Reliable Spectrum Sharing Management for Cognitive Radio Networks

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Abstract— **Cognitive Radio Network (CRN) is a promising network that aims to improve the utilization of the wireless spectrum by enabling unlicensed (secondary) users to reuse the underutilized bands. CRN utilization of residual spectrum bands of Primary (licensed) Networks (PNs) must avoid harmful interference to the users of PNs and other overlapping CRNs. Numerous Internetwork spectrum sharing frameworks have been proposed in the literature; however, spectrum sharing among overlapping CRNs presents significant challenges. This paper comprises two major contributions; firstly, it proposes a novel CRNs management framework, CogMnet, which regulates the operation of centralized CRNs. CogMnet aims to ensure the reliability of CRNs' spectrum sharing by tackling the Primary User Emulation Attack (PUEA) issue and avoiding an overcrowded CRNs scenario. Secondly, it proposes CRN Admission Control (CRNAC) algorithm capable of determining the maximum number of CRNs allowed in any location. To the best of our knowledge CogMnet is the first Internetwork framework able to distinguish an attacker CRN that may perform PUEA. Furthermore, CRNAC is the first network admission decision making algorithm in the CRNs literature. Analytical results are presented to demonstrate the performance of the algorithm. Assigning the number of CRNs is very important to avoid saturated spectrum situation.**

Keywords—CRNs; Internetwork Spectrum sharing; QoS; PUEA; Maximum Allowed CRNs.

I. INTRODUCTION

The overwhelming proliferation of new operators and innovative services during the last decade has resulted in a scarcity of available spectrum due to the fixed and conservative spectrum allocation policies applied by government regulators. However, according to the Federal Communications Commission (FCC), there is inefficient spectrum utilization by the licensed networks, where the spectrum is only utilized sporadically [1]. Therefore, cognitive radio (CR) technology has been proposed to utilize the residual spectrum bands more efficiently. The basic concept of CR builds on an Opportunistic Spectrum Access (OSA) (also called Overlay), where the CR user (also called Secondary User (SU)) is a wireless device capable of utilizing unused portions of the spectrum by avoiding harmful interference to the licensed user (called Primary User (PU)) [2]. As CR Networks (CRNs) are wireless in nature, they inherit all topologies present in traditional wireless networks, which are classified into: a) Centralized CRNs such as Wireless Regional Area Networks (WRANs), consisting of a Base Station (BS) and related SUs (called customer premise equipments in WRAN) [3]; and b) Distributed or CR Ad Hoc Networks (CRAHNs), where the SUs communicate directly with each other without any central node [4]. In this paper, the centralized CRNs that communicate in overlay mode are considered.

The competition for unoccupied spectrum bands often results in the misuse of the spectrum resources, thus causing interference with existing networks (PNs and other CRNs) [5]. Therefore, to enable efficient CRN communication, the spectrum sharing of CRNs should address two types of co-existence issues: incumbent co-existence (between SUs and PUs) and self-coexistence (among SUs in overlapping CRNs) [6]. Numerous research studies have effectively addressed the incumbent coexistence challenges by improving spectrum sensing accuracy (we refer the reader to [7] for a detailed survey). In other hand the self-coexistence problems pose a significant number of challenges need to be tackled. The major self-coexistence problems include the following:-

Challenge 1: Two or more CRNs move to utilize the same channel simultaneously.

Challenge 2: Adjacent channel interference among base stations.

Challenge 3: Scarcity of available spectrum in case of overcrowded CRNs.

Challenge 4: Unreliable spectrum sharing from security threats such as Primary User Emulation Attack (PUEA).

To the best of our knowledge, there is no internetwork framework capable of tackling these four major challenges together. We therefore propose a novel CRNs Management (CogMnet) framework capable of organizing the operation of CRNs via databases. Each database consists of three storage units coordinated by the regulators for certain functions. Unlike conventional frameworks, CogMnet records in real time the transmission parameters of utilized channels of each CRN in a particular database to ensure the reliability of spectrum sharing. Therefore, CogMnet enables detection of an attacker CRN that

triggers other CRNs to evacuate their best channels (i.e. it tackles the PUEA issue). To demonstrate the effectiveness of CogMnet, we propose the first CRN Admission Control (CRNAC) algorithm in the literature. CRNAC is a decision-making algorithm capable of calculating the maximum number of operating CRNs allowed in any location. Analytical results and comparisons are presented to illustrate the performance of CRNAC

This paper proceeds as follows. Section II explains the architecture of the CogMnet framework and the suggested conditions to manage CRNs spectrum sharing. Section III presents the CRNAC algorithm. Section IV evaluates the behaviour of CRNAC with numerical results in different scenarios. Section V discusses the expected merits of the paper. Finally, Section VI provides some conclusions and directions for future work.

II. PROBLEM STATEMENT

To mitigate Challenges 1 to 3 above, two types of internetwork resource sharing mechanism are provided in the literature: *Channel allocation schemes* [6 - 10], and *Resource renting* [11, 12]. In the first type the researchers proposed resource allocation schemes based on either spectrum efficient traffic awareness (e.g. [6]), or minimizing interference across the networks (e.g. [9]). The main drawbacks of such spectrum assignment algorithms are that they assume that all BSs (of all CRNs) are willing to exchange their spectrum bands. Additionally, they assume reliable control channels for the networks to exchange their channel information. In the second mechanism (*Resource renting*), the proposed schemes are based on a spectrum pooling concept and consider the cost-benefit trade off (i.e. cost = paying to PNs, and benefit = achieving spectrum bands for CRNs). For example, the authors in [12] proposed a spectrum sharing scheme, where each CRN requests an available spectrum from servers located at cloud computing for an unfixed fee (depending on the channel's properties and number of requested networks).

However, we ask here, who will guarantee that whenever a new CRN operates, it will cooperate with the existing CRNs? Furthermore, who will be responsible for and capable of administrating and coordinating the cooperation among CRNs?

On the other hand, PUEA (the fourth challenge), which is an attack by a selfish or malicious node (belonging to a CRN) through transmitting signals, has the same power and characteristics of PUs to trigger another CRN to evacuate some of its channels [13]. Most research studies in the literature concentrate on proposing algorithms capable of distinguishing real PU signals from PUEA, such as [14-17]. In [14] the authors proposed a game theory-based approach to counteract three types of PUEA (selfish, malicious, and mixed). Exploiting a cyclostationary features approach to received signals was proposed in [15]. The authors in [17] evaluated the performance analysis in terms of outage, dropping and blocking probabilities when the network is under PUEA. They showed that the performance of a CRN may deteriorate severely according to PUEA rate arrival. Accordingly, even when PUEA is identified, channels under attack can no longer

be utilized; consequently the attacked channel must be evacuated. Therefore, we ask, what is the benefit in distinguishing PUEA if it cannot be stopped? Also how can the victim network be able to prove the attack and the attacker identity? Moreover, to whom may the attacked network complain in order to stop the aggressive network?

III. CRNS MANAGEMENT FRAMEWORK

Considering the addressed challenges, we have good reasons to propose an Internetwork framework capable of regulating the CRNs spectrum sharing. By regulating we mean only coordinating their spectrum sharing rather than licensing spectrum bands to them, because CRNs have no dedicated spectrum bands. Accordingly, we propose CRNs Management (CogMnet) as an internetwork framework that aims to ensure reliable spectrum sharing among centralized CRNs. CogMnet must be administered by the regulator which is responsible for spectrum management of wireless systems in the country (e.g. FCC in the USA, and Ofcom in the UK).

A. CogMnet Implementing Procedure

Consider a scenario of multiple centralized CRNs, each consisting of a base station (BS) and related SUs. The communication range of each BS is assigned by its network and may overlap with other CRNs in its vicinity. Spectrum resources that are not being used by the licensed incumbents can be exploited by existing CRNs. We assume that no CRN is able to operate without permission from the regulator. Furthermore, the regulator has exclusive right to stop the operation of any CRN that does not follow CogMnet conditions. As illustrated in Fig. 1, CogMnet architecture design can be summarized very briefly as follows:-

1) Locations: Divide the entire country (any country) coverage area into L locations (e.g. each location represents a city), where $\{L \in \mathbb{Z}^+; L \geq 1\}$. The size of the locations must be assigned by the regulator, which may differ from one country to another.

2) Real time Databases: Dedicate a real time database for each location which can be defined as $\{DB_1, DB_2, ..., DB_l, ..., DB_L\}$ where $\{l \in L\}$. Each DB_l comprises three storage units:

a) Networks locations storage unit (NL_{DB_l}), which is a storage unit that can be used to record the networks' BSs details: **position** (longitude and latitude), the **status** (active, inactive), **date of status**, and **communication range** (radius) All CRN musr provide these details to the regulators, and inform them of any changes. Consequently, the regulator must update the storage unit for any change (e.g. inserting a new network).

b) Real time storage unit (RT_{DB_l}) that can be used to record the specification of the channels that are currently in use by the existing CRNs.

c) Historical storage unit (HS_{DB_l}), which is a large size storage unit that can be used to record the details of the channels evacuated by any BS (transferred from RT_{DB_l}).
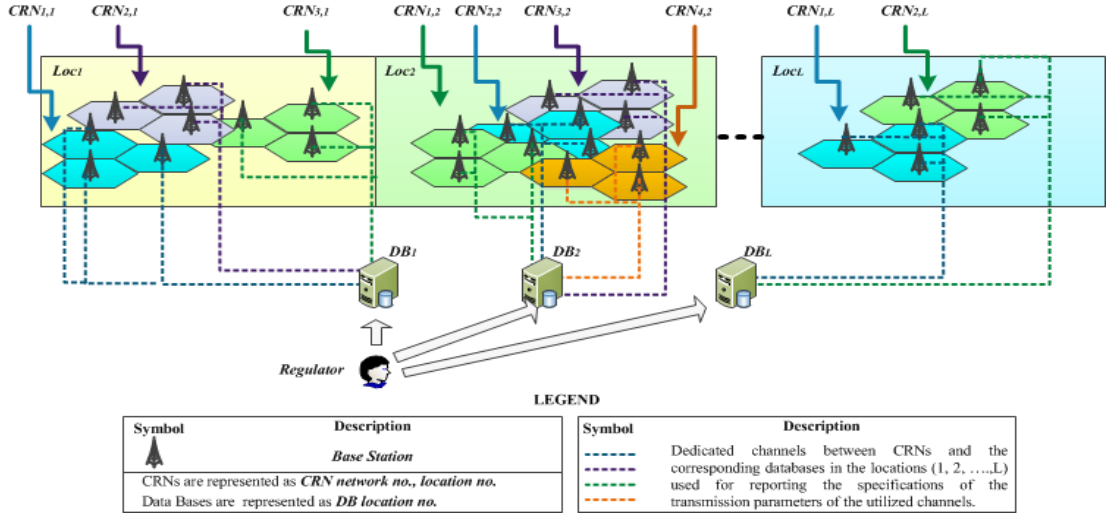
Fig. 1. CogMnet framework design.

3) Recording forms: To record the specifications of CRNs, each base station must send in real time the transmission parameters of its utilized channels to the corresponding database, that is, in RT_{DB_l}. The recorded parameters are as follows:

a) Band widths (BWs): the frequencies of the utilized channels (i.e. f_{min}, and f_{max}).

b) Utilization: Date and time of starting to utilize the channel once they are being exploited.

c) Evacuation: Date and time of evacuating their channels after handing off.

d) Power: Maximum transmission power of each channel.

e) Modulation: Modulation and Coding scheme (MCS) of each radio resource.

According to the above, if any channel is evacuated then its specifications will be removed from RT_{DB_l} to HS_{DB_l}. Additionally, the evacuation date and time of the channels will be inserted.

B. Modelling CogMnet

Clearly, each location will consist of a different number of CRNs. Additionally, each network will consist of a certain number of base stations; thus we define $Net_{n,l}$ as any network in any location. Accordingly, we define $BS^x_{Net_{n,l}}$ as any base station (x) of network (n) in a location (l), where $\{x \in \mathbb{Z}^+\}$. For example, if network 3 in location 5 (i.e. $Net_{3,5}$) has 7 base stations, the base stations can be defined as $\{BS^1_{Net_{3,5}}, BS^2_{Net_{3,5}}, ..., BS^7_{Net_{3,5}}\}$. As mentioned earlier, the details of each base station of each CRN must be recorded in the network location storage unit. Thus we define the longitude and latitude of $BS^x_{Net_{n,l}}$ as $Lo_{BS^x_{Net_{n,l}}}$ and $La_{BS^x_{Net_{n,l}}}$ respectively. Furthermore, the status of each base station will be denoted as Active (Inactive) when operating (or stopped). Moreover, we define the current date of $BS^x_{Net_{n,l}}$ status $D_{BS^x_{Net_{n,l}}}$ (i.e. date that it has started or stopped). In addition,

the radius of the potential communication range of $BS^x_{Net_{n,l}}$ is defined as $R_{BS^x_{Net_{n,l}}}$.

Accordingly, the storage units (NL_{DB_l}, RT_{DB_l}, and HS_{DB_l}) are exemplified in Tables I, II, and III respectively, *where the specifications of the networks and the channels do not represent any real data, and are given simply to clarify the recoding form*. Note that, the dates are defined as (dd/mm/yy), while the times are denoted as (hour: minute: second: second parts).

C. Exploiting Data Bases conditions

In this sub-section we suggest certain conditions that all CRNs must follow in exploiting the storage units. Thus, the conditions to exploit the databases can be summarized as follows:

1) Database Inside Network Location: Each CRN can access its location's database (i.e. storage units) in order to obtain information about the bands utilized by other networks. However, to preserve the privacy of the CRNs' utilization, the access to the storage units must be performed without revealing the identity of the networks. Therefore, the green columns in Tables I, II, and III are only what can be introduced by existing CRNs. For that reason, each BS has been given a sequence number "**Base Station Sequence in CogMnet**" that does not reflect to which network mat it belongs. Accordingly, if any BS attempted to perform PUEA to another network, it would be very easy to detect it. Consequently, CogMnet will guarantee that no network can trigger other CRNs to leave their best channels. As a result, the PUEA issue will be tackled permanently.

2) Database Outside Network Location: CRNs must be capable of utilizing the databases of other locations in order to build a cognitive engine about other locations that the network may plan to extend to. However, in this case each network must pay an extra fee which depends on the amount of utilized information such as channel utilized in all or part of location, number of base stations, etc.

TABLE I.
EXAMPLE OF RECORDING FORM IN NETWORKS LOCATIONS STORAGE UNIT (EXAMPLE OF TWO CRNs)

CRN	Base Station	Base Station Sequence in CogMnet	Longitude	Latitude	Status	Date of status	Communication range
1	1	1	$Lo_{BS^1_{Net_{1,5}}}$	$La_{BS^1_{Net_{1,5}}}$	Active	$D_{BS^1_{Net_{1,5}}}$	$R_{BS^1_{Net_{1,5}}}$
	2	2	$Lo_{BS^2_{Net_{1,5}}}$	$La_{BS^2_{Net_{1,5}}}$	Active	$D_{BS^2_{Net_{1,5}}}$	$R_{BS^2_{Net_{1,5}}}$
	3	3	$Lo_{BS^3_{Net_{1,5}}}$	$La_{BS^3_{Net_{1,5}}}$	Inactive	$D_{BS^3_{Net_{1,5}}}$	$R_{BS^3_{Net_{1,5}}}$
2	1	4	$Lo_{BS^1_{Net_{2,5}}}$	$La_{BS^1_{Net_{2,5}}}$	Active	$D_{BS^1_{Net_{2,5}}}$	$R_{BS^1_{Net_{2,5}}}$
	2	5	$Lo_{BS^2_{Net_{2,5}}}$	$La_{BS^2_{Net_{2,5}}}$	Inactive	$D_{BS^2_{Net_{2,5}}}$	$R_{BS^2_{Net_{2,5}}}$

TABLE II.
EXAMPLE OF RECORDING FORM FOR THE SPECIFICATIONS OF UTILIZING CHANNELS IN REAL TIME STORAGE UNIT

CRN	Base Station	Base Station Sequence in CogMnet	Channel frequency		Starting utilization time	Starting utilization date	MCS		Max. transmit power (watt)
			f_{min}	f_{max}			Modulation	Code	
1	1	1	2230	2240	23:59:24:13	08/05/15	64 QAM	2/3	16
1	1	1	2570	2580	23:59:24:13	08/05/15	64 QAM	2/3	14
2	1	4	720	730	23:59:32:56	08/05/15	QPSK	1/2	20
2	1	4	960	970	23:59:32:56	08/05/15	QPSK	1/2	20
2	1	4	1470	1480	23:59:32:56	08/05/15	QPSK	1/2	18
1	2	2	820	830	23:59:34:15	08/05/15	16 QAM	1/2	20
1	2	2	1580	1590	23:59:34:15	08/05/15	16 QAM	1/2	20
1	2	2	1790	1800	23:59:34:15	08/05/15	16 QAM	1/2	16
2	1	4	1590	1600	23:59:44:04	08/05/15	QPSK	1/2	16
2	2	5	1390	1400	23:59:51:67	08/05/15	BPSK	1/2	18
2	2	5	2130	2140	23:59:51:67	08/05/15	BPSK	1/2	16

TABLE III.
EXAMPLE OF RECORDING FORM FOR THE SPECIFICATIONS OF EVACUATED CHANNELS IN HISTORICAL STORAGE UNIT: (THE CHANNEL (720-730) MHZ IS EVACUATED IN 09/05/15 AT 00:03:22:35, THE CHANNEL (1390-1400) MHZ IS EVACUTATED IN 09/05/15 AT 00:04:43:21)

CRN	Base Station	Base Station Sequence in CogMnet	Channel		Utilization time	Utilization date	Evacuation time	Evacuation date	MCS		Max. transmit power (watt)
			f_{min}	f_{max}					Modulation	Code	
1	1	4	720	730	23:59:32:56	08/05/15	00:03:22:35	09/05/15	64 QAM	2/3	14
1	1	5	1390	1400	23:59:51:67	08/05/15	00:04:43:21	09/05/15	BPSK	1/2	18

The amount of fees for exploiting databases inside and outside network location are out of this research scope, because it may need an extensive study from an official regulator or a technology company on CogMnet implementing requirements. These fees must be small, and should represent the costs of achieving reliable spectrum sharing among the networks and to improve their performance. Finally, to demonstrate the effectiveness of CogMnet, the next section will propose a decision-making algorithm capable of calculating the maximum possible number of CRNs allowed to operate in any location.

IV. NETWORK ADMISSION CONTROL ALGORITHM

With the anticipated growth in the number of CRNs, the available spectrum bands will rapidly decrease (i.e. saturated spectrum situation). As a result, there will be degradation in QoS provision of the existing networks; and the new networks will perform poorly. To the best of our knowledge this issue has not been investigated before. In this section a CRN Admission Control (CRNAC) algorithm is proposed. CRNAC is a decision-making algorithm capable of allowing a new CRN to operate in any location under certain constraints. Additionally, it is able to calculate the maximum number of networks allowed in any location by exploiting the information on each CRN from CogMnet.

A. Preliminaries to Applying CRNAC

The same system model that has been modelled for CogMnet will be adopted for CRNAC. Since the algorithm can be applied in any location, we consider $L = 1$. Additionally, we assume that the location consists of N centralized CRNs, where the BSs of each CRN report the utilized spectrum specification to the databases of CogMnet. The regulator should periodically (for example annually) perform two major spectrum measurements: a) Calculate total spectrum availability; and b) Calculate the spectrum utilized by each CRN. These two measurements can be described as follows:

1) Spectrum Measurements Campaigns: In the first set of measurements the regulator should perform several campaigns to measure spectrum occupancy (occupied by both PNs and CRNs). The measurements should cover the suitable frequency range for CRN operation (e.g. 30MHz to 3GHz as usually assumed in the literature). Thus, assuming the average occupation measurements (in percentage) of one campaign are $O = \{o^1, o^2, ..., o^t..., o^T\}$ where $\{o^t \in \mathbb{R}^+ : 0 \leq o^t \leq 100\}$, $\{t \in \mathbb{Z}^+, 0 \leq t \leq T\}$ and T is the total unit time of one campaign, the percentage of spectrum availability measurements can be defined as $X = \{x^1, x^2, ..., x^t..., x^T\}$, where $\{x^t \in \mathbb{R}^+ : 0 \leq x^t \leq 100\}$ and $x^t = 100 - o^t$. Finally, to achieve a more reliable decision, we suggest that the campaign must be repeated D times.

2) CRNs Spectrum Usage: While measuring X, the regulator exploits the CogMnet database (the historical storage unit) to perform the second set of measurements. These measurements include calculating the percentage of spectrum usage in the same frequency range by each CRN $Y_n = \{y_n^1, y_n^2, ..., y_n^t ..., y_n^T\}$, where $\{Y_n \in \mathbb{R}^+ : 0 \leq y_n^t \leq 100\}$, $n \in N$, and N is number of CRNs. Similarly to spectrum measurements campaigns, Y_n must be repeated D times.

B. Admission Steps of CRNAC Decision Making

Admission for a new CRN should be based on the fact that there are enough spectrum bands to operate. Furthermore, the operation of a new CRN will impact on the existing CRNs through sharing the available spectrum. Therefore, when CRNAC admits any new network, it confirms to the administrators of the existing CRNs that there are enough available spectrum bands for the new CRN to operate. Furthermore, it assures the administrator of the admitted CRN that there are enough bands for its operation. *Since we aim to address the self-coexistence problems by resource management at **network level** rather than **user-level**, the metric used to measure networks performance is total utilized spectrum bands*. The suggested constraints of the CRNAC to admit a new CRN can be as follows:

1) Needed spectrum for the new CRN: There must be unoccupied spectrum bands for a new network, which must be similar to the utilization of existing CRNs. Therefore, the question here is: which CRN from the existing networks should be used as a reference network in CRNAC's decision? If the decision is based on the utilization amount of the poorest CRN performance (i.e. lower spectrum bands utilizing), this means

an overcrowded CRNs and saturated spectrum scenario is likely to occur. Therefore, we propose a hypothesis that there must be unoccupied spectrum bands equal to the average needed spectrum by the highest performance CRN (i.e. higher spectrum bands utilizing). Thus, the first constraint states that there must be available bands equal to average required spectrum by highest performance CRN from its measurements $\overline{Y_n}$ (where $\overline{Y_n} = \sum_{t=1}^{T} y_n^t / T$). We refer to it as $Spec$, that can be calculated as:

$$Spec = max\{\overline{Y_1}, \overline{Y_2}, ..., \overline{Y_N}\} \qquad (1)$$

2) Scalability of existing CRNs: The spectrum utilization of all existing CRNs is strongly expected to increase. Therefore, the percentage increase in bands utilization of each network must be considered in CRNAC. Thus we define ψ_n to be the expected scalability of a CRN (n), where $\{\psi_n \in \mathbb{R}^+ : 0 \leq \psi_n \leq 100\}$. ψ_n can be easily anticipated (using a prediction method) from quantities of average utilizations $\overline{Y_n}$ in all previous campaigns Thus, ψ_{total} is the total expected scalability of all existing networks and is calculated as $\psi_{total} = \sum_{n=1}^{N} \psi_n$.

3) Scalability of PNs: Increasing spectrum utilization from PNs on their licensed spectrum is another important factor that must be taken into consideration by CRNAC. Therefore, the regulator should predict the percentage increase of spectrum utilization $\Delta_{PN \ scalability}$ by PNs' users $\{\Delta_{PN \ scalability} \in \mathbb{R}^+ : 0 \leq \Delta_{PN \ scalability} \leq 100\}$. Similar to ψ_n, $\Delta_{PN \ scalability}$ can be predicted from previous measurements.

4) Safety spectrum guard: Due to the fact that spectrum availability fluctuates most of the time. Furthermore, there is a heterogeneity of channels with different characteristics available over a wide frequency range. Thus, not all available channels can be exploited for several reasons (e.g. low channel holding time, channel switching delay etc.) [19]. There must be consideration for a safety guard spectrum factor. It must be assigned carefully and needs continuous extensive calculation on spectrum bands characteristics. Thus we define it as Δ_{guard}, where $\{\Delta_{guard} \in \mathbb{R}^+ : 0 \leq \Delta_{guard} \leq 100\}$.

According to the aforementioned factors, the admission of a new CRN can be calculated as follows:

$$Diff = \overline{X} - Spec - \psi_{Total} - \Delta_{PN \ scalability} \geq \Delta_{guard} \quad (2)$$

$\overline{X}$ is the percentage average of spectrum availability measurements X. The meaning of (2) is that if the $Diff$ is larger than or equal to Δ_{guard}, then a request for new CRN can be accepted. Thus the number of existing CRNs will be incremented by one. At the same time the CRNAC algorithm is capable of calculating the maximum number of CRNs allowed in the location. In this step there is no need to consider ψ_{Total} and $\Delta_{PN \ scalability}$; instead, only $Spec$ and Δ_{guard} are considered. Accordingly, admission of another new CRN can be based on the following constraint:

$$Diff_{new} = Diff - Spec \geq \Delta_{guard} \qquad (3)$$

Consequently, as long as the constraint in (3) is valid, it is possible to admit new CRNs. Thus, the maximum number of allowed CRNs will be obtained by repeating (3). The next section will examine the performance of the CRNAC algorithm.

V. CRNAC Performance Evaluation

To examine the effectiveness of CRNAC, a numerical test was carried out using MATLAB (8.2.0.701). Before starting the evaluation, it was very necessary to investigate spectrum measurement campaigns. We studied most of the campaigns that were surveyed recently in [18]. Clearly, the majority of the campaigns focused on the frequency range between 30MHz and 3GHz. The maximum measurement was found in the Barcelona campaign [19], where the occupancy was 22.57% in the frequency range 75 MHz to 3000 MHz. Accordingly, we consider this occupation in some of the experimental scenarios.

Turning now to the experimental assumptions, in order to achieve precise decisions by CRNAC, we assume that the regulators measure spectrum availability once in each hour, and repeat the measurements for 60 days (i.e. $T = 24$, and $D = 60$ in CRNAC specifications). In addition, we assume that there are five CRNs that coexist in the available spectrum (i.e. $N = 5$). As shown in Table IV, different percentages of the spectrum bands utilization and expected scalability for the CRNs are assumed. Moreover, $\Delta_{PN\ scalability}$, and Δ_{guard} are assumed to be 1% and 5 % respectively. Due to page restrictions, we evaluate the algorithm in three scenarios only, and defer some scenarios to the full paper. Finally, Table V summarizes the scenarios' assumptions as well as the remaining aforementioned factors.

Scenario 1: Δ_{guard} Evaluation

Based on tables IV and V, in the first scenario, we examine the effect of the most important constraint of the CRNAC algorithm by varying the safety guard Δ_{guard} of equation (2) in three different percentage amounts: 5, 10, and 15. It is clear from Figure 2 that the admission started with less guard (e.g. 5%). Furthermore, the admission of smallest Δ_{guard} (i.e. 5) increased up to two CRNs in comparison with the largest Δ_{guard} (i.e. 15) at maximum spectrum availability. It is worth mentioning that in fact the maximum spectrum availability is not 55%, as illustrated in Figure 2. Instead, it is what remains from the utilization of existing CRNs (i.e. five CRNs), PNs (i.e. 22.57% [19]), and safety guard. Furthermore, we suggest that the safety guard amount should be primarily dependent on the fluctuation of spectrum availability, which is the next scenario of evaluating CRNAC.

Scenario 2: Variations in Spectrum Availability

The second scenario was inspired by [20], where the spectrum occupancy measurements revealed that the spectrum utilization varies between 4% and 15% of the total frequency range 700 MHz to 3 GHz. Therefore, the second scenario addresses the impact of the fluctuation of spectrum availability measurements on the CRNAC decision. In this scenario, three

TABLE IV.
UTILIZED SPECTRUM BANDS AND EXPECTED SCALABILITY ASSIGNED FOR EXISTING CRNs AND PNs.

Network	The Utilized Spectrum (%)	Expected Scalability (%)
CRN1	3 – 6	0.5
CRN2	6 – 9	1
CRN3	8 – 12	1.5
CRN4	5 – 8	0.6
CRN5	3 – 5	0.4
PNs	Variable	5

TABLE V.
FACTORS ASSIGNED IN THE CRNAC EVALUATION

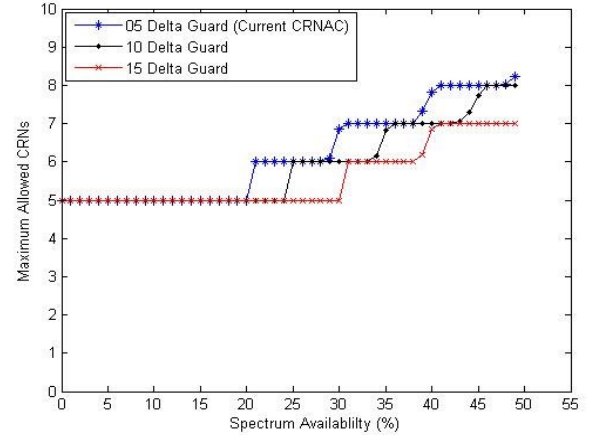| Factors	Assigned value	
Average spectrum occupancy before experiments ($\overline{X}$)	22.57% [19] in Scenarios 1, 2, and 3 (part 1)	13% [21] in scenario 3 part 2 & 3
Δ_{guard}	5%	
Number of location	1	
Number of runs	1440 (= 60 * 24)	

Fig. 2. Maximum numbers of CRNs Allowed according to different Δ_{guard} (first scenario)

different fluctuations in spectrum availability are considered: firstly, less than 1% (i.e. $\overline{X} \pm 0.499$) (referred to as **Less than 1 variation**); secondly, 5% variations (i.e. $\overline{X} \pm 2.5$) (referred to as **Up to 5 variation)**; and thirdly, 10% fluctuations (i.e. $\overline{X} \pm 5$) (referred to as **Up to 10 variation**). As observed in Figure 3, there are significant differences in admitting new CRNs at a higher variation (i.e. in **Up to 10 variation**) than the other cases. However, the differences in decision making between **Up to 5 variation** and **Less than 1 variation** increased above 30% of available spectrum (due to existing networks' activities).
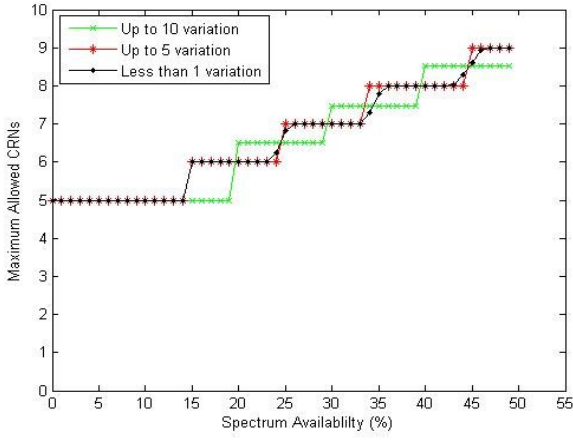
Fig. 3. Maximum number of CRNs Allowed in terms of different variations in spectrum availability measurements (second scenario)

Scenario 3(part 1): Spec Evaluation

Ensuring that the admission is based on enough spectrum bands for new networks is very important to avoid deterioration in QoS of the existing CRNs. Since we do not have counterparts to prove the superiority of our algorithm, in the last scenario, we evaluated the *Spec* constraint in equation (1). Thus we adopted five cases instead of choosing the average of highest performance CRN. These suggested cases are as follows:

- *Case1: Average of the minimum utilized spectrum by each CRN.*

- *Case2: Average of the average utilization of all CRNs.*

- *Case3: Average of the maximum utilized spectrum by each CRN.*

- *Case4: Average of the minimum usage of all CRNs together of each measurement in the campaigns.*

- *Case5: Average of the maximum usage of all CRNs together of each measurement in the campaigns.*

The first three cases are related to CRNs' utilization, and the remaining cases are in terms of the usage in each test (i.e. measurements). Accordingly, we prefer to compare our algorithm with the first three cases in a particular figure, and the last two cases in another figure. As observed from Figure 4 (a, and b), admitting new CRNs in the aforementioned cases is better than our adopted case. A best explanation for these results is because of reducing the required spectrum for admitting networks. For instance, in Figure 4a, case 1 is the less strict, while case 4 is the less strict one in Figure 4b.

Scenario 3 (part 2): CRNAC Evaluation in Ruwi [21]

In this part we used Ruwi spectrum occupancy measurements in the Sultanate of Oman [21] to calculate the admission of the aforementioned cases as well as our adopted case. The calculations are listed in the second column of Table VI. It can be seen from the Table that our adopted constraint admitted seven new CRNs only, while the cases admitted more
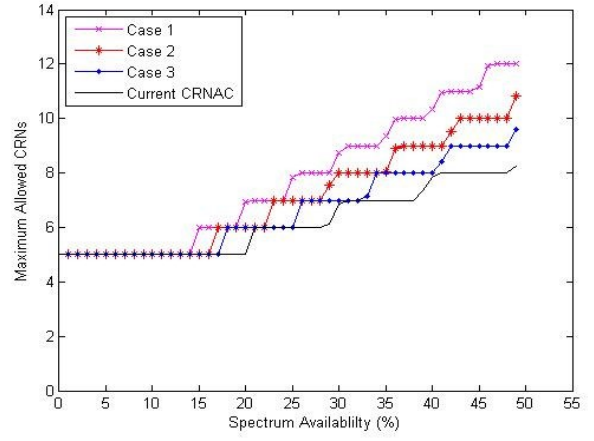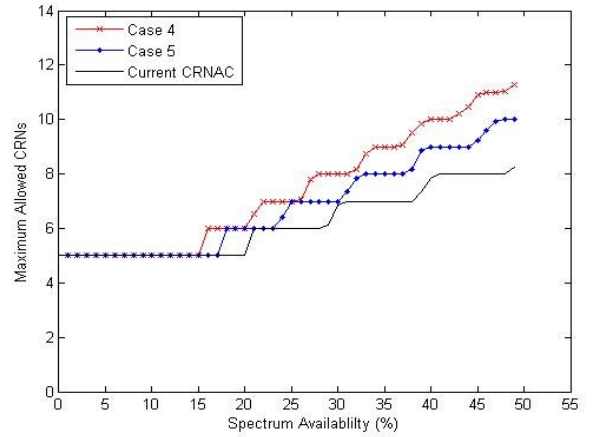

(a)

Fig. 4. Maximum numbers of CRNs allowed in different cases (third scenario, part one)

networks. Additionally, case 1 is the least strict among the cases, and case 5 is the nearest to what we adopted in the current CRNAC. However, admitting a large number of CRNs may lead to a saturated spectrum situation, resulting in poor QoS in the new CRNs and degradation in QoS of existing networks. This argument will be debated in the last part of this scenario.

Scenario 3(part 3): CRNAC Evaluation in different cases

Although each CRN may have totally different spectrum requirements according to per-CRN secondary user population and spectrum usage policies, we assume that there must be enough spectrum bands for a new network to serve users similar to existing networks. To verify the reason of our adopted case of *Spec*, in the third part of the current scenario we compared the spectrum bands needed by existing CRNs with the admission constraint of each case. As observed from the third column of Table IV, all the cases failed in operating new admitted networks as CRN3, because their admission spectrum was low. The nearest case was when the CRNAC decision was based on case 3, where the reference spectrum was able to operate the new CRN as well as most existing networks.

TABLE VI.
EXPECTED PERFORMANCE OF THE ADMITTED CRNs

CRNAC decision is based on	Scenario 3: part 2	Scenario 3: part 2				
	Maximum allowed CRNs according to Ruwi [21]	Percentage of expected performance of admitted networks in compare with existing CRNs				
		CRN1	CRN2	CRN3	CRN4	CRN5
Case 1	10	70.6	0.0	0.0	3.7	100.0
Case 2	9.5	91.5	0.1	0.0	24.8	100.0
Case 3	9	100.0	16.5	0.0	50.2	100.0
Case 4	8.2	100.0	41.4	0.0	75.5	100.0
Case 5	8	100.0	65.6	0.0	97.2	100.0
Current CRNAC	7	100.0	100.0	50.0	100.0	100.0

VI. MERITS OF COGMNET

We believe that CogMnet will play important roles towards realzation of spectrum sharing of centralized CRNs. In this section, we now summarize the possible expected merits of CogMnet:

A. Main Merits

1) Maximum number of CRNs allowed in any location: Based on the suggested constraints in CRNAC, the regulators will be capable of assigning a number of CRNs in any location.

2) PUEA detection: After each compulsory evacuation (the channel occupied by another network's user), the network must monitor the utilizations in the real storage unit of the overlapping BSs (for other CRNs) in order to check for any PUEA. Since the evacuation may be caused by either a real PU or a PUEA of another CRN, the checking can be performed by comparing the frequencies and times of the evacuated channels with the currently utilized channels in the unit. When an attack is detected, the CRN may complain to the regulator about the attacks, with evidence for them. Otherwise, the compulsory evacuations have occurred due to the return of PUs, in which case the network's cognitive engine must be updated.

B. Emerging merits

1) Model SUs activities: Exploiting the historical storage unit of CogMnet, it will be easy for any CRN to model SUs activities. To the best of our knowledge this is the first piece of work that enables modelling of SUs' activity. Distinguishing between the activities of PUs and SUs is very important to devise reliable models for spectrum behaviour and characteristics.

2) Improving Sensing efficiency: Exploiting the information of real time storage unit before starting to sense may improve sensing efficiency by removing currently utilized channels from sensing. For example, if the network uses a filter-bank wide band detection technique in [22], then the number of operated filters (for detection) will be reduced, consequently reducing power consumption.

3) Collision Avoidance: To avoid transmission of more than one CRN on the same channel, CRNs can check the currently utilized spectrum bands in real time storage unit (on the overlapped BSs) before starting communication. During spectrum sensing, the network must monitor the storage unit to prepare a list of the channels that fall within the sensing frequencies range.

4) Avoiding Co-channel interference: It is known that the license cellular networks reuse their group of channels in their cell; however, the same frequencies are not reused in adjacent neighboring cells as that would cause co-channel interference. By exploiting real time storage unit in CogMnet, CRNs will be able to avoid reuse channel what are in use in vicinity.

5) CRNs security: Since all CRNs coverage area will be known to regulators, they will thereby ensure that the CRNs cannot be utilized by malicious or terrorist groups. Since it is impossible to detect any CRN operation (because it transmutes in non-predefined bands); therefore, CRN must be kept away from any aggressive group.

6) Further protection of Non-permitted channels: The regulators can utilize CogMnet for guaranteeing that no CRN may utilize the non-permitted channels (e.g. military, and security bands).

7) Candidate locations for CRNs: Any CRN will be able to analyse the utilizations in the historical storage unit of non-overlapping base stations in order to make a list of candidate areas (inside the network location) where the network may plan to operate. The same procedure can be performed for outside network locations by exploiting the information in the databases of other locations.

8) New income to regulators: Coordinating CogMnet will guarantee a new income to the regulator, because all CRNs will pay a certain fee for being within CogMnet. These fees will be insignificant in comparison to guaranteeing reliable spectrum sharing without self-coexistence issues.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, for a reliable spectrum sharing without self-coexistence issues, an internetwork framework CogMnet was proposed. Unlike conventional frameworks, CogMnet records in real time the utilized spectrum from the existing CRNs. Therefore, it is capable of treating challenges in CRN spectrum sharing such as PUEA. Furthermore, it contributes in preventing degradation of CRNs' performance in an overcrowded CRNs scenario. Accordingly, the first network admission decision-making algorithm CRNAC has been proposed. Several constraints that impact on CRNAC decisions have been modelled and analyzed numerically. It has been argued that correct selection of CRNAC constraints in the CRNAC will ensure that there are sufficient spectrum bands available for the newly admitted CRNs in addition to the existing ones. Clearly, tackling these challenges will pave the way for ensuring reliable spectrum sharing among CRNs.

Nevertheless, it can be said that although CogMnet needs no extra equipment for the network to achieve reliable spectrum sharing, CRNs must implement certain protocols on how to exploit the storage units. Finally, it is very important for the administration issues of CogMnet to be verified, because implementing this requires: 1) buildings; 2) storage units; 3) administration and maintenance technicians; and 5) regular annual spectrum measurement campaigns. These cannot be calculated by academic researchers; instead, they need to be calculated either by official regulators or technology companies. Finally, the following areas are the authors' future work:

1) *Related to CogMnet Framework:* Evaluating the emerging merits of CogMnet.

2) *Related to the CRNAC algorithm:* Examining call dropping and blocking probabilities of the existing CRNs in order to calculate the deterioration in QoS provisioning in a saturated spectrum situation.

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