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Clustering-Based Channel Allocation Scheme for Neighborhood Area Network in a Cognitive Radio Based Smart Grid Communication

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ABSTRACT Cognitive radio ((CR))-based standards are apt to cater the diverse communication requirements for the humongous volume of data generated by Smart Grid applications. Although CR technology is one of the most promising techniques to increase the spectral efficiency of any wireless communication network, efficient spectrum allocation among secondary user (SUs) in different application scenarios remains an intriguing area for researchers. In this paper, we propose a clustering-based approach to deal with channel allocation ((CA)) problem among SUs considering practical constraints in SG environment. We first present a simple CR based SG communication network architecture by dividing the service area into groups of SUs called neighborhood area network clusters, depending upon the distance of Smart Meters from data concentrator unit. Then we formulate a multiple constraint NP-hard CA problem using interference avoidance strategy by considering two practical scenarios: fairness-based allocation and priority-based allocation. We then propose our CA algorithm based on cat swarm optimization to eliminate the severe integer constraints of the problem under consideration. We simulate the two above-mentioned practical scenarios to measure a number of allocations per SU, Jain's Fairness Index and per user average rewards. Moreover, conventional average user rewards are compared for a varying number of channels, SUs, and rounds to evaluate the performance of proposed CA scheme. The results indicate that our proposed CA algorithm works well, for both fairness-based and priority-based cases.

INDEX TERMS Cognitive Radio, smart grid communication, neighborhood area network, channel allocation, cat swarm optimization ((CSO)).

I. INTRODUCTION

The obsolescent electrical grids are suffering from epidemics like inefficient generation, distribution and delivery of power, lack of automation, blind monitoring and passive control. The consequences of these problems are load shedding due to frequent shortages in electricity, mounting electricity rates, inferior power quality and harmful ecological effects. On top of it, the demand and supply gap for electric energy is expanding at an alarming rate. Smart Grid ((SG)) is the transformation of the traditional electrical grid in response to the above ill-posed issues. SGs answers these questions by allowing distributed electrical generation and integrating renewable energy resources [1]. However, the key to achieving the full benefits of SG is only possible through efficient design and deployment of a cost-effective, secure and reliable SG communication network (SGCN). An SGCN supports a two-way flow of information thus enabling self-healing, self-monitoring, remote testing and active control thereby increasing overall efficiency [2].

Three-layer hierarchy model of SGCN consist of (i) Home Area Network (HAN): The customer premises, ((ii)) Neighborhood Area Network ((NAN)): covering mainly distribution domain (iii) Wide Area Network ((WAN)): covering transmission lines to control Centre. These three sub-domains differ by covered area and data rate, therefore each requiring different communication technologies.

Communication in complex and diverse SG environment have challenges like unreliable communication, dynamic changes in topology, degrade in quality of service (QoS) due to impairments electromagnetic interference and noise from

TABLE 1. List of acronyms.

Acronyms	Full Name
SGCN	Smart Grid Communication Network
CR	Cognitive Radio
SU	Secondary User
PU	Primary User
CSO	Cat Swarm Optimization
CA	Channel Allocation
HAN	Home Area Network
NAN	Neighborhood Area Network
WAN	Wide Area Network
HGW	Home Gateway
CNGW	Cognitive NAN Gateway
CWGW	Cognitive WAN Gateway
NSM	NAN Spectrum Manager
DCU	Data Concentrator Unit
SM	Smart Meter
TVWS	Television White Spaces
OFDM	Orthogonal Frequency Division Multiplexing
MSR	Max Sum Rate
JFI	Jain's Fairness Index
HSM	Hybrid Spectrum Management
DTV	Digital Television

equipment, multipath, and fading [3]–[5]. Among various challenges in SG communications, one of the most critical issues is how to tackle data in the range of thousands of terabytes over these communication links having diverse requirements. Moreover, the data produced by various SG applications itself is varied in nature, specifically regarding latency requirements. Therefore, we cannot tackle different data is the same manner. A mixture of the licensed and unlicensed spectrum will thus be needed to transport this massive, diverse data regarding time criticality [2].

CR technology is a natural solution to meet the random and varied traffic requirements of SGCN. Primarily, it increases the spectral efficiency by fully exploiting the under-utilized scarce wireless spectrum and alleviate the burden on the network. CR technology is a paradigm for radio resource management, where unlicensed users (Secondary users or SUs) can opportunistically use the unused channels (called holes) in a licensed spectrum without interfering with licensed users (called Primary users or PUs). Particularly, CR based IEEE 802.11af and IEEE 802.22 WRAN are widely adopted standards in most of the CR based SGCN architectures in literature. *IEEE 802.11af also termed as Super Wi-Fi or White-Fi,* is a CR based communication standard exploiting TV White spaces ((TVWS)) in 54-790 MHz band. Owing to better propagation behavior, it expands the Wi-fi to a range greater than 1 Km with a max data rate of 40Mbps.

Evolutionary or heuristic algorithms are bio-inspired solutions that follow the natural behavior of living systems. These solutions are widely adopted in many fields owing to their flexibility, proficiency, and robustness, to solve optimization problems where a number of constraints are significant, and search space is enormous that makes them very challenging for conventional computing techniques. In literature many nature-inspired solutions for CA problem are proposed [6]–[12] however, we focus on CSO which is a comparatively new heuristic algorithm based on the natural behavior of cats (detailed in section IV).

Clustering is usually arranging of nodes in groups to optimize the network performance. In CR networks, the main reason for clustering is the better management and facilitation of essential operational tasks such as spectrum sensing and sharing [13]. Most of the existing research on clustering in smart grid is either on load profiling or data analysis [14]–[19]. However, it is not straightforward to extend the same approach to CR based SG for CA problem. Nevertheless, it can be very effective to manage transmissions to ease off some spectrum congestion. Mainly, CR has simple infrastructure without the requirement of providing seamless coverage to all users but only those SUs that have some latency tolerant data to transmit. Thus, using clustering-based CA to manage interference and allocate channels in a way to improve utilization and fairness of the network, is the motivation of our research. In fact, we have considered two cases, perhaps first work of its kind, that is common in practical scenarios. First one is fairness-based allocation: when all the SMs are treated equally and the second is priority-based allocation: when some of the SMs are given a significant share of resources.

In this research article, we investigate a channel allocation ((CA)) problem in a typical CRSGCN scenario where IEEE 802.11af based communication is used for opportunistically transmitting less time-critical data for applications such as Advanced Metering Infrastructure ((AMI)), Demand Response Management ((DRM)), and Home Energy Management System ((HEMS)) within NAN. Therefore, it is indispensable to restrict no. of simultaneous transmissions in a particular service area. Notably, for CR communication it is imperative to manage the channel assignment among SUs meeting the interference constraints. The clustered approach offers better spectrum management to deal with the mutual interference between SUs by controlling their transmissions, which is motivated by the co-tier interference avoidance strategy in the heterogeneous environment.

Our contributions in this research are manifold, that can be summarized as:

- We propose a radical network architecture based on licensed spectrum and CR technology for SG communication using clustering approach for NANs. Our proposed architecture gives insight on how to fully realize the capability of CR technology in SG environment to meet the diverse requirements of SG applications.
- We have extended the clustering approach to CR based SG scenario to fully benefit from cluster management regarding interference reduction and network utilization.
- We investigate and formulate CA problem for a novel scenario in a CRSGCN for a NAN cluster using IEEE 802.11af standard.
- To best of our knowledge, this is the first work where a heuristic based CA algorithm is developed to tackle

both fairness based and priority-based CA problem for a NAN cluster in CR based SGCN.

- We have used Cat Swarm Optimization ((CSO)) for the problem under consideration, which itself is seldom utilized in any CA problem scenario before.
- All NAN clusters are independent of each other, regarding spectrum management. Therefore, same CA scheme applies to all the clusters.

The rest of the article is organized as Literature survey of related work is presented in Section II. In Section III, the system model is illustrated, and CA problem is formulated. Proposed heuristic based CA scheme is detailed in next Section IV. Simulations and results are described in Section V and paper are concluded in the final Section VI.

II. LITERATURE REVIEW

Although, a plethora of literature is available on CA in CR networks, investigating CA in SGCN scenario is still in early stages. Some of the recent researches addressing the problem under consideration are reviewed below:

Wei *et al.* [20] have proposed a non-cooperative CA strategy based on game theory for 750MHz TV band in SG scenario to improve isomerism and capacity of the system. A Dynamic Spectrum Allocation (DSA) scheme based on fairness is proposed for SGCN using Binary Particle Swarm Optimization ((BPSO)) in [21]. A novel Orthogonal Chip Sequence (OCS) based allocation in Code Division Multiple Access ((CDMA)) for SU transmission is used in [22], to improve the number of SUs. Miao*et al.* [23] have proposed a heuristic approach to address the problem of finding location and minimum no. of central nodes to fulfill connectivity of the clustered smart meter network. Alam *et al.* [7] have discussed a general CRSGCN scenario and used meta-heuristic techniques like Genetic Algorithm (GA), BPSO and Cat Swarm Optimization ((CSO)) to solve the channel allocation problem using fairness and Max-Sum Reward ((MSR)). GA based allocation scheme for both channel and power using the Spectrum Engineering Advanced Montel Carlo Simulation Tool ((SEAMCAT)), by interference limitation, is proposed in [24]. Huynh *et al.* [25] have used a Hungarian Algorithm (HA) based joint power allocation and CA method to maximize the channel capacity under minimum interference constraint to PU. A comprehensive survey on resource allocation ((RA)) for underlay CRNs is presented in [26], covering RA process, components, taxonomy to state-of-the-art algorithms. Jingyi *et al.* [27] have done some comprehensive work on clustering-based spectrum sharing in CRNs using multi-user Orthogonal Frequency Division Multiplexing ((OFDM)). First, a clustering approach is introduced to group SUs by mutual interference, and then optimal resource allocation is done to maximize the sum rate in a cluster.

A clustering-based routing protocol is proposed in [7], to improve the reliability and packet retransmission in the Wireless sensor network ((WSN)) based SG environment. This energy efficient and QoS aware algorithm using bio-inspired bird mating optimization ((BMO)) to optimize packet delay, packet delivery and energy consumption.

In [28], a clustered resource allocation approach is adopted by authors to reduce co-tier and cross-tier interferences in femtocells. Analysis and simulation of DSA using master-slave parallel immune optimization in comparison to serial algorithms are discussed in [8]. Peng *et al.* [29], in their revolutionary paper, have presented detailed research on spectrum assignment considering fairness and utilization in opportunistic spectrum access. They have based their CA strategy using color graph theory. Elhachmi *et al.* [9], [10] and Latif *et al.* [11] have extended the work of [29] using evolutionary computing techniques. Eletreby *et al.* [30] have used a low-complexity heuristic algorithm to solve a multi-constraint problem having coverage, interference, minimum data rate, and power budget constraints in cognitive sensor networks. Tabakovic *et al.* in [31], have proposed a novel solution by weighting and categorizing interference as an extension to graph coloring approach to CA problem. The results of this interference sensitive algorithm in comparison with benchmark algorithm have shown improved spectral efficiency, reduced interference, and higher throughput. A Novel decentralized spectrum allocation algorithm using history of spectrum usage, to solve channel assignment problem in CRNs, is presented in [32].

III. SYSTEM MODEL

A. NETWORK MODEL

We model our scenario for a rural area on a fixed topology where SUs are fixed, and radio environment is slow-varying, meaning location and duration of holes do not change during a single channel assignment exercise (rounds). Data Concentrator Unit ((DCU)) continually updates its database ((DB)) to adapt quickly to the changes in spectrum availability. This assumption is realistic considering open-loop regulatory paradigm where the list of channels remains unchanged for as long as 48 hrs. [33].

Table 2 shows some of the SG applications along with their communication requirements [34]. Table 3, illustrates the comparison of physical layer specification for IEEE 802.11af with IEEE 802.22 WRAN [35]. Comparing Tables 1 and 2 suggest that IEEE 802.11af and IEEE 802.22 WRAN fulfills all the communication requirements for SG applications for less time-critical data [36].

Figure 1 shows a typical CR based Smart Grid communication network ((CRSGCN)) architecture along with the feasible communication links for CR technology. SG application data can be classified as less-time critical and time-critical data on the basis of latency requirements. Data generated by applications such as AMI, DRM, and PEV, etc. is less critical in terms of latency, while control data such as outage detection, power restore acknowledgments, remote connection, and disconnection, tampering detection, out-of-range voltage conditions, etc. has to be delivered

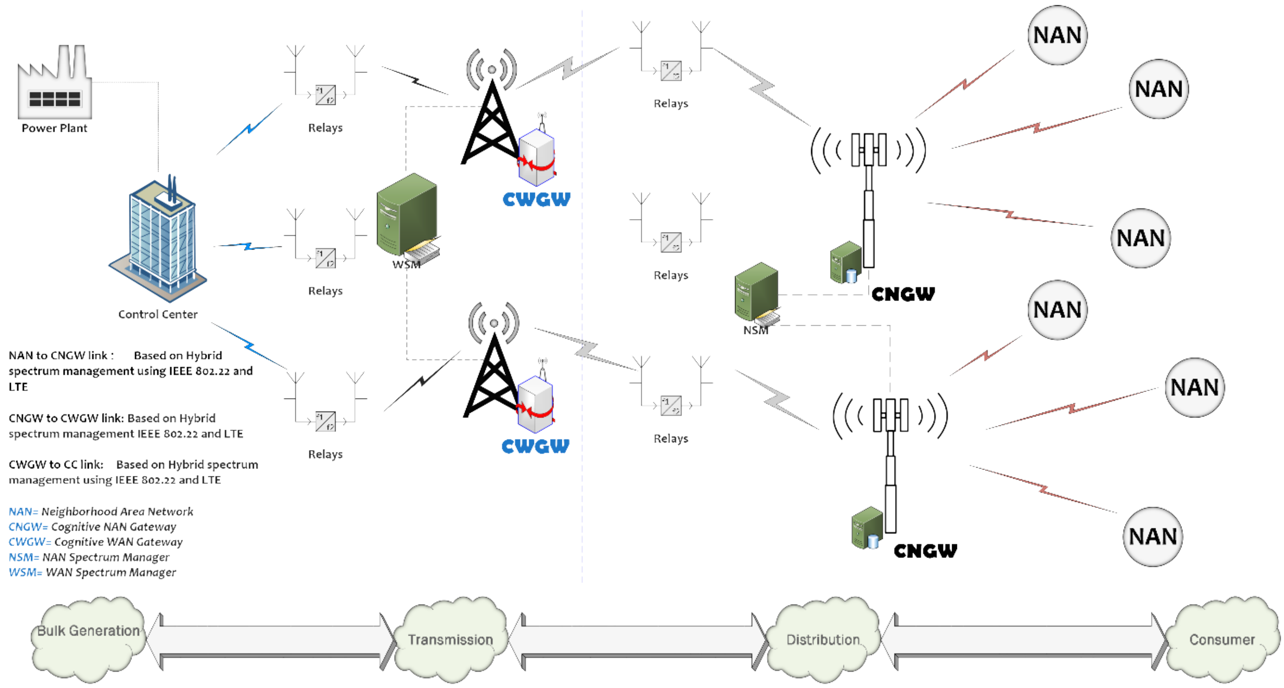

FIGURE 1. A CR based Smart Grid Communication Network Architecture.

TABLE 2. Communication requirements for SG applications.

SG Application	Latency	Data Rate Kb/s	Reliability %
Advanced Metering Infrastructure (AMI)	2-15 s	10 - 100	99 - 99.99
Distribution Automation (DA)	20 - 200 ms	9.6 - 56	99 - 99.99
Substation Automation	15 – 200 ms	9.6 - 56	99 - 99.99
Demand Response Management (DRM)	500 ms – 1 min	14 – 100	99
Home Energy Management (HEMS)	300-2000 ms	9.6 – 56	99 - 99.99
Distributed Energy Resources and Storage (DERS)	300 ms – 2 s	9.6 – 56	99 - 99.99
Plug-in Electric Vehicle (PEV)	2s – 5 min	9.6 – 56	99 - 99.99

TABLE 3. Comparison between IEEE 802.11af and IEEE 802.22 WRAN.

	IEEE 802.11af	IEEE 802.22
Range	Indoor: ~few 100m Outdoor: ~1 Km	30-100Km
Max delay(μs)	<1 1-10	11 to 60
Total B.W(MHz)	5, 10, 20, 40	6, 7, 8
Modulation	OFDM	OFDM
Payload Modulation	BPSK QPSK 16-QAM 64-QAM	QPSK 16-QAM 64-QAM
Error Correction	Convolutional code	Convolutional code Optional: CTC, LDPC, SBTC

immediately. Therefore, following the footsteps of [2], we have also used Hybrid Spectrum Management ((HSM)), where CR based communication is primarily used for less time-critical data such as AMI, DRM, and PEV, etc. For time-critical data such licensed spectrum based Long Term Evolution ((LTE)) is preferred.

Clustering is performed merely on the basis of the distance of a node from cluster head, fulfilling the constraint that a service node can only be registered in a single cluster and all the clusters are independent of each other. Use of clustering strategy is justified in our scenario since a single cluster head has to manage all the resources and facilitate the several hundred nodes within the 1Km^2 radius.

NAN is a cluster of several home gateways (HGWs) and a single data concentrator unit ((DCU)) using IEEE 802.11af/LTE, as shown in figure 2. DCU is a central entity, acting as a cluster head in a NAN cluster, responsible for spectrum management in a NAN. DCU is equipped with a Database ((DB)) carrying all the related information such as availability of holes to manage the transmission of all HGWs within a NAN cluster. In general, a DCU can connect to several hundred to more than thousands of SMs in a particular region but is limited by the communication technology used and congestion due to mutual interference between SMs. Smart meters (SMs) acting as a gateway

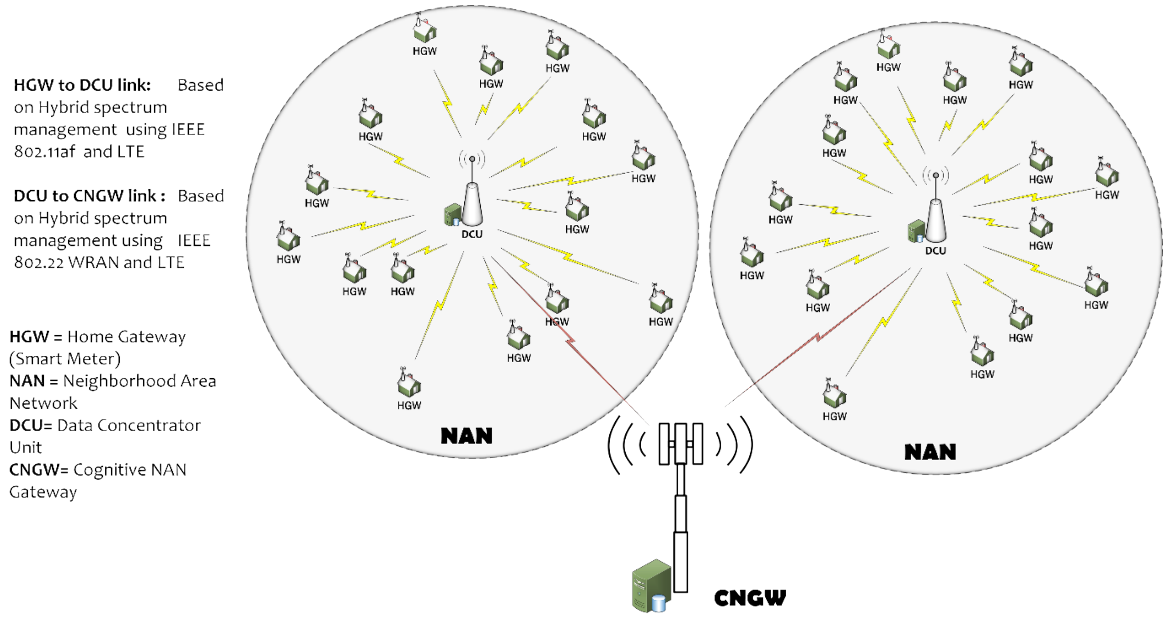

FIGURE 2. CR based Clustered NAN Architecture.

between HAN and NAN are termed as HGWs, and all HGWs behave as cluster members. Several NAN clusters communicate with a Cognitive NAN gateway ((CNGW)) using IEEE 802.22/LTE link and these CNGWs communicate with control center ((CC)) through Cognitive WAN gateways ((CWGW)). NAN spectrum manager ((NSM)) and WAN spectrum manager are used for spectrum management in their respective domains. Size of a NAN cluster, supporting a data rate of 100 Kbps-10Mbps, depends upon power grid topology (distributed or centralized) and smart grid applications.

A severe Quality of Service (QoS) constraint will occur without adopting any optimal spectrum allocation strategy since the number of HGWs are more than the available channels (holes). DCU is responsible for CA within each cluster using the DB that is continuously updating by spectrum sensing information which can be done in a centralized manner or distributed manner.

Our channel allocation scheme is based on interference avoidance strategy that ensures conflict-free assignment meeting two primary constraints:

i. Interference with Incumbent service or PUs: Digital Television (DTV) or wireless microphones services are considered as incumbent users or PUs. All SUs are assigned those channels which are left vacant by PUs.

ii. Interference among SUs: Both HGWs and DCU are considered as SUs. Within a cluster, a separate channel is assigned to each SUs thus avoiding the co-channel interference.

It must be noted that all the channels are not available for every SU at every time and location due to spectrum heterogeneity and presence of cognitive users (CUs), other than smart grid SUs (HGWs + DCU). A single channel cannot be re-used within a cluster during a single channel assignment, but SUs may have more than one channel assignments provided that no channel is re-used and availability conditions are satisfied.

B. MATHEMATICAL MODEL

Consider a CR based SG communication scenario having S number of SUs (HGWs + DCUs), coexisting with P active incumbent services (PUs). Consistent with literature in [14] and [15], we group SUs into C disjunct NAN clusters having a single cluster head ((DCU)). All cluster members (HGWs) in a specific range connects to a single DCU. Let $\mathcal{S}$ denotes set of all the SUs in a service area, $\mathcal{S} = \{1, 2, 3 \ldots\ldots S\}$ and $\mathcal{C}$ denotes set of all clusters, $\mathcal{C} = \{1, 2, 3 \ldots\ldots C\}$ where. A NAN cluster $\mathrm{C_i} \subseteq \mathcal{S}, \forall\, \mathrm{i} \in \mathcal{C}$, C1: $\cup_{\mathrm{i}=1}^{\mathrm{C}} \mathrm{C_i} = \mathcal{S}$ and each SU can be part of a single cluster only, i.e., C2: $\cap_{\mathrm{i}=1}^{\mathrm{C}} \mathrm{C_i} = \emptyset$, where C1 & C2 denotes clustering constraints. Let $\mathcal{N} = \{1, 2, 3 \ldots\ldots \mathrm{N}\}$ be set of channels left vacant by active PUs that can be assigned by DCU to $\mathcal{K} = \{1, 2, 3 \ldots\ldots \mathrm{K}\}$, set of all SUs in a NAN cluster; then we define following key components essential to our mathematical model:

Channel Availability, L: Since all the channels are not available for every SU in a cluster, so binary matrix $\mathcal{L}$ defines the list of available channels (holes) for each SU for a single channel assignment exercise (round) such that $\boldsymbol{L} = \{l_k^n | l_k^n \in \{0, 1\}\}_{\mathrm{KxN}}$, where l_k^n denotes that $\mathrm{n^{th}}$ channel for $\mathrm{k^{th}}$ SU. If the $\mathrm{n^{th}}$ channel is available for $\mathrm{k^{th}}$ SU, then $l_k^n = 1$ otherwise 0.

Channel Reward, B: Each available channel for every SU in a NAN cluster, carries a reward or weight which is represented by reward matrix $\boldsymbol{B} = \left\{b_k^n\right\}_{\mathrm{KxN}}$, where b_k^n denotes reward of the $\mathrm{n^{th}}$ channel that is available to $\mathrm{k^{th}}$ SU.

Obviously for $l_k^n = 0$, the reward $b_k^n = 0$. This channel reward b can be taken in terms of throughput or bandwidth or coverage area depending upon the problem and scenario under consideration. Further discussion on choosing the suitable reward for our CR based SGCN scenario is presented in later section.

Interference Matrix, F: Within a NAN cluster, active PUs may use any available channel first, and the rest of the pool is available to SUs.

A necessary condition to avoid co-channel interference among SUs in a single cluster is that no channel can be re-used in a single cluster. Then we define a binary interference matrix $\boldsymbol{F} = \{f_{k,m}^n | f_{k,m}^n \in \{1,0\}\}_{\text{KxKxN}}$, where $f_{k,m}^n$ denotes that n^{th} channel is assigned to both k^{th} and m^{th} SUs. If $f_{k,m}^n = 1$, it means that same channel is used by two SUs at the same time. So $f_{k,m}^n = 0$ must be true for any single channel assignment exercise for k^{th} and m^{th} SUs belonging to same cluster.

Assignment Matrix, A: The binary matrix $\boldsymbol{A} = \{a_k^n | a_k^n \in \{0,1\}\}$ represents the conflict-free channel allocation meeting both interference constraints C3 and C4.

C3: $l_k^n \text{x} l_p^n = 0$, *where* $p, k \in C$ *and* $n \in \mathcal{N}$, means n^{th} channel cannot be available to both k^{th} SU and p^{th} PU in a same cluster at the same time i.e., if $l_p^n = 1$, then $l_k^n = 0$.

C4: $f_{k,m}^n = 0, \forall k \neq m$ *where* $k, m \in \mathcal{K}$ and $n \in \mathcal{N}$, means n^{th} channel cannot be re-used in a single NAN cluster.

It must be noted that a particular hole may be available to many SUs at the same time, but it cannot be allocated to more than one SU during a single round. Therefore, the conflict-free assignment demands that: $a_k^n \text{x} a_m^n = 0$, *where* $m, k \in C$ *and* $n \in \mathcal{N}$.

Assignment Limit, a_{max}: A single channel may not be re-used during a single round, but theoretically one may have more than one assignment to a single SUs provided both availability and interference constraints be met. Thus, a_{max} represents the maximum allowed channel allocation to a single SU, which facilitates in implementing our two allocation cases, i.e., fairness-based allocation and priority-based allocation, explained in later sections.

User Reward, R: let $\boldsymbol{R} = \{\gamma_k\}_{\text{Kx1}}$, where γ_k denotes the reward of k^{th} user, where

$$\gamma_k = \sum_{n=1}^{N} a_k^n b_k^n \tag{1}$$

Where $a_k^n \in \{0,1\}$ and b_k^n reward of n^{th} channel assigned to k^{th} SU.

History Matrix, H: This matrix $\boldsymbol{H} = \{h_k^t\}_{\text{Kx1}}$ represents user reward history of each channel assignment exercise (round). The term h_k^t denotes user reward history of k^{th} user at the end of round t, given by:

$$h_k^t = \gamma_k^{t-1} + \gamma_k^t \tag{2}$$

Where γ_k^t is k^{th} user reward in current round t and γ_k^{t-1} is the k^{th} user reward in the previous round. History matrix ($\mathbf{H}$) is updated at the end of every round. It is imperative for implementing overall fairness through our proposed algorithm.

The fairness among user is measured by calculating no. of allocation to each SU during a single round, represented by:

$$\rho_k = \sum_{n=1}^{N} a_k^n \tag{3}$$

Jain's Fairness Index (J.F.I), given by (3), is another way of evaluating fairness among SUs.

$$J.F.I = \frac{\left(\sum_{k=1}^{K} \gamma_k\right)^2}{\sum_{k=1}^{K} (\gamma_k)^2} \tag{4}$$

Max-Sum Reward ((MSR)) which aims to optimize the overall reward during a single channel assignment exercise, given by:

$$U_{sum} = \sum_{k=1}^{K} \gamma_k \tag{5}$$

Utilization Factor, U(R): The utilization factor U(R) depends upon the objective of the problem under consideration. To maximize the utilization factor U(R), we have to optimize the channel assignment $\boldsymbol{A}$ meeting multiple constraints, which can be written as:

$$\begin{aligned}
\boldsymbol{A}^* = \max_{c,f,l,b,p} \; & \boldsymbol{U}(\boldsymbol{R}) \\
s.t.\; & \text{C1}: \cup_{\text{i}=1}^{\text{C}} \text{C}_\text{i} = \mathcal{S}, \quad \textit{where } \text{C}_\text{i} \subseteq \mathcal{S} \\
& \text{C2}: \cap_{\text{i}=1}^{\text{C}} \text{C}_\text{i} = \emptyset, \quad \textit{where } \text{C}_\text{i} \subseteq \mathcal{S} \\
& \text{C3}: l_k^n \text{x} l_p^n = 0, \quad \textit{where } p, k \in C \textit{ and } n \in \mathcal{N} \\
& \text{C4}: f_{k,m}^n = 0, \quad \forall\, k \neq m \textit{ where } k,\; m \in \mathcal{K} \\
& \qquad \textit{and } n \in \mathcal{N} \\
& \text{C5}: \rho_k \leq a_{max} \\
& \text{C6}: b_k^n \in [0,1] \textit{ and } b_k^n = 0 \textit{ if } a_k^n = 0
\end{aligned} \tag{6}$$

C1 and C2 represent clustering requirements. C3 ensures that SUs can only be assigned channels left vacant by PUs and C4 dictates that no channel is re-used in a single round. C5 puts an upper limit of maximum allocations to any SU and C6 is intuitive.

IV. CSO BASED CA ALGORITHM

In this section, we first brief CSO technique and general steps involved. Then we present our proposed algorithm applied to CA problem under consideration.

In 2006 Chu *et al.* [37] proposed a new heuristic algorithm, Cat Swarm Optimization ((CSO)) is based on the natural behavior of cats. Most of the time cats remain in seeking mode ((SM)) to rest and analyze the surroundings of the possible target [38]. In tracing mode ((TM)), cats move towards the prey depending upon its velocity. A parameter called mixing ratio ((MR)) is used to define how many cats are in SM and TM, where Flag is used to tell whether the cat is in SM or TM. A generic CSO algorithm can be described in following steps:

Step 1 (Parameter Initialization): Initialize the parameters such as no. of cats, SPC (self-position consideration), SMP (seeking memory pool), CDC (counts of dimensions to change), SRD (seeking a range of the dimensions), flags and MR (mixing ratio).

Step 2 (Mode Selection (TM or SM)): Mode selection is determined by checking flag indicator, and MR determines that how many cats will be in SM and TM.

Step 3 (Fitness Check): Calculate fitness of each candidate/Cat according to fitness function and keep the cat with the best fitness.

Step 4 (Seeking Mode ((SM))): According to SMP value, j copies of the cats are created in SM mode. CDC and SRD values are used to update each copy randomly. The fitness of each cat is calculated, and a cat is selected at random.

Step 5 (Tracing Mode ((TM))): The next best possible mode of each cat is then determined through TM. To update the position and velocity of each cat, following equations are used:

$$V'_{i,j} = V_{i,j} + r_1 c_1 (X_{gb,j} - X_{i,j}) \tag{7}$$

$$X'_{i,j} = X_{i,j} + V_{i,j} \tag{8}$$

Where $V'_{i,j}$ = updated velocity, $V_{i,j}$ = previous velocity, r_1 = random number from [0,1], c_1 = constant factor for global best (X_{gb}), $Xg_{b,j}$ = cat with the best fitness, $X_{i,j}$ = previous position and $X'_{i,j}$ = updated position of the cat. Cats in both TM and SM are then combined.

Step 6 (Re-Picking): Re-select no. of cats and according to MR set them into TM and rest of the cats to SM

Step 7 (Stoppage Criteria): Terminate the algorithm if required fitness is achieved, or no. of the rounds have reached to the max value, otherwise, repeat step 2 to step 5.

In our scenario, we are dealing with two types of allocation modes: Fairness based allocation and Priority based allocation, described below.

Case 1 (Fairness-Based Channel Allocation): An everyday routine, when all the SMs have scheduled data regarding AMI and DRM, to be transmitted to DCU. Fairness based allocation demands that all SMs to be treated fairly, thus available channels are assigned the SMs during first channel assignment exercise (round). User rewards and allocated channels are measured using (1) and (3), and J.F.I (4) is used as the fitness function. History matrix H is updated with the reward of each user at the end of each round. Both allocations a_k^n and channel rewards b_k^n affect the user reward γ_k. They are assigned in each round in a way to maximize the fairness indicator J.F.I. After number oa f rounds, all SUs should have almost same number of allocations and per user reward. The fitness function in this case is J.F.I, as describes by (4) used as utilization function in (6). To compare the user reward among SUs, we formulate Mean Square Error ((MSE)) to represent Max-Min Reward ((MMR)) which aims at optimizing the share of the SU with least reward, given by:

$$\gamma_e = \|\gamma_{max} - \gamma_{min}\|^2 \tag{9}$$

Where, γ_{max} is the maximum user reward and γ_{min} is the minimum user reward in one round.

Case 2 (Priority-Based Channel Allocation): In this case, we consider another practical scenario where priority is required for few SUs for short period of time. For example, customer needs to check the load profile of his/her house remotely, or DCU needs to transmit some data on priority basis so such SUs must be assigned more resources. Thus, we deal with such cases in a way that 50% available channels are allocated to SUs with priority and rest of the channels are distributed among remaining SUs. Moreover, available channels with best rewards are also allocated first to priority users. Let K be the total no. of SUs and Pr be a number of Priority users in one NAN cluster. The fitness function used in (6) for this case is the reward of priority users, given by:

$$Avg\ \gamma_{pr} = \frac{1}{Pr} \sum \gamma_{pr} \quad where\ pr = Priority\ user \tag{10}$$

Where γ_{pr} is user reward for priority users, then average reward for standard users D (other than priority users) is given by:

$$Avg\ \gamma_d = \frac{1}{D} \sum_{d=1}^{D} \gamma_d \quad where\ d \neq pr \tag{11}$$

Pr = 1 is taken as a special case where single priority user is assigned 25% of total available channels otherwise 50% of channels are divided among priority users. After some rounds, prioritized SUs should have more allocations, and user reward compared to other standard users.

Pseudocode for our proposed algorithm is shown in figure 3 and flowchart in figure 4.

V. SIMULATIONS, RESULTS, and DISCUSSION

Consider the service area is divided into NAN clusters, each covering the 1x1 Km^2 area where a number of PUs and SUs are randomly placed with a single DCU at the center, as shown in figure 5. We have set the range of each DCU as ~1Km and channel bandwidths, consistent with IEEE 802.11af PHY specification [5]. Since each NAN cluster is independent of each other, so our proposed algorithm can be implemented in all clusters at the same time. Each PU occupies one channel from the pool of available channels and rest of the channels are then allocated among SUs. The parameter values used to initialize BCSO is shown in Table 4. We evaluate our CA algorithm for two particular scenarios: Fairness based allocation and Priority based allocation.

For ***case 1*** we take No. of channels available to SMs, N = 40, and No. of SMs, K = 50. Availability matrix $\mathcal{L}$ is generated randomly, and channels are allocated meeting constraints C1-C6. The reward of each allocated channel ($b_k^n \in [0, 1]$) is randomly assigned according to supported bandwidths of IEEE 802.11af standard i.e., 5 MHz, 10 MHz, 20 MHz and 40 MHz. Number of allocation per SU (3) and J.F.I (4) are calculated at the end of each round and algorithm is allowed to run for 20 rounds using $a_{max} = 1$.

Fairness (4) and MSE (9) are plotted against No. of rounds in figure 6 and 7 respectively. Fairness plot is increasing gradually and MSE, which shows the difference between max and min reward, is minimizing after each round. The improvement at the end of each round is the result of a heuristic approach that every new assignment shows better fitness than

CSO based CA Algorithm

1. **Step I: Initialization**
   Set P, K, N, T, Pr, D, a_{max} meeting C1, C2, C3
   Set CSO parameters ($Cats_k$, MR, SMP, w, CDC, SRD, SPC)
2. **Step II:**
   Generate availability matrix $\mathbf{L}_{KxN}$
   for n=1: N
   Assign channel reward b meeting C6
   end

Case1: Fairness-based allocation selected

3. **Step III:**
   for all K
   Using CSO, assign channel to each SU according to availability matrix **L** meeting C4, C5 with (4) as fitness function
   Calculate γ_k and store in history matrix **H**
   end
4. **Step IV:**
   for all K
   Using CSO, assign channels with max reward *b* to the SUs with min user reward and channel with min reward to SUs with max reward in the previous allocation, according to availability matrix **L** meeting C4, C5 with (4) as fitness function
   Calculate γ_k , J.F.I, ρ_k and update history matrix **H** using (2)
   end
5. **Step V:**
   Repeat IV until the termination criteria are reached.

Case 2: Priority-based allocation selected

3. **Step III:**
   for all K
   Using CSO, assign 50% channels with max reward *b* to among priority users Pr and remaining among standard users *D* according to availability matrix **L** meeting C4, C5 with (10) as fitness function
   Calculate γ_k and store in history matrix **H**
   End
4. **Step V:**
   Repeat III until the termination criteria are reached.

FIGURE 3. Proposed CSO based channel allocation algorithm for CRSGCN.

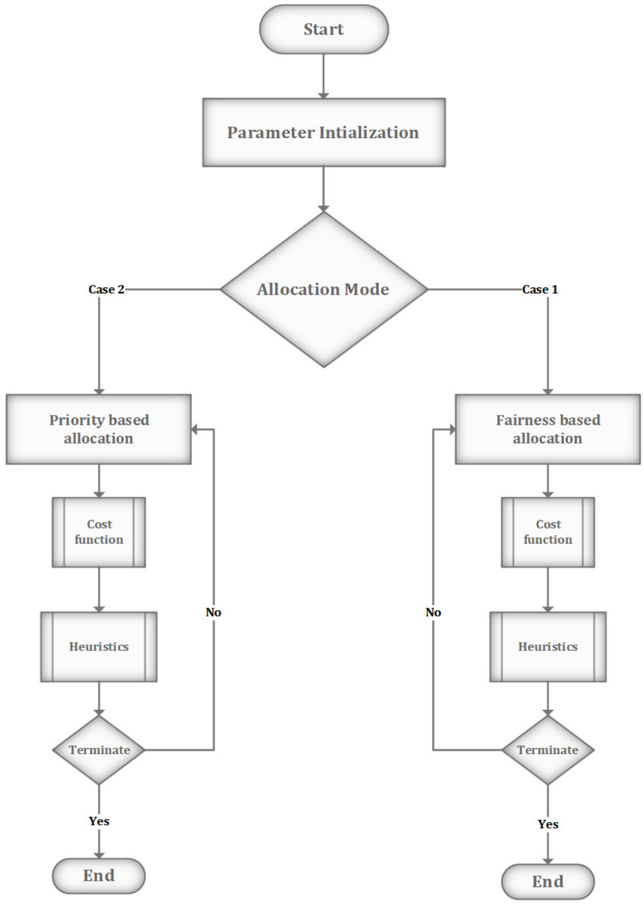

FIGURE 4. Flowchart CSO based CA algorithm.

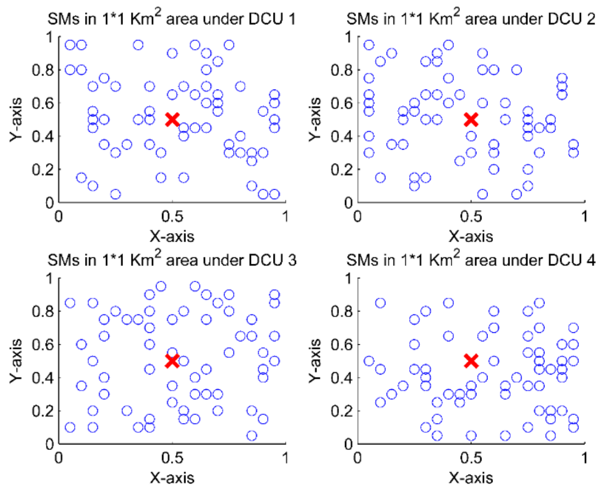

FIGURE 5. Random mapping of SUs in a NAN cluster of 1 × 1 Km sq. area.

the previous generation. Total no. of allocations per SU is plotted for 20 rounds in figure 8. It can be seen that only 6 out of total 50 SUs have been allocated 15 channels and 44 SUs are at 16 allocations each.

It can be seen through figures [6]–[8], that after completion of 20 rounds, almost all the users have same reward and no. of allocations even though the availability is not same for each SU, which proves and validates the effectiveness of algorithm regarding fairness.

For ***case 2*** we take No. of channels available to SMs, N = 40, No. of SMs, K = 50, and No. of priority users, Pr = 2. Availability matrix L is generated randomly, and channels are allocated meeting constraints C1-C6. The reward of each allocated channel ($\boldsymbol{b_k^n} \in [\mathbf{0}, \mathbf{1}]$) is randomly assigned according to supported bandwidths of IEEE 802.11af standard i.e., 5 MHz, 10 MHz, 20 MHz and 40 MHz. Number of allocation per SU (3), priority user reward $\boldsymbol{\gamma_{pr}}, \boldsymbol{\gamma_d}$ (10-11) are

TABLE 4. Parameter initialization for BCSO.

Sr no	Parameter	Value
1	No. of Cats	20
2	Mixing Ratio (MR)	0.7
3	Seeking Memory Pool (SMP)	10
4	Inertia weight (w)	0.7
5	Count of dimension to change (CDC)	10%
6	Seeking range of dimension (SRD)	10
7	Self-position consideration (SPC)	20x1

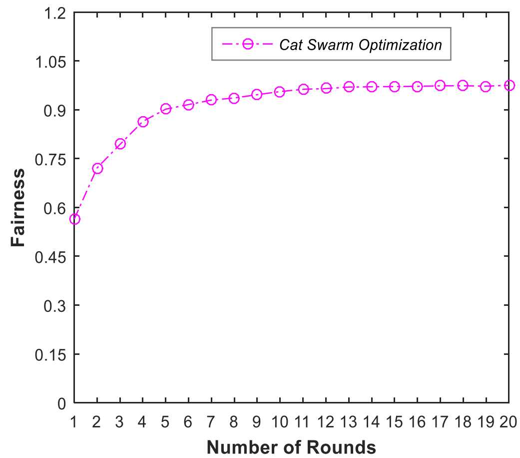

FIGURE 6. Case 1: Fairness vs. No. of rounds for No. of SUs = 50, No. Of channels = 40.

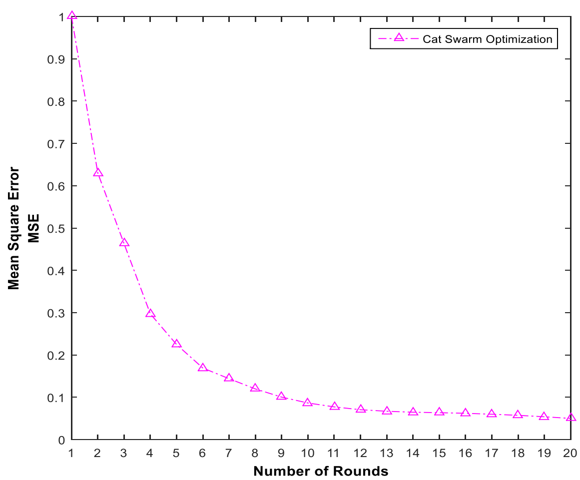

FIGURE 7. Case 1: MSE VS Rounds plot for No. of SUs = 50, No. Of channels = 40.

calculated at the end of each round and algorithm is allowed to run for 50 rounds using a_{max} = 25% of N for each priority user.

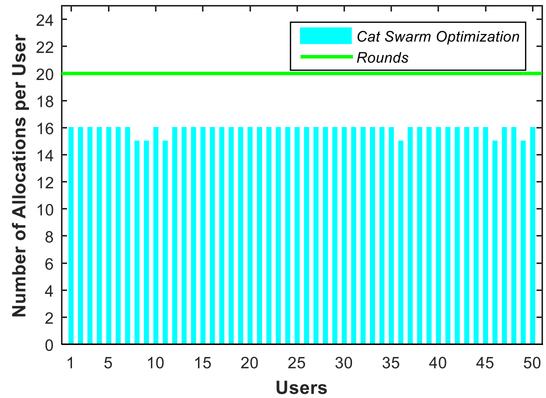

FIGURE 8. Case 1: Comparing no. of allocations per users after 20 rounds.

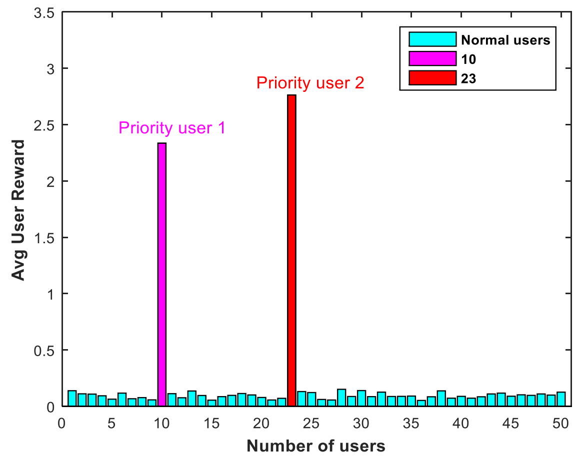

FIGURE 9. Case 2: Average user reward for 50 rounds.

SM 10 and 23 are randomly picked as priority users and rest 48 SMs are treated as standard users. User rewards (1) averaged over 50 rounds is plotted in figure 9. Round-wise comparison of priority users with standard users for user reward (1) is shown in figure 10. No. of channel allocations (3) after 50 rounds are plotted in figure 11. Both priority users have a substantial share of resources as depicted in figure 9-11 which shows the effectiveness of our proposed algorithm. The difference between rewards of two priority users is due to the different availability of channels for both priority users.

A. EFFECT OF VARYING NUMBER OF AVAILABLE CHANNELS AND SUs

We now investigate how our proposed algorithm performs for a different number of available channels and different user density. MSR, U_{sum} (5) averaged over 50 rounds for ***case 1*** is shown in Table 5. It can be observed through Table 5 that avg. MSR only improves if channels are increased keeping no. of SUs fixed because increasing channels means more availability and reward. On the other hand, increasing user density keeping channel fixed has little or no effect on MSR

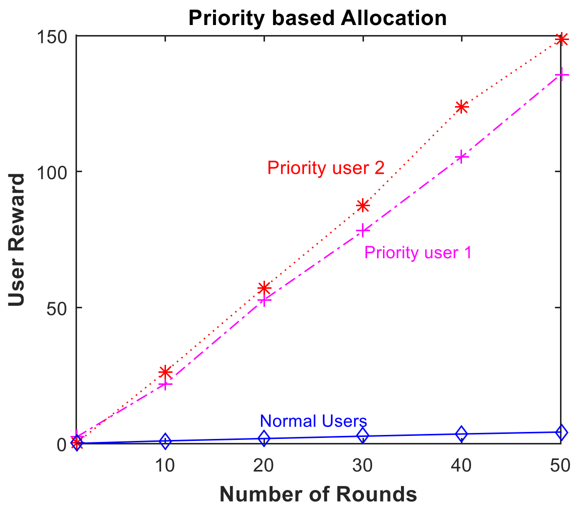

FIGURE 10. Case 2: User Reward vs. Rounds.

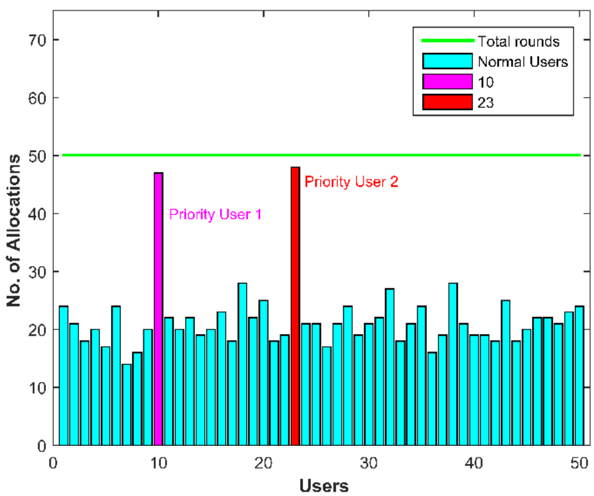

FIGURE 11. Case 2: No. of Allocations per user after 50 rounds.

as long as no. of channels are below no. of SUs since most of the SUs go allocation less.

It must be noted that we have considered a rural area, explicitly focusing on dealing with data that is suitable to transmit using CR technology. Therefore, a maximum of 100 users is considered bearing in mind a practical 1x1 Km sq. area using IEEE 802.11af standard. As far as DCU is concerned, it can facilitate up to 1000 nodes, but we are transmitting data that is not time-critical. So, users can be scheduled in a way that all the remaining users/nodes can be serviced/facilitated within the required time frame.

Table 6 compares the average user rewards for priority users (10), and standard users (11) averaged over 50 rounds for case 2 considering Pr = 2 for all combinations. As the number of channels is increased, the difference between avg. rewards of both users also increased. On the other hand, increasing user density and keeping a number of channels fixed degrades the rewards.

TABLE 5. Max-Sum Reward averaged over 50 rounds for different channels and SUs.

	No. of SUs		
	50	70	100
No. of Channels	U_{sum}	U_{sum}	U_{sum}
40	17.9	18	18
60	21.95	26.475	26.97
80	21.975	30.6	35.675

TABLE 6. Comparison of avg. priority user reward and standard user reward for 50 rounds for Pr = 2.

	No. of SUs					
	50		70		100	
No. of Channels	Avg. γ_{pr}	Avg. γ_d	Avg. γ_{pr}	Avg. γ_d	Avg. γ_{pr}	Avg. γ_d
40	2.8431	0.0864	5.3712	0.0251	4.6738	0.0162
60	3.8532	0.1265	7.895	0.0601	7.3262	0.0363
80	4.535	0.1493	10.865	0.0701	10.915	0.0485

B. EFFECT OF VARYING NUMBER OF PRIORITY USERS

To evaluate the effect of varying the number of priority users we simulate the same scenario of case 2 which is used to present Table 6 except we now take Pr = 4% of total SUs. Results are compared in Table 6, showing a decrease in average rewards as the number of users is increased, which is justified since it also increases the priority users. On the other hand, increasing channels, keeping user constant improves both average rewards.

It must be noted that slight variations while comparing Table 6 & 7 are because for Table 6 we have Pr = 4% of total SUs while for Table 6 we have fixed Pr = 2. Another reason for different values of average rewards under same combinations of K and N is that channel availability is generated randomly. Nevertheless, our proposed algorithm performs well for all cases.

C. IMPACT OF ALLOCATING 50% CHANNELS TO PRIORITY USERS

Impact of allocating 50% of the resources (available channels) can be seen by comparing users rewards and no. of allocations per users for both cases 1 and 2. Apparently, the significant increase can be observed in the rewards and allocations of priority users, which actually affects the overall fairness of the system.

TABLE 7. Comparison of avg. priority user reward and standard user reward for 50 rounds for Pr = 4 % of K.

		No. of SUs					
		50		70		100	
		Avg. γ_{pr}	Avg. γ_d	Avg. γ_{pr}	Avg. γ_d	Avg. γ_{pr}	Avg. γ_d
No. of Channels	40	2.8368	0.2002	1.4971	0.1482	0.9797	0.0929
	60	3.4419	0.2762	2.2996	0.2113	1.4528	0.1446
	80	4.4369	0.3417	2.7621	0.2519	1.7778	0.1684

However, it must be noted that in practical case scenario, this priority demand is not of very long duration. So, as soon as the on-demand data from priority users is completed, the channels can be again allocated to maximize fairness.

VI. CONCLUSION

Optimum channel allocation on CR networks among SUs for a practical application has always been an area of interest for researchers. In this research work, we intended to provide a framework to further explore the CA problem in CR technology when applied to SG. This paper investigates the problem of CA in CRSGCN, where first an efficient clustering technique is used for better spectrum management for the novel scenario of a clustered NAN. A system model is presented next considering IEEE 802.11af CR standard as the leading communication technology to connect DCU with SMs. Then a mathematical model is developed, considering practical limitations and boundary values. We then propose a CSO based CA allocation algorithm, dealing two allocation objectives that are totally opposite i.e., fairness-based and priority-based. The simulation results have shown that our proposed algorithm attains desirable outcomes to this multi-constraint problem.

We are confident that our research will pave the way for further studies regarding CA problem in CRSGCN for more practical scenarios. In our work, we have considered fixed topology under slow-varying SG environment with interweave CR network adapting interference avoidance strategy. For future work, it will be an exciting but complex problem to deal with, if one considers a dynamic topology in underlay CR network. Also, the impact of fast-varying environment for channel availabilities and performance of SUs at boundaries of clusters will also be a challenging task. We have used CSO for optimized channel allocation in CRSGCN; future work should concentrate on improving the performance using other heuristic techniques for this scenario.

Clustering in CR based SGCN can be done considering many performance metrics such as cluster size, number of nodes, number of channels per cluster, network connectivity, energy efficiency, etc. For SG scenario, this alone is a broad topic requiring extensive time and research.

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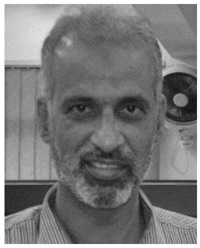

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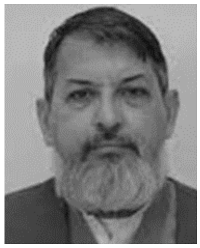

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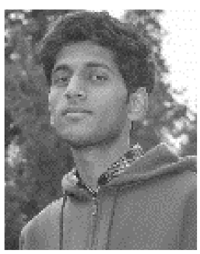

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