QoS-Aware User Cohabitation Coordinator in Cognitive Radio Networks

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***Abstract*—In Cognitive Radio (CR) Networks, the licensed but vacant spectrum bands are shared by the unlicensed users (CR users) in an opportunistic manner. The CR users should operate and *cohabit* in the licensed bands without causing any interference to the Primary Users (PUs). This CR user cohabitation which is managed by a spectrum coordinator, enables several design challenges. Therefore, A *User Cohabitation Coordinator,UCC,* should be designed considering the heterogeneous Quality of Service (QoS) requirements for the CR users and the short-term fluctuations in the available licensed spectrum bands. Moreover, the spectrum coordination among the CR network operators for CR users should also be considered by the UCC for an effective and fair spectrum sharing. Considering these challenges, the main contribution of this paper is to design a QoS-based spectrum coordinator for CR user cohabitation in order to achieve high throughput and fairness. The proposed UCC uses the first-difference filter clustering and correlation based PU modeling to integrate the fluctuations of the PU activities into the spectrum sharing. The UCC characterizes the QoS requirements of CR users by adopting queuing theoretic models. The proposed scheme enables the cohabitation of the CR operators dynamically. The evaluations demonstrate that the proposed UCC provides high throughput while maintaining the fairness in the CR networks.**

I. Introduction

The key enabling technology for dynamic spectrum access techniques is the CR networking where the vacant spectrum bands of PUs are opportunistically shared by the CR users [1]. This spectrum sharing requires that the CR users should operate and *cohabit* in the licensed bands. In order to achieve this feature, also called the *CR User Cohabitation*, first, CR users should intelligently monitor the ongoing PU activities in the bands and determine the presence of PUs. Then, CR users are to detect the spectrum holes to identify transmission opportunities so that the total throughput is maximized. Considering the PU activity, CR users cohabit the available spectrum according to their heterogeneous Quality of Service (QoS) requirements. Moreover, the CR network operators should compete for the CR users in order to provide high total throughput while maintaining the fair coordination of user cohabitation.[1], [2].

In CR networks, the user cohabitation function must consider the fluctuations in the PU bands due to the following reasons: CR users can transmit data only if the vacant (available) licensed spectrum bands are accurately detected. However, this 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 PU activities [3]. Besides the determination of the available spectrum, the spectrum sharing mechanisms should also be aware of the heterogeneous QoS requirements of the CR users [4]. 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*.

CR network operators should coordinate the user cohabitation for the PU spectrum in order to give better service to their CR users. This can be organized by a User Cohabitation Coordinator (UCC). There are some efforts in the literature for the UCC design .In [5], a Spectrum Policy Server (SPS) is designed for the coordination. In this scheme, each operator announces its bandwidth request according to the service requirements of the corresponding CR users. Then, the SPS collects these requests and allocates to the operators the available spectrum accordingly. The main challenge in this procedure is to decide the proper strategy for the operators to maximize the usage and fairness.

In recent studies, there are some efforts to address the user coordination problem in CR networks. In [6], a novel spectrum and power allocation framework is proposed for inter-cell spectrum sharing CR networks, achieving high fairness and network capacity but considering a basic QoS classification. In [5] SPS-based systems are introduced for the coordination of spectrum demands in inter-network spectrum sharing. However, the bidding strategies employed in [5] do not consider neither the short term PU activity fluctuations nor the heterogenous traffic types. In [7], [8], [9], the proposed spectrum sharing algorithms give solutions for only limited QoS requirements. In addition, the proposed spectrum sharing schemes in [10], [11], [12] are not adaptive to the dynamic changes in CR users' requests.

Overall, all these aforementioned studies do not account a detailed QoS classification of CR users in the spectrum

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coordination. However, the spectrum allocation and sharing should consider a clear and more detailed distinction in the heterogeneous service requirements of CR users [2]. This is necessary to achieve high total throughput while maintaining the overall fairness among CR networks. Furthermore, the spectrum sharing schemes in [5], [7], [8] are not adaptive to the dynamic QoS requirements. However, dynamic QoS requests should also be integrated into the spectrum sharing mechanisms for more realistic results. Moreover, the SPS concept in [5] should also be evaluated for environments with multiple operators to investigate the effect of the request mechanisms in spectrum allocation. Besides, none of these studies consider the PU activity fluctuations as well as the short term spiky characteristics of the PU traffic in their spectrum sharing mechanisms.

Based on the drawbacks given above, in this paper, we design a QoS-aware User Cohabitation Coordinator (UCC), by making the following contributions:

- The heterogeneous QoS requirements of CR users are considered for the UCC by modeling the QoS requirements using four different queuing disciplines as in [13].
- The first-difference filter clustering and correlation based PU activity model is integrated to the UCC scheme to capture the short-term fluctuations of the PU activity[3]. This scheme catches the spiky characteristics of the PU traffic and utilizes the bandwidth more efficiently.
- A novel adaptive QoS-based spectrum sharing scheme is proposed in order to coordinate dynamic spectrum demands. This scheme provides an adaptive approach according to bandwidth requests coming from the CR operators.

The rest of the paper is organized as follows. In Section II, we explain the network architecture employed and introduce the proposed UCC. The designed modules of the proposed system which are *the CR Users QoS Classification Module*, *the PU Modeling Module*, and *the Spectrum Sharing Module* are detailed in Section III. In Section IV, we evaluate the performance of the proposed system considering total throughput and overall fairness among CR operators. We conclude the paper by summarizing the results obtained in Section V.

II. The Proposed System

A. Network Architecture

We consider a network topology with multiple CR operators, as shown in Fig.1. Each CR operator is assumed to have an infrastructure-based CR network integrated in a licensed PU network. The CR operators have access to multiple spectrum bands coordinated by the UCC and has associated CR users. The CR users are equipped with multiple software-defined radio (SDR) transceivers in order to transmit at a given spectrum band [4]. The monitored information is gathered by the operators to model the PU activity at each band. The considered network environment contains the proposed UCC to manage the spectrum sharing among CR operators as seen in Fig.1. Here, the UCC has two agents; server agent and client agent. The operators communicate with *the server agent of the UCC* and compete for the spectrum [5]. Each operator announces its bandwidth request using the heterogeneous QoS requirements of the corresponding CR users. The UCC also has a *client agent* at each CR operator, to collect these requests from the CR users. The available spectrum bands are then shared by the CR users of the chosen operators.

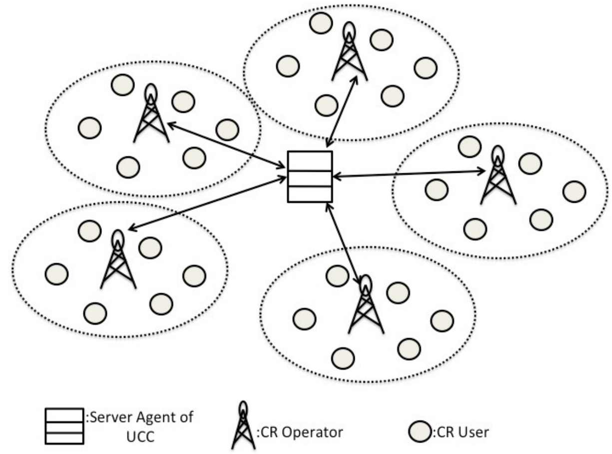


Fig. 1. The Network Architecture

B. Proposed System

The system we propose has three modules as shown in Fig.2. This system characterizes the heterogeneous CR users according to their QoS requirements in *The CR User QoS Classification Module* which is detailed in Section III. This module uses the QoS parameter called *the QoS Index*, κ, developed using specific queueing disciplines for the employed traffic types [13].

The operators collect the bandwidth requests of the CR users and send the total amount requested to the *The Spectrum Sharing Module* in the Server Agent of UCC. This agent collects these accumulated bandwidth requests from the CR operators and allocates the available vacant spectrum accordingly. If the bandwidth assigned to a CR operator is less than its request, the spectrum sharing module allocates the vacant spectrum to the requesting CR users, based on the QoS types of them. Definitely, in this case, the allocated bandwidth to a CR user will be less than the requested one.

The UCC also has a Client Agent at each CR operator. The spectrum sharing module in the Server Agent is also fed by *The PU Modeling Module* in order to catch the vacant spectrum of the PU. This module models the PU activities by characterizing the spiky behavior and the short-term fluctuations of the PU traffic by employing the first-difference filter clustering and correlation scheme [3]. The details of the scheme is given in Section III.

III. System Features

A. PU Modeling Module [3]

In recent studies, the PU activities are modeled by using Poisson distribution. The Poisson model approximates the

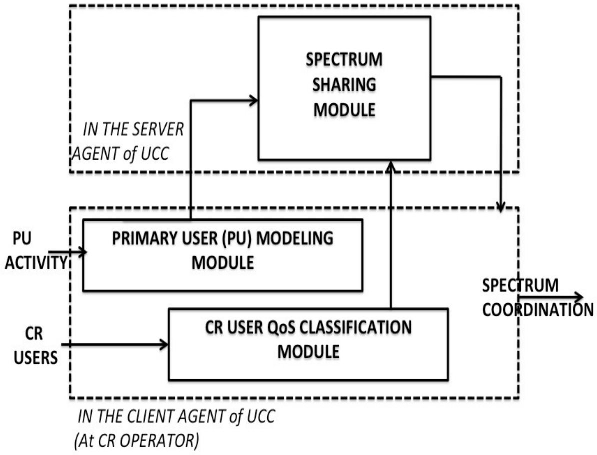


Fig. 2. The Proposed System

PU activities as smooth and burst-free traffic, thus the short-term temporal diversities of PU activities are not captured accurately. This misassumption caused by Poisson modeling degrades the network performance significantly. Moreover, this approach also decreases the spectrum decision accuracy. On the other hand, the PU activity model developed in [3] considers the spiky fluctuations of PU activities over time and models the PU traffic more accurately than Poisson Modeling. Therefore<m in this work, we adopt the PU Model of [3] into our UCC system. More information of the PU Model can be obtained in [3].

B. CR User QoS Classification Module,[13]

In this module, the QoS Index κ_n, is employed to characterize the heterogenous QoS requirements for the CR users. In that work, CR users are grouped according to their QoS requests. κ_n, the QoS index for CR users of type-*n*, is the ratio between the spectrum request of CR users R_n and the available bandwidth R_a. κ_n is the request of CR users of type-*n* to use the available spectrum band, considering their QoS requirements[13].

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

In this module, the CR users of four different types are modeled using appropriate different queuing disciplines. These four CR User types and the corresponding queuing disciplines are summarized as follows:

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

C. The Spectrum Sharing Module

The Spectrum Sharing Module, located in the Server Agent of UCC, is used to organize the bandwidth requests of the CR networks. Once the CR operators analyze the heterogeneous QoS requests of CR users and characterize requested bandwidths, they send them to the spectrum sharing module in the the Server Agent of UCC. It also receives the PU activity model from *the PU Modeling Module* in order to catch the vacant spectrum of the PU. Then, the spectrum sharing module assigns available spectrum of PUs to each CR operator. Consequently, CR operators allocate this available spectrum to the CR users. There are two situations that the spectrum sharing module can face, while allocating the available spectrum to the CR operators.

- If the total requested bandwidth of CR operators is higher than the assigned spectrum by the UCC, the CR operator allocates by the available spectrum band of the corresponding PU, according to a priority-based strategy. In this case, the bandwidth allocated to a CR user will be less than the requested one. Specifically, this strategy gives priority to each CR user type. CR user priorities are defined according to the QoS requirements of the corresponding applications. The priorities for the traffic types are defined as follows: Type-1 CR users have highest priority with $\epsilon_1 = 0.4$, Type-2 CR users have second highest priority with $\epsilon_2 = 0.3$, Type-3 CR users have the third-highest priority with $\epsilon_3 = 0.2$ and Type-4 CR users have the lowest priority with $\epsilon_4 = 0.1$. Using this strategy, the operators offer $\kappa_n^{(p)}$, which is calculated using the QoS indices κ_n as

$$\kappa_n^{(p)} = \epsilon_n . \kappa_n, \qquad \forall\ n \in [1, 2, 3, 4]. \tag{2}$$

- If the total requested bandwidth of CR operator is equal or less than the assigned spectrum by the the Server Agent of UC, It allocates the entire available spectrum to the operators' requests. Here, the available spectrum is shared proportionally among the CR operators according to their requests.

IV. Performance Evaluations

A. Simulation Environment

We implement all the system modules and the algorithms in the MATLAB environment. We use an inter-network topology with 1 UCC, 20 CR operators and 200 CR users. We assume 20 licensed spectrum bands as in [4]. The PUs arrive with PU activity indices Φ of [3], which is summarized in Section III.

Moreover, we consider that the CR users are randomly distributed and they are equipped with software defined radios (SDR) transceivers in order to select the appropriate spectrum band over a wide frequency range [4]. There are four different types of CR users *(n=4)* and the total number, 200, is distributed among different types. Specifically, we state that $\beta_1 + \beta_2 + \beta_3 + \beta_4 = 200$ where β_1 is the number of Type-1 CR users, β_2 is the number of Type-2 CR users, β_3 is the number of Type-3 CR users and β_4 is the number of Type-4 CR users . We assume that the channel is AWGN, and the noise power is selected as -115 dBm as in [4]. The results obtained for a confidence interval of %95 percentage, which are shown in the figures whenever they are not negligible.

The performance of the proposed system is compared based on total throughput and fairness. The performance is compared with those of two other CR network systems:

- CR Network System-1: In this system, there is an the Server Agent of UCC in order to organize the spectrum coordination among CR operators. Here, the spectrum allocation among operators is more dependent to the total available spectrum than the individual bandwidth requirements. This system utilizes the Sum-Rate Scheduling maximization. This scheme is aimed to maximize the total spectrum usage, by guaranteeing a minimum spectrum allocation of each CR operator. This approach is realized by allocating the fixed minimum spectrum to each CR operator.
- CR Network System-2: In this system, there is no UCC to organize the spectrum coordination among CR operators. Therefore, the spectrum allocation among operators is more dependent to the individual bandwidth requirements than the total available spectrum. It is the spectrum sharing mechanism of [7] where a minimum amount of available spectrum is assigned to the CR operators which is proportional with the individual bandwidth requests. This scheme aims maximizing the allocated available spectrum for individual operators, thereby increasing the overall fairness in the CR networks.
- CR Network System-3: It is the system proposed in the paper.

B. The Consistency of the QoS Index

The consistency of the proposed QoS index , $\kappa_n \quad \forall \quad n \in [1, 2, 3, 4]$ is verified by simulation results for different number of channels as shown in Fig.3. It could be observed that, the analytical and the simulation results are very close to each other for all QoS indices.

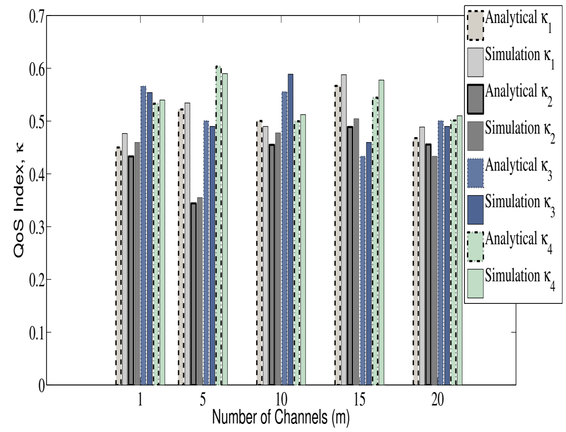


Fig. 3. The Consistency of the QoS Index κ for Different Number of Channels

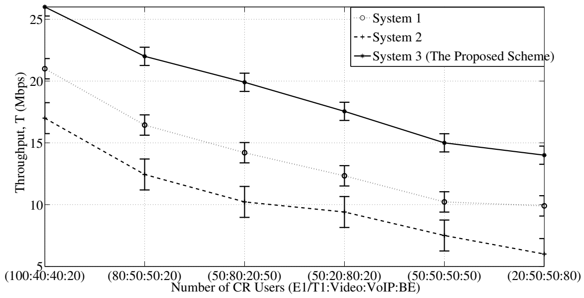
C. The Cohabitation Coordination in terms of Total Throughput

The total throughput *T* is the total spectrum band capacity that is assigned to CR operators.

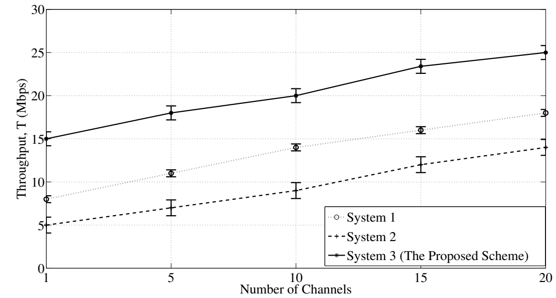
In Fig.4(a), the throughput is maximized in all three systems when the number of type-1 CR users (E1/T1) is greater than the other types (for x=100:40:40:20 values). This is due to the number of type-1 CR users in all three systems being significantly higher than the other traffic types. In Fig.4(a) we also see that the total throughput decreases when the number of CR users with less QoS requirements increases. When the system has more CR users with less QoS requirements, such as BE, the operators offer their bandwidth requests without strictly considering the QoS requirements of different user types, hence the total available throughput decreases. In Fig.4(a), the total available throughput in System 1 is higher than System 2 because the CR users may utilize the available spectrum since the scheduling mechanism in System 1 aims to maximize the throughput. Moreover, as shown in Fig.4(a), the total throughput of the proposed UCC (System 3) is higher than Systems 1 and 2. System 3 has an adaptive request mechanism for operators in order for them to adjust their request strategies according to the QoS requirements of the CR users. Besides, the UCC proposed employs a PU model which characterizes more accurately the spectrum holes in the spectrum bands, thereby increasing the total throughput compared to Systems 1 and 2.

In Fig.4(b), the total throughput for different number of channels is shown. By increasing the 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 total throughput. Moreover, the proposed scheme achieves higher throughput than the other two systems because of the adaptive request mechanism of the operators considering the heterogeneous QoS requirements of users and the accurate PU modeling.

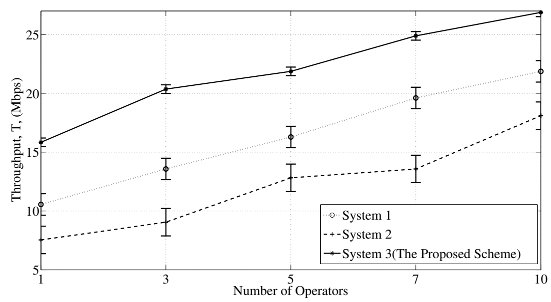
In Fig.4(c), we show the total throughput for various number



(a) Number of CR Users



(b) Number of Channels



(c) Number of Operators

Fig. 4. The Total Throughput Comparison

of operators. When the number of operators increases, more transmission opportunities are introduced. Moreover, the proposed scheme achieves the highest throughput than the other two systems because of the adaptive request mechanism of the operators considering the heterogeneous QoS classifications and the accurate PU modeling.

D. The Cohabitation Coordination in terms of Fairness

The proposed system is aimed to provide a feasible spectrum sharing among the CR operators. We define the fairness among the CR operators in terms of allocated bandwidth, F, using the Jain's fairness index of [14]. F fluctuates within 0 and 1 [14]. When it approaches 1, it indicates that the fairness among CR operators increases.

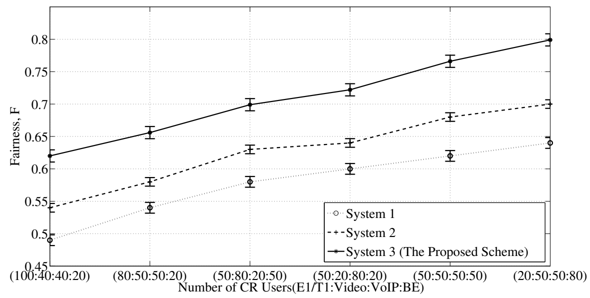
In Fig.5(a), we see an increase in the fairness while the number of CR users with less QoS requirements increases for all three Systems. When there are more CR users with less QoS requirements in the CR operators, the available spectrum is mostly assigned to these operators. In order to satisfy the high bandwidth requirements of CR users, the CR operators with low bandwidth requests must sacrifice their assigned spectrum, which may lead to an increase in fairness as seen in Fig.5(a). Moreover, in Fig.5(a), the fairness in System 2 is higher than System 1, because the sharing algorithm in System 2, assigns the available spectrum considering the individual QoS requirements, leading an increase in overall fairness. Moreover, the proposed framework achieves higher fairness than the other two Systems as seen in Fig.5(a). This is because It provides an spectrum sharing mechanism with an adaptive request, achieving a dynamic spectrum sharing with the consideration the different QoS requirements of CR users. This mechanism is also enhanced by a more accurate PU modeling which is another factor of an higher fairness. Consequently, the proposed mechanism (System 3) causes a better fairness for CR users since the spectrum bands are allocated according to their dynamic QoS requirements.

In Fig.5(b), we show the variation of the fairness for different number of channels. The fairness for all three Systems increases with the number of channels because the CR operators are more likely to find available spectrum in the system. The scheme we propose (System 3) achieves higher fairness than the Systems 1 and 2 because System 1 and 2 do not account for the dynamic bandwidth requirements of CR operators whereas the proposed system provides an adaptive system for operators in order for them to share the spectrum considering the different user types.

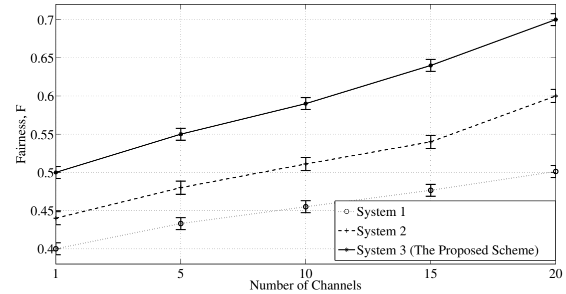
Fig.5(c) shows the variation of the fairness for different number of operators. As seen, The scheme we propose (System 3) achieves higher fairness than the Systems 1 and 2 when number of operators increases because of its adaptiveness towards heterogeneous service requirements of CR users.

V. Conclusion

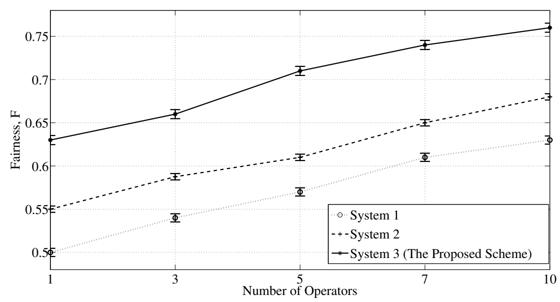
In this paper, we propose a QoS-based User Cohabitation Coordinator, UCC, for cognitive radio networks. In this mechanism, the QoS characterization module parametrizes the heterogeneous QoS requirements of CR users with a QoS parameter called *QoS index*, κ. With the help of the QoS characterization of CR users, the proposed UCC allocates the available spectrum among all operators' bandwidth requests.



(a) Number of CR Users



(b) Number of Channels



(c) Number of Operators

Fig. 5. The Overall Fairness Comparison

The first-difference filter clustering and correlation based PU modeling is employed in this work. Performance evaluations show that the proposed system achieves a significant increase in total throughput and fairness among CR operators. As a future work, it is planned to adapt the proposed QoS- based spectrum sharing scheme to the Cognitive Radio Ad-Hoc Networks (CRAHNs). In this case, it is planned to optimize each module of the proposed scheme in order to deal with the the multi-hop characteristic of the ad-hoc networks, as well as the message dissemination and heterogenous channel conditions of the CR operators.

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