, thanks to the spectrum mobility algorithm.

D. Overall Fairness among CR users

Our framework is aimed to provide a feasible spectrum decision for all types of CR users. We use the Jain's fairness index F of [12]. We modify F as $\frac{\sum_{m=1}^{\iota}(\sum_{n=1}^{4}\delta_n^{(m)})^2}{m\sum_{m=1}^{\iota}(\sum_{n=1}^{4}(\delta_n^{(m)})^2)}$. As seen, the fairness index depends on the assigned spectrum index of each CR user over the total assigned spectrum. When F approaches 1, it indicates that the fairness among CR users increases. In Fig.3(c) we show the changes in the fairness dependent on different number of CR users. We observe an increase in the fairness while the number of smaller priority users increases. When there are more high priority CR users in the system, the available spectrum is mostly assigned to them. In order to satisfy the QoS requirements of high priority CR users, the low priority CR users must sacrifice the spectrum. Therefore, the $\delta_n^{(m)}$ increases as the number of low priority CR users increases, leading to an increase in fairness as seen in Fig.3(c). In Fig.3(c), the fairness in Approach 1 is higher than Approach 2. In Approach 2, the CR users are more dynamically assigned to the available spectrum compared to Approach 1, according to the PU avoidance and without considering static weights. Moreover, the proposed framework achieves higher fairness than the other two approaches as seen in Fig.3(c). This is because the CR users are not subject to an admission control mechanism in Approach 1 and Approach 2. Thus the CR users can degrade the QoS assignments of existing users in the system. In Approaches 1 and Approach 2, the decision is based on a weighted fair queueing (WFQ) mechanism which does not consider the dynamic QoS requirements of CR users. On the other hand, the proposed framework has a dynamic spectrum decision mechanism with three different decision procedures (perfect, smooth and aggressive) in order to achieve a dynamic spectrum decision as explained in Algorithm 2. This dynamic decision procedure causes a better fairness for CR users since the spectrum bands are allocated according to their dynamic QoS requirements.

In Fig.3(d), we show the variation of the fairness in a multi-channel environment. The fairness for all three approaches increases with the number of channels because the CR users



(a) (b)

(c) (d)

Fig. 3. The Throughput For Different Number of CR users (a),The Throughput in Multi-Channel Environment (b), The Fairness For Different Number of CR users (c) and The Fairness in Multi-Channel Environment (d)

are more likely to find available spectrum in the system and leading to an increase in their assigned spectrum index ($\delta_n^{(m)}$). The proposed framework achieves better fairness than the Approach 1 and Approach 2, because no admission control is used in these approaches and accordingly, CR users can degrade the QoS assignments of existing users in the system.

IV. CONCLUSIONS

In this paper, we propose a QoS aware spectrum decision framework for cognitive radio networks. A novel spectrum characterization module captures the available spectrum fluctuations. We parametrize the available spectrum by defining a novel QoS parameter called the *opportunity index*, Ψ, and characterize the heterogeneous QoS requirements of CR users by introducing another novel QoS parameter called the *request index*, κ. The heterogenous QoS requirements are stabilized and controlled by a novel admission control mechanism using the opportunity index and the request index. Moreover, A spectrum mobility module is integrated to the framework to dynamically adapt the spectrum decisions of CR users. Performance evaluations show that our framework achieves a significant increase in total throughput and fairness among CR users. For future work, we consider to evaluate the proposed framework for the cases where some spectrum fragmentation occurs due to the spectrum allocation. In this case, the proposed parameters, Ψ and κ should be revisited for the optimum performance of the proposed framework.

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