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Review

Radio Resource Allocation Improvements in CRSN for Smart Grid: A Survey

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Abstract: A cognitive radio sensor network (CRSN) based Smart Grid (SG) is a new paradigm for a modern SG. It is totally different from the traditional power grid and also different from the conventional SG that uses a static resource allocation technique to allocate resources to sensor nodes and communication devices in the SG network. Due to the challenges associated with competitive sensor nodes and communication devices in accessing and utilizing radio resources, the need for dynamic radio resource allocation (RRA) has been proposed as a solution for allocating radio resources to sensor nodes in a CRSN based smart grid ecosystem (network). These challenges include energy/power constraints, poor quality of service (QoS), interference, delay, spectrum efficiency issues, and excessive spectrum hand-offs. Hence, the optimization of resource allocation criteria, such as energy efficiency, throughput maximization, QoS guarantee, fairness, priority, interference mitigation/avoidance, etc., will go a long way in addressing the problems of RRA in a CRSN based SG. Consequently, this work explores RRA in CRSNs for SGs. Various resource allocation schemes, as well as its architecture in a CRSN for SG environment, are presented. The work reported in this paper introduces a model called the "guaranteed network connectivity channel allocation" for throughput maximization (GNC-TM) and optimal spectrum band determination in RRA for improved throughput criteria in CRSNs for SGs. The results show that the model outperforms the existing protocol in terms of throughput and error probability. Finally, the contribution to knowledge and future research direction, such as energy efficiency and hybrid energy harvesting schemes are highlighted.

Keywords: Adaptive Modulation, TVWS, CRSN, RRA, Smart Grid, Distributed Heterogeneous Clustered (DHC), Dynamic radio.

Nomenclature

CPG	Central power generation
CR	Cognitive radio
CRN	Cognitive radio network
CRSN	Cognitive Radio Sensor Network
CSMA/CA	Carrier sense multiple access and collision avoidance
DA	Distribution automation
DER	Distributed Energy Resources
DREG	Distributed renewable energy generation
DES	Discrete event simulation
EV	Electric Vehicle
EMC	Electromagnetic Comparability
EMI	Electromagnetic Interference
GSM	Global System for mobile communication
HAN	Home Area Network
IoT	Internet of Things

IPO	independent power operator
ISM	Industrial scientific and medical
LPWAN	Low power wide area network
MAC	Medium access control
MDMS	Meter data management system
NAN	Neighborhood area network
NETSIM	Network simulator
NIST	National Institute of Standards and Technology
PHY	Physical layer
PLC	Power line communication
PMU	Phasor management unit
PU	Primary user
QoS	Quality of Service
RRA	Radio resource allocation
SCADA	Supervisory control and data acquisition
SU	Secondary user
TV	Television
TVWS	TV white space
CVWS	Cellular white space
UDP	User datagram protocol
UHF	Ultra high frequency
VHF	Very high frequency
UMTS	Universal Mobile Telecommunications Service
WAN	Wide area network
WIFI	Wireless fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless local area network
WSN	Wireless Sensor Network

1. Introduction

1.1. Background

Traditional power grids use a top-down layer approach where the communication flow is only in one direction from the utility to the consumers. A Smart Grid (SG) has a bidirectional communication and information flow between utility and consumer. There are several communication technologies such as wired or wireless technologies, which can be used to realize the bidirectional communication in SG. Wireless communication is a good communication technology option to drive SG due to the extensive coverage area required in SG. However, the wireless channels in the wireless communication undergo a wide range of impediments such as fading, path loss and interference caused by other wireless devices operating in the Industrial, Scientific, and Medical (ISM) free band. There is also spectrum limitation and spectrum efficiency issues due to the high cost of acquiring a spectrum channel and poor spectrum utilization (only about 15% of the allocated spectrum is utilized).

To this end, to address the impairments and spectrum issues, a CRSN which is a combination of CR and WSN is proposed as adequate communication technologies in SG. The CRSN will enable Power Generation, Transmission, Distribution, Utilities, and Customers to transfer, monitor, predict, control and manage energy usage effectively and in a cost-efficient manner. CRSN can leverage television white space (TVWS) for SG communication. TVWS has been recommended in high-speed communication technology for balancing energy production and consumption in SG [1].

The realization of CRSN for the smart grid mainly requires efficient RRA strategies to manage the Dynamic Spectrum Access (DSA) of cognitive radio sensor nodes in harsh smart grid propagation environments. To meet the requirements of data rate and power constraints of the CRSN users, as well as to avoid interference, researchers all over the world are working hard to develop radio RRA scheme to effectively manage radio resources. CRSN has the potential advantages of reconfigurability and DSA capabilities; to exploit these potential advantages of CRSN, a dynamic efficient RRA among the sensor nodes is essential.

A traditional electricity grid has shortfalls in terms of effective monitoring, predicting, control and management of the energy in a cost efficient manner. This can fall short of the expectation of a modern electricity market.

1.2. SG Architectural Framework

An SG has functional subsystems that interact independently or cooperatively as shown in the framework in Figure 1. This framework shows the components or subsystems that make up the SG. The functional subsystems are as follows:

1.2.1. Power system layer

This comprises of the central power generation (CPG), distributed renewable energy generation (DREG), transmission, and distribution by utilities, with power supplied to the consumers.

1.2.2. Control layer

This subsystem consists of control systems such as the meter data management systems (MDMSs), supervisory control and data acquisition (SCADA), algorithmic applications and the MDMS server at the control/substation/data centre. It enables the control and management functions in the SG.

1.2.3. Security layer

This involves cybersecurity and provides data confidentiality, integrity, authentication, and availability for safe electricity distribution and counter-theft. Industrial Control Systems (ICS) such as SG comprising actuator and sensor networks are vulnerable to attacks that could lead to a devastating impact on the entire SG [2]. Hence, the security layer handles the vulnerability in the SG ecosystem.

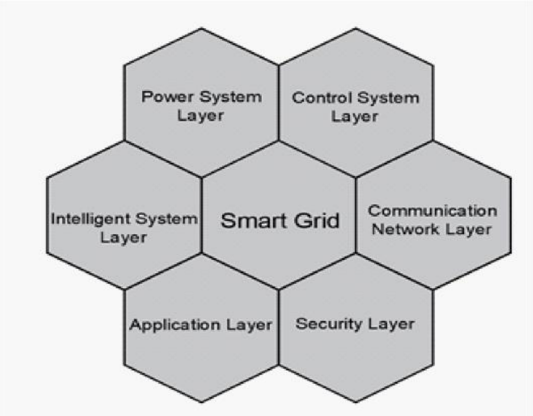

Figure 1. Smart Grid Architectural Framework

1.2.3 Application layer

This delivers numerous SG applications such as DER, AMI, DRM, and so on, to customers as well as utilities.

1.2.4. Intelligent layer

This consists of intelligent electronic devices (IEDs) and sensors for monitoring and control in SCADA, MDMSs, and communications.

1.2.5. Communication network layer

This allows bi-directional communications in an SG. It consists of wireless cellular communication (GSM, GPRS, LTE, UMTS, EDGE, and so on), WiMAX, power line communication (PLC), Digital Subscriber Line (DSL), Ethernet, Fiber optics, machine-to-machine communication (M2M) such as WI-FI, WSN, CRSN, ZigBee, Bluetooth, Low power wide area (LPWA) devices, and so on [3].

A critical analysis of the framework will deduce that the communication network layer is the key enabler for the delivery of information/data about the power system, control, applications, and so on. However, the aspect of M2M communication is of the utmost importance in an SG implementation. This paper considers RRA in CRSNs based M2M communication for a SG. This is because a CRSN has numerous advantages than WSN and CRN as shown in Table 1, which emphasizes the comparative framework that characterizes WSN, CRSN, and CRN based on some features or metrics. Another emerging area in M2M communication that is also advantageous for a SG and internet of things (IoT) implementation is the LPWA devices. Though LPWA is not the focus of this work.

1.3. *Challenges of CRSN in SG*

There are challenges associated with a CRSN, which can adversely affect adequate resource allocation within a CRSN in an SG. There are described below:

1.3.1. Intermittent channel availability for a SU network

PU activities can cause intermittent channel availability to an SU network. This is because whenever a PU arrives to use the channel, the SU relinquishes it. When this occurs too frequently it mars the correct communication of the CRSNs for adequate resource allocation.

1.3.2. High bit error probability of detection of the PU

When the SU has a high probability of an error in the detection of the presence of a PU, it will lead to false detection which affects the SU network negatively or causes harmful interference in the PU network. Hence, this issue is a research challenge that requires the mitigation of the high probability of an error in detection by the SU.

1.3.3. The problem of limited spectrum holes due to PU activities

Frequent PU activities will lead to fewer spectrum holes. There can impact adversely on the performance of the SU network. Creating multiple spectrum channels for the SU will lead to more spectrum holes which will help to avert the problem. Part of this challenge is addressed in Section 4.2,

where further analysis was carried out in order to establish a suitable spectrum band with more white space for CRSNs in a SG.

1.3.4. Adequate protocol for CRSN in an SG

Protocols that are suitable for a CRSN in a SG are in their infancy since a CRSN is a new paradigm and its protocol is quite different from that of a conventional wireless system which has higher computational complexity.

Table 1. Comparative framework for WSN, CRSN, and CRN

Features/Metric	WSN	CRSN	CRN
Channel access	Fixed channel access	Multiple/dynamic	Multiple/dynamic
Organizing and self-healing	Moderate	Very high	Very high
Interference avoidance	Low	High	High
Network topologies	Star, Cluster-tree, and Mesh	Star, Mesh, Cluster, Hierarchical, Mobile Ad Hoc, and Distributed Heterogeneous Clustered (DHC)	Star, Mesh, Hierarchical, Mobile Ad Hoc (MANET)
Communication protocol stack	Physical, Data link, Network, and application layer	Physical, Data link, Network, Transport, and application layer	Physical, Data link, Network, Transport, and application layer
Data centricity/unification	Highly supported	Highly supported	Less supported
Energy conservation/harvesting	High	High	Medium
Efficient energy consumption	Low (More energy waste)	High (energy efficiently used)	High (energy efficiently used)
Application specific driven	Highly Supported	Highly supported	Less supported
scalability	Large scale (supports thousands of nodes)	Large scale (supports thousands of nodes)	Medium scale (supports hundreds of nodes)
Coverage range	Short range	Short to medium range	Long range
Environment sensing	Sense any target phenomenon	Sense any target phenomenon and radio properties	Sense mainly radio properties (spectrum channels, modulation, power control)
Computational complexity	Low	Medium	High

It is different from a conventional WSN which has lower complexity, but the computational complexity for a CRSN is of medium complexity; hence, it requires a protocol that matches its functionalities which will help to realize adequate resource allocation in an SG communication system. Its protocol is unique due to the dynamic multiple channel access, whereas the protocol for conventional wireless has fixed channel access.

1.3.5. Problems of communication infrastructure in SG with regards to the requirements for SG deployment

The communication equipment is susceptible to challenges associated in a SG environment. For example, power-frequency electromagnetic fields and radiofrequency (RF) noise exist in the SG environment due to corona and partial discharges, solid-state and substation switching devices, and circuit breaker switching, including commutating processes [4]. These can result in electromagnetic interference (EMI) issues which are known to cause interference and failure of electronic devices and communication infrastructure [4]. These disturbances and environmental changes negatively impact communications infrastructure and its operation.

Therefore, communications infrastructure needs to be strong enough to operate in harsh SG environments. The International Special Committee on Radio Interference (CISPR) investigated radio noise originating from high voltage (HV) power equipment and provided recommendations for reducing the radio noise generated in SGs [5]. Impulse noise has been investigated in HV substations including its influence on the performance of wireless channels and modulations [6]. EMI impacts SG wireless communication equipment and this was studied in [7]. Hence, it is necessary to define the appropriate compliance requirements in an SG to ensure the reliable performance of the wireless communications infrastructure.

To this end, the International electrotechnical commission (IEC) has enacted the following key immunity compliance requirements for use in SGs with regards to the communication network infrastructure:

- IEC 61850-3 - Part 3: General requirements for communication networks and systems for SG utility automation.
- IEEE 16.13-2003 - IEEE standard environmental and testing requirements for communications network infrastructure in SG Substations. Its
- IEEE 16.13.1-2013 - IEEE standard environmental and testing requirements for communication network infrastructure Installed in SG transmission and distribution facilities.

Consequently, RRA in CRSNs for other applications is different from the RRA in CRSNs for SG applications. That makes this survey quite different from other related surveys on CRSNs. Hence, RRA in CRSN for SG applications should be based on the following considerations:

- Consideration of key immunity compliance requirements for the CRSN in an SG as stated earlier.
- Appropriate resource allocation architecture to cope with the EMI in the SG environment.
- Consideration of appropriate electromagnetic comparability (EMC) for the CRSN to operate effectively in a varying EMI SG environment.

1.4. Protocol Architecture for a CRSN in an SG

The SG has applications in order to operate in the various SG communication layers such as HAN, NAN, and WAN. Hence, heterogeneous communication technologies are required for the delivery of SG application data. The tough SG environment caused by harmonics, power line disturbance, co-channel interference from grid instruments, and severe propagation conditions, impairs SG communication. Hence, conventional protocols are not suitable for SG communication because of the varying applications, heterogeneous communication requirement and unsteady nature of the SG environment. To address these challenges, the protocol architecture for CRSN based SG communication must be:

(1) Application-Specific driven/Aware; and
(2) Cross-layer framework.

- Application-Specific driven/Aware: since SG applications are for specific grid needs, they cannot be regarded as general purpose applications. Hence, the protocol architecture should be designed to support the specific purpose of the SG application, i.e., the heterogeneous communication requirement. The protocol architecture for the application should be spectrum aware. This means that the application should have an interaction with the MAC protocol of the CRSN in the SG.
- Cross-layer framework: since the channel condition in a CRSN based SG changes dynamically, there is a need for the underlying protocol stack to interact and change the information/signal. Thus, the protocol architecture should be designed in such a way that the Physical, MAC, Routing, Transport, and Application protocol layers interact with each other for information exchange.

Other considerations of the protocol architecture for a CRSN based SG include consideration of the common attributes of the CRSN such as low power, limited complexity, and channel characteristics. Hence, these attributes should be included in the protocol architecture. This signifies that the protocol architecture in the CRSN based SG should be based on energy efficiency as well as being spectrum aware.

Furthermore, the protocol architecture may be designed to typify a particular RRA architecture, such as centralized, clustered, distributed, and DHC architecture respectively. The channel characteristics/energy efficiency and device connectivity are common in the MAC and Routing protocols. Thus, most concerns are in these protocol layers, which can be designed to interact with the application layer by implementing the protocol design with a cross-layer framework.

The notable protocol architecture characteristics based on MAC protocol for a CRSN in a SG are:
- CRB-MAC: this protocol was proposed in [8]. The nodes leverage an optimal transmission by using a wake and sleep schedule timer for detecting the PU activities. It goes to sleep when PU is actively using the channel, and resumes again at the expiration of the time. However, this protocol is a receiver-based MAC protocol and is energy efficient with a reduced delay. However, it is not based on a cross-layer framework.
- CSMA/CA MAC: this protocol was proposed in [9]. This is based on a cross-layer framework approach that incorporates the CSMA/CA MAC protocol with dynamic spectrum access (DSA) to assess the available channels. The advantages of this protocol include the supporting of application-specific driven application, addresses QoS requirements, has a reduced delay, and has optimal throughput.

The notable protocol architecture characteristics based on Routing Protocol for a CRSN in a SG are:
- Distributed control algorithm (DCA): this protocol was proposed in [10]. This protocol is based on a cross-layer framework that interacts jointly in optimizing the routing, MAC and physical layer protocol functions in a CRSN to avoid the tough propagation conditions in a SG. This includes QoS support for SG applications.
- RPL (routing protocol for low power and lossy networks) modification: this protocol modification was proposed in [11] for energy and spectrum efficiency in a CRSN at the SG utility. This protocol is based on a multi-layered framework approach, and has the following advantages: reliability and low latency routing support for large-scale CRSNs.

Based on the above, it can be seen that the existing protocol architecture for a CRSN in a SG are very few. None of the protocol architecture for a CRSN in a SG supports a cross-layer framework that cuts across the five entire protocol stacks. Hence, a reliable cross-layer framework approach that jointly interacts with the Physical, MAC, Routing, Transport, and Application layer protocols would be advantageous in CRSN based SG communication. The protocol should be energy efficient as well as spectrum-aware for optimal SG communication.

The remainder of this paper is structured as follows in the following sections: Related works are discussed. Description of the overview, functionalities, and unique characteristics of a CRSN in a SG are presented. The RRA in a CRSN for SG is presented. Performance analysis of RRA based on throughput improvement criteria in CRSN for SG is presented. Recommendations and future research directions are discussed. Finally, the survey article ends with conclusions.

The focus of this paper is to explore RRA in a CRSN based SG, thus leading to the following contributions in this survey:

- A comprehensive survey of RRA in a CRSN based SG is presented.
- The overview, functionalities and unique characteristics of a CRSN in a SG are discussed.
- An SG Architectural Framework, including a comparative framework for WSN, CRSN, and CRN, is exemplified.
- A guaranteed network connectivity channel allocation for throughput maximization (GNC-TM) in CRSNs for SGs.
- Optimal spectrum band determination in RRA for improved throughput criteria in order to establish suitable spectrum band operation in CRSNs for SGs.
- The protocol architecture for a CRSN in a SG is highlighted.
- Radio resources optimization criteria in a CRSN based SG are discussed in this survey.
- An RRA scheme in a CRSN based SG, including its architecture, is presented.
- Recommendations and future research directions regarding the RRA in a CRSN based SG are highlighted.

1.5. Overview, functionalities, and unique characteristics of a CRSN in an SG

1.5.1. Overview of CRSN

In a CRSN, there are two types of users: primary and secondary. Primary users (PUs) are the licensed (authorized) users, who have the license to operate in an allotted spectrum band so they can access the primary base station. Secondary users (SUs) or Cognitive Radio users (CRs) are unlicensed users without a spectrum license. CRs use the existing spectrum through opportunistic access without causing harmful interference to the PUs. CRs look for the available portion of the spectrum that is not in use, which is called a spectrum hole or White Space. The SUs can share the spectrum channels with the PUs by using one of the two methods known as overlay and underlay methods. In an overlay method, SUs can opportunistically access the PU spectrum channels only if the channels are completely unused by the PUs. Whereas, in the underlay method, the SUs can simultaneously access the PU channels even when the PUs are using the channels so long as the harmful interference caused to the PUs is below a predetermined threshold value.

However, there are problems associated with the two methods. For instance, in the overlay method, some wireless services, such as TV and cellular networks, the PU channels may be predominantly busy for a long time, resulting to no white space. Hence, the SUs may be unable to opportunistically access the spectrum channels since there is no white space available in the PU networks. On the other hand, the problem in the underlay method involves the inability of the SUs to opportunistically access channels in an area predominantly deployed with PUs. This is because more interference will be caused to closely located PUs, thereby making it difficult for the SUs to access these channels within a state of interference. Therefore, it is essential to solving these problems that are associated with the overlay and underlay methods in CRSNs.

Therefore, this paper employs the overlay method in CRSNs and throughout this paper the overlay method is adopted. The SUs use the optimal available channel only if there is no PU operating in the licensed bands [12]. The problem of the inability of the SUs to access channels in overlay method has been addressed in previous work [13]. In the work, a channel fragmentation strategy is used in a (CFS)-based Alamouti space-frequency block coded (SFBC) scheme to improve the performance of the SU networks.

1.5.2. Functionalities of CRSN

A CRSN has the following cognitive functionalities to enable the secondary users to have dynamic and opportunistic access to the spectrum holes [14]. These functionalities are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. These four main cognitive radio functionalities are required to determine the accurate communication parameters of SG communication and adjust to the dynamic radio environments [15].

1.5.2.1. Spectrum Sensing

Spectrum sensing is the process of discovering of the available spectrum bands and detection of the spectrum holes in the PUs [16]. Spectrum sensing operation is a very power-consuming function and poses great challenges for providing seamless communications in large-scale SG deployments. Therefore, some solutions need to be deployed to achieve viable CRSN based SG communications. Minimum hardware, for example using single radio, and less advanced spectrum sensing functionalities, can be used to lower the complexity level of the sensing operations and reduce energy consumption [12], [17]. Reducing the sensing durations to an appreciable level can be a good solution. There are various spectrum sensing techniques, such as energy detection, feature detection, matched filter, and interference temperature [15]. Using one or a combination of these methods can be achieved.

Generally, spectrum sensing comes with additional energy consumption. Hence, there is a trade-off between sensing accuracy and energy efficiency. Therefore, an optimized DSA is required in order to address the spectrum accuracy which involves the lowering of packet collisions and the ability of switching to the best available channel, including less contention delay and enhanced bandwidth.

Spectrum sensing faces the challenge of being very sensitive to the detection mechanism due to harsh environmental conditions such as multipath fading and environmental noise in a SG environment. However, an optimised DSA will help in addressing this.

1.5.2.2. Spectrum Decision

The spectrum decision process involves two steps: spectrum characterization and spectrum selection. These are the necessary steps for the characterization of the spectrum band in terms of the received signal strength, interference, power of transmission and energy efficiency, number of communication users, QoS, and security requirements of SG applications [18]. Therefore, providing a QoS-aware cognitive communication network is essential in order to choose the appropriate spectrum band to meet the specific requirements of CRSN based SG communications. This is part of the spectrum decision process. However, a SG system environment has a distributed nature, and interference from radio signals, as well as the network density and channel characteristics, vary over a wide geographical area. This limits obtaining optimal knowledge about the spectrum availability. Consequently, this problem poses challenges in making precise spectrum decisions and meeting QoS requirements of CRSN SG applications.

1.5.2.3. Spectrum Sharing

The spectrum sharing process involves the selection of the best channel and power allocation. Some of the functionalities are related to the main functionalities of medium access control (MAC) layer protocols. Hence, it can be incorporated into the MAC layer. However, there are challenges associated with efficient spectrum sharing which include time synchronization and distributed power allocation [19]. For instance, methods of controlling power are essential for the spectrum sharing process in large SGs. These can adapt to the radio environments and maximize the network life-time [20]. Precise time measurements and time synchronization are required for some SG applications, such as equipment fault diagnostics and phasor measurement monitoring applications.

An effective spectrum sharing technique helps to meet the QoS requirements in a CRSN SG by adaptively allocating communication network resources. The opportunistic dynamic spectrum access capability can be used to adjust the communication transmission parameters to lessen redundant power consumption of CR sensor nodes thereby preventing the performance degradation of CRSN based SG communications.

1.5.2.4. Spectrum Mobility

Spectrum mobility, which is also called spectrum handoff, is used to mitigate the interference caused by SG communication infrastructure. Spectrum handoff occurs when changing the physical regions of the existing congested communication path or switching of the currently used spectrum band [10]. In both cases, the QoS requirements for the current SG communication transmission will be affected. Hence, the choice of switching activities should be made with respect to the requirements of different SG applications [15]. However, spectrum mobility passes interference to the current communication transmission. Because of this, schemes to prevent buffer overflows and minimize communication contention delay should be developed in order to allow for seamless, reliable and real-time monitoring in a CRSN based SG [21].

1.5.3. Unique characteristics of CRSN

CRSNs have numerous unique characteristics that differentiate them from the conventional wireless networks such as cellular/LTE, satellite/microwave and Wi-Fi. Since they incorporate the cognitive capabilities of CRN into a WSN they therefore differentiate themselves from CRN and WSN. Hence, a CRSN has unique features (possessing dualized features: CRN and WSN). These unique characteristics of a CRSN include:

- Capability of sensing the current radio frequency spectrum channel environment.
- Policy with configuration repository. Policies specify how the radio is to be operated, while the repository is formed usually from sources used to constrain the operating process of the radio so that it remains within regulatory or physical limits.
- Dynamic Spectrum Access (DSA) capabilities with multiple channels availability.
- Spectrum handoff capabilities
- Adaptive algorithmic mechanism. During the radio process, the cognitive radio is sensing its environment. It is following the constraints of the policy and configuration by exchanging with sensor nodes to best employ the radio spectrum and meet user demands.
- Low traffic flow.
- Reconfigurability and distributed cooperation capabilities.
- Limited memory and power constraints.

Due to the presence of these unique CRSN features, radio RRA schemes that are used for conventional wireless networks cannot be directly applied to a CRSN due to the dynamic availability of multiple channels in the CRSN and the dynamic spectrum access in the presence of primary user activity. Hence, while designing resource allocation schemes for CRSNs, their unique features should be considered as well as the primary user activity

Table 2 shows unique criteria and constraints to be considered in CRSN-based SG applications when compared with CRSNs for other applications.

Table 2. Criteria for CRSNs deployment for SG applications compared with other applications

Unique criteria/constraints to be onsidered in CRSNs deployment	CRSNs for SG applications	CRSNs for other applications
Key immunity compliance requirements of communication infrastructure in SGs.	Key immunity compliance is essential general requirements for communication networks and systems for SG utility automation [7]	Key immunity compliance requirement is optional
CRSN Protocols for SGs applications	CRSN Protocols for SGs includes CRB-MAC, CSMA/CA MAC, Distributed control algorithm (DCA), and RPL (routing protocol for low power and lossy networks) [8] - [11]	CRSNs for other applications are based on generic protocols for sensor network.
Spectrum sensing in CRSNs for SG	An optimized DSA is required for spectrum sensing in CRSNs for SG [15]	Generic DSA is used for spectrum sensing in CRSNs for other applications.
Spectrum mobility in CRSNs for SG	Improved spectrum mobility scheme is required to prevent buffer overflows and minimize communication contention delay in CRSNs for SG [21]	Generic scheme is used for spectrum mobility in CRSNs for other applications.

2. Related Works

The RRA has been well investigated for various wireless networks, though not in the perspective of a SG. Numerous studies on RRA for different wireless networks such as cognitive radio networks (CRN), CRSN, and WSN, can be found in the literature [22]–[29]. These works are not in the context of a SG; they do not involve the integration of a wireless network into a SG in their surveys. Only a very few articles survey RRA from a CRSN perspective. Yet, their emphasis is not on the intersection of a CRSN in a SG for the RRA. This paper presents a survey that focuses on RRA in a CRSN based smart grid.

Surveys on RRA in a CRSN for SG environments have rarely been investigated. Refs. [30]-[32] survey works on RRA in terms of CR functionalities in a CRN. Ref. [30] conducted a survey on RRA in a WSN. Ref. [33] surveys works on RRA in a CRSN. In this work, CRSN resource allocation schemes are categorized and some optimization criteria highlighted for a CRSN. The work is not in the context of a SG. Other works which are not mainly concerned with the survey of resource allocation, but highlight some aspects of resource allocation strategies, are found in [34]-[42]. Ref. [34] presents a survey on spectrum sensing methodologies for cognitive radio. This work is centred on a spectrum sensing strategy. Ref. [35] shows that resources in cognitive radio networks (CRNs) should dynamically be allocated according to the sensed radio environment.

Le and Hossain, in [36], presented a resource allocation framework specifically for spectrum underlay in cognitive wireless networks. Ref. [37] studies resource allocation in an Orthogonal Frequency Division Multiplexing (OFDM)-based cognitive radio network (CRN). This was with the consideration of many practical limitations such as imperfect spectrum sensing, limited transmission power, and different traffic demands of secondary users.

Table 3 presents a comparison of RRA surveys in CRN, CRSN and CRSN based SGs. It helps to show whether a survey of radio RRA has been considered in a CRSN based SG.

Table 3. Comparison table on radio resource allocation in CRSN based SG.

Survey References for resource allocation	CRN	CRSN	CRN based SG	CRSN based SG	Resource allocation
Tragos et al. [23]	Yes	No	No	No	Yes
Naeem et al. [24]	Yes	No	No	No	Yes
Ahmad et al. [33]	No	Yes	No	No	Yes
Ireyuwa et al. [34]	Yes	No	No	No	No
Xie et al. [35]	Yes	No	No	No	No
Le et al. [36]	Yes	No	No	No	No
Li et al. [37]	Yes	No	No	No	No
Yu et al. [38]	Yes	No	No	No	No
Khan et al. [57]	No	No	Yes	No	No
Akan et al. [43]	No	Yes	No	No	No
Gungor et al. [42]	No	No	Yes	No	No
Faheem et al. [59]	No	No	No	Yes	No

Ref. [38] studied the energy efficiency aspect of spectrum sharing including power allocation in heterogeneous cognitive radio networks with femtocells. Ref. [39] proposed a correlation-based admission control strategy for efficient resource utilization in CRN. [40] proposed a distributed lightweight protocol for reduction of energy and communication overhead in CRSN. [31] presents throughput maximization for machine to machine communication using electromagnetic energy harvesting-based CRSN. [42] carried out investigative studies on WSN for SG.

Resource allocation was generally discussed in the above works, but the survey of resource allocation strategies was not their major target. Ref. [43] discussed issues regarding dynamic spectrum management in a CRSN. This work does not provide any survey on resource allocation strategies. Refs. [44] and [45] discuss CRN but RRA was not their main objective.

The authors in [46]-[50] carried out experimental work in RRA for CRN. Their experimental results validate improvements in some optimization criteria for resource allocation in a CRN. However, these works are not carried out from the perspective of a CRSN based SG.

Ref. [51] reported on experimental work in a CRN for the improvement of spectrum and energy efficiency using RF energy harvesting as an alternative data transmission for the SUs if the channel is occupied. However, the work does not involve RRA in a CRSN based SG nor evaluation of frequency spectrum for throughput improvement in a CRSN based SG. Ref. [52] carried out experimental work for RRA based on a CRN for a IoT sensor network. Though the work did not address a CRSN based

SG. Ref. [53] proposed channel selection strategies in a CRN with Energy Harvesting for Internet of Everything.

Ref. [54] proposed a spectrum and energy harvesting enabled Heterogeneous Cognitive Radio Sensor Network (HCRSN) for a RRA solution based on two algorithms that allocate the transmission time, power, fairness, and channels access including minimal energy consumption of the data sensors.

Ref. [55] conducted an experiment for RRA in a CRSN. The experimental results validate improved spectrum allocation, priority among sensor data, energy efficiency and reduce spectrum handoff. Experimental work was presented in [56] in which proposed energy efficient opportunistic spectrum allocation in a CRSN. However, this work does not involve RRA in a CRSN based SG.

Surveys of SGs that highlight some aspects of resource allocation are found in [12], [57] - [60]. They discuss spectrum sensing, they did not highlight resource allocation extensively such as including spectrum, QoS, fairness, priority, and power allocation schemes, etc. Resource allocation schemes were not their main focus. They did not consider evaluation of the frequency spectrum for throughput improvement in a CRSN based SG.

From the above discussion, some of the works focus on RRA in only CRNs or CRSNs, or other aspects of wireless networks without addressing the SG. None have surveyed the integration of resource allocation in a CRSN into a SG. The survey that involve a SG domain discussed some aspects of resource allocation without delving into the full details of the resource allocation scheme; and RRA is not the main aim of the articles.

Hence, this paper extends the work on RRA into the SG domain, as well as performance analysis of the frequency spectrum for throughput improvement in a CRSN based SG. Based on the literature, improvement of the throughput in a CRSN in a SG has rarely been investigated. Thus, the performance analysis work put forward here serves as the contribution to RRA in terms of the improvement of throughput. This contributes to other optimization criteria in a CRSN based SG.

3. Radio Resource Allocation in CRSN Based SG

3.1. *Radio resource performance improvement criteria*

RRA involves strategies or schemes of allocating radio resources such as frequency bands, transceiver power, time slots, handoff criteria, user fair allocation, modulation schemes, transmit antennas and sensing signal/channel detection probability, to the channel state information based on some performance improvement strategies or optimization criteria. Optimizing these radio resource criteria will go a long way to improve the overall performance of the CRSN in a SG environment. Hence, the aim is to utilize the limited spectrum, power constraints and network infrastructure efficiently. The following optimization criteria metrics are considered:

3.1.1. Energy efficiency metric

Realizing energy efficiency with power algorithm schemes is usually required to extend the lifetime of the battery of the sensor node. The energy efficiency criterion is necessary for a CRSN in a SG because the sensor nodes have limited power battery constraints. However, the schemes used for this criterion are based on energy preservation and power consumption minimization which cannot achieve maximum power performance. Energy/power efficient schemes for CRSN related applications in general and in the SG in particular have been widely studied [61]-[80]. Since SG applications are mission critical, it is essential to incorporate an energy harvesting scheme in the energy efficiency metric to provide a perpetual life for the sensor node.

3.1.2. QoS guarantee metric

SGs have various applications with different and stringent QoS requirements. Hence, the resource allocation scheme design should consider different QoS support for a SG application. Resource allocation schemes involving CRSN applications that consider the QoS requirements are found in [69], [9], [10], [81]-[87]. Ref. [9] considered the QoS guarantee for heterogeneous traffic in a SG application such that each traffic type has an associated priority with specific QoS support. QoS support is imperative especially for SG surveillance and multimedia applications including distribution automation [88].

3.1.3. Maximizing throughput metric

Giving scheduling priority to data flows in terms of consumed network resources per amount of information transferred will help to maximize the total throughput of a CRSN based SG. Schemes utilizing throughput maximization scheduling based criterion in CRSN applications have been investigated in [70], [73], [74], [11], [89]-[95].

3.1.4. Interference mitigation and avoidance

Destructive interference from the external network to the CRSN based SG network should be avoided. Also, co-channel interference within the network as well as interference to the primary networks should be mitigated or cancelled. This interference avoidance and minimization criterion improves both the primary and secondary network. Resource allocation schemes that utilize this criterion in protecting the links of both the primary users and the secondary network have been studied in [11], [80], [94].

3.1.5. Fairness scheduling criterion

Fairness among SUs in opportunistic spectrum access and scheduling and fairness in transmission power allocation to SUs are essential in the design of RRA schemes for CRSN based SGs. Since there is trade-off between QoS guaranteed and maximum throughput and fairness, consideration of fairness between multiple sensor nodes when prioritizing traffic should be done in such a way that throughput improvement and QoS support are maintained. Work that utilized this fairness criteria in a SG is reported in [61]. They considered QoS guaranteed for heterogeneous traffic in SG applications such that each traffic type has an associated fairness. Resource allocation strategies that utilize fairness criteria are also found in [66], [11], [96]-[101].

3.1.6. Priority scheduling criterion metric

The need to prioritize various SG application traffic is essential so that it has the capability to adapt to varying network conditions in real time [102]. A typical traffic type are the control commands having small packet size [102]. Hence, prioritizing traffic types per their order of importance, bandwidth/spectrum demand, real time, and power of consumption is highly beneficial in the CRSN based SG domain. Prioritizing traffic in a CRSN based SG was also considered in [9], [100].

3.1.7. Reduced Adaptive modulation overhead and probability of detection

The adaptive modulation scheme in a CRSN based SG can dynamically adapt to other modulation types due to the DSA capability. This leads to an overhead as well as supplemental energy consumption that results in the event of adapting or switching to another modulation type [51] at the sensor node. Hence, there is need to design a resource allocation scheme in a CRSN based SG that has reduced complexity in terms of the adaptive modulation mechanism.

3.1.8. Reduced spectrum handoff

Spectrum handoff occurs too often in CRSN applications. This leads to overhead as well as extra energy consumption at the sensor nodes. When occurring during the hand-off, the buffer overflows result in packet losses and affects the transmission reliability. Works that make use of this criterion for the resource allocation in CRSN applications have been reported in [61], [63], [66], [71]. The authors in [64] presented a reduced handoffs technique using a home gateway (HGW) for a home area network in a cognitive radio-based SG. Ref. [47] investigated a resource allocation scheme involving reduced spectrum handoff for CRSN applications. Ref. [66] presented a dynamic spectrum access scheme that accomplishes the reduction in the number of spectrum handoff. The resource allocation algorithm in [47] also minimizes the spectrum handoffs.

The summary of the literature with respect to various resource optimization criteria used in different CRSN contexts has been tabulated in Table 4. This table highlights each resource optimization criterion used in the different CRSN context including CRSN based SGs. It can be deduced from the table that the utilization of the optimization criteria for RRA in a CRSN based SG is limited. In this scenario, resource optimization criteria such as energy efficiency, throughput maximization, and adaptive modulation, are yet to be applied in a CRSN based SG. Hence, attention should be drawn to this.

Table 4. Summary of resource optimization criteria for CRSN based SG.

Resource optimization criterion	CRSN	CRN based SG	CRSN based SG	References for various optimization
Energy efficiency	Yes	Yes	No	[63][64][61][66][70][74][104][107][20]
QoS guarantee	No	Yes	Yes	[62][70][80]-[83][93][83][67][68]
Throughput	Yes	No	No	[66][69][72][73][74][80][81][93]
Interference mitigation	Yes	Yes	Yes	[63][66][69][75][81][90][109][110][19] [20]
Fairness	Yes	No	Yes	[63][66][81]
Priority scheduling	Yes	Yes	Yes	[11][91][102]
Adaptive modulation	Yes	No	No	[67][115]
spectrum handoff	Yes	Yes	Yes	[62][63][108][71]

3.2. Radio resource allocation scheme architecture

The RRA architectural strategy in a CRSN based SG is divided into four groups: centralized architecture, cluster architecture, distributed architecture and distributed heterogeneous architecture. The resource optimization criteria which have been highlighted in the preceding section are implemented using each specific resource allocation scheme architecture. These architectures will be looked at in turn.

3.2.1. Centralized Architecture

A centralized RRA scheme consists of the central node or sink node which serves as a base station that is responsible for providing network operation services such as spectrum allocation, power/energy control, node localization, link/modulation adaptation and routing among the sensor nodes. A logical topology for this architectural approach is a star network as illustrated in Figure 2.

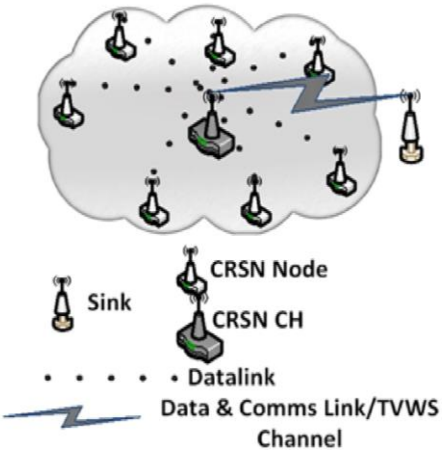

Figure 2. Centralized resource allocation architecture for a CRSN based SG

The centralized scheme can be classified in terms of how the information is processed, which includes the following: single sink, multi sink (for large coverage area and redundancy), and multiple task devices (for auxiliary devises and specific task within the network). RRA is made based on selected optimization criteria by the sink node which is then communicated to the sensor node. The selected optimization criteria may address more than one or two criteria. Centralized architecture schemes in CRSN related applications have been investigated in [61], [63]-[64], [65]–[68], [73], [11], [103]–[107], [89]–[91], [92] There are several advantages to centralized schemes. The main advantages include: (i) simplified energy efficiency management; and (ii) conflict avoidance in the transmission and reception link because the sink node coordinates every sensor node. However, there are some disadvantages in this architecture. The main disadvantages of these schemes include: (i) the network cannot support large density sensor nodes; and (ii) there is high signaling overhead leading to high energy consumption.

Notable RRA schemes that utilize centralized architecture are:

- Energy efficient joint source and channel sensing: A joint source and channel sensing scheme and power consumption minimization in a CRSN was proposed in [65]. The basis of this scheme is the perception of energy efficient joint source and spectrum sensing. The work involves two critical energy consuming tasks in a CRSN which are jointly considered. Specific and joint power consumptions are mathematically modeled to minimize the power consumption of each senor node.
- A home area network gateway (HGW) assisted cross-layer cognitive spectrum sharing mechanism was proposed in [61]. This was for a home area network (HAN) solution. The mechanism has two main algorithms: the spectrum access controller and power coordinator. These operate at the medium access control (MAC) and physical (PHY) layers, respectively. Each wireless sensor node in a HAN accesses the spectrum only if it is permitted by the centralized access controller. However, the power coordinator works in a decentralized architecture; it makes use of a non-cooperative game between the wireless sensor nodes to adjust their transmitting power.
- Fair and energy efficient dynamic spectrum allocation: this scheme involves was presented in [66]. This scheme is for a low density CRSN. The sensor nodes are presumed to be located within a cell or segment boundary. The main objective of this scheme is to reduce handoff as well as signaling overhead. This is achieved by increasing the energy efficiency of an “interleaved FDMA” based CRSN and ensuring fairness between the spectrum sensor nodes. In this scheme, interference avoidance in the primary network is considered. This includes priority and fair spectrum allocation in the sensor nodes, and reflects the priority in the sensor data. Only the sensor nodes

having data to transmit are assumed to send a spectrum resource request to the central nodes. Hence, this scheme supports unified multiple criteria goals.

- A hybrid dynamic spectrum access (H-DSA) strategy was proposed in [61]. This can significantly enhance the flexibility of communications infrastructure and spectrum efficiency, and improve a neighborhood area network (NAN). In this scenario, the spectrum bands in a NAN contain leased and licensed spectra from the telecommunication operator, which is referred to as the primary network, and the unlicensed spectra are used in an opportunistic manner.
- Energy Efficient Adaptive Modulation: a joint life-time maximization and adaptive modulation framework for realizing high power efficiency in CRSNs was presented in [67]. Adaptive modulation helps to improve the energy efficiency in a wireless network. This work considered a CRSN that contains uniformly distributed nodes within a low density area. This scheme performs adaptive modulation by utilizing parameters like time slot, synchronization, spectrum sensing, and Rayleigh fading characteristics. This scheme has the capability for interference detection and avoidance of the primary network.
- Energy Efficient Power Allocation: [73] investigated an energy efficient power allocation scheme for a CRSN. The aim of this scheme is to maximize the ratio of throughput to power. This work considers a CRSN such that each of the sensor nodes communicates on an orthogonal or at a right angle channel to the cognitive radio sink node or base station. There is a limit to the transmitted power of the sensor node. This is in order to limit the interference which is caused in the primary network to below a certain threshold.
- Cross-Layer Design for QoS Support: a cross-layer design that ensures the QoS requirement for CRSN based SGs was proposed in [9]. The varying characteristics of the data traffic for various applications in a SG means that the different QoS requirements need to handle the SG application traffic. This work handles the issues of heterogeneous traffic in a CRSN based SG by defining different classes of traffic with different priority levels. This classification is significant for separating the traffic with respect to the services and their network requirements e.g., latency, link reliability, and data rate.
- A hybrid guard channel (HGC) strategy has been proposed for cognitive NANs in a cognitive radio network based SG. The centralized scheme in [61] was designed with a hybrid guard channel that addresses the QoS of the sensor nodes and maintains it at a satisfactory level. This is because the dynamic nature of spectrum availability causes difficulty in stable and guaranteed QoS provisioning. The HGC strategy reduces overhead in the spectrum handoffs, this is achieved by reserving a certain number of channels in both the licensed and unlicensed bands for the use of spectrum handoffs.

3.2.2. Cluster Architecture

On a topology level, cluster architecture is obtained by grouping the CRSN nodes within a smaller sub-network transmission area. A designated node usually known as Cluster Head (CH) controls this group of sensor nodes as shown in Fig. 3. The CH performs a similar role of allocating resources as the sink node in a centralized scheme. However, the CH has less overhead and utilizes less power for the common control channel in each cluster compared to the sink node in a centralized scheme. Hence, this scheme can achieve better spectrum use with the help of the distribution of nodes in several clusters, and with bandwidth reuse. Cluster schemes have been studied in [94], [92], [82], [75], [92], [84]–[85], [108]-[110]. A close cluster member can perform the role of the CH if the CH fails. Since there is a small number of cluster members in each cluster, this leads to low signaling overhead at each CH compared to the overhead at the sink node of a centralized architecture. The main advantages of this scheme are: (i) information is local since a sensor node keeps the information of its neighboring node within a cluster; (ii) the cluster architecture is scalable; and (iii) reconfiguration is done locally on only the affected part.

However, there are some drawbacks with this architecture. The main drawback is the high number of broadcasts which is equal to the number of clusters; thus, leading to a broadcast storm in the network.

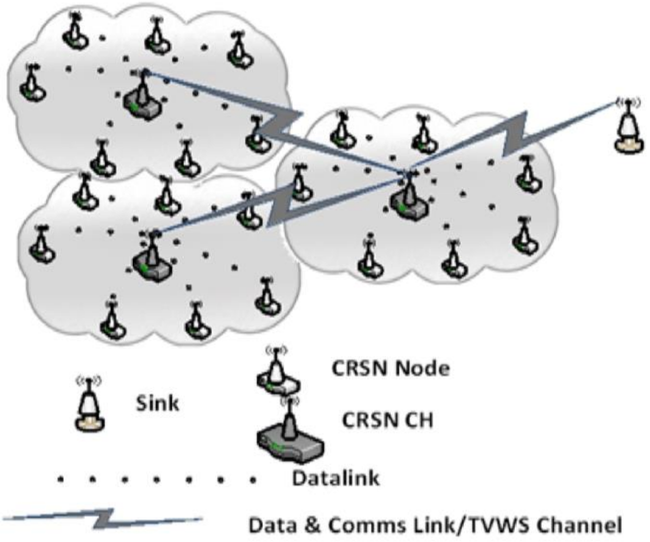

Figure 3. Cluster resource allocation architecture for a CRSN based SG

Notable RRA schemes that utilized the cluster architecture are:

- Periodical sensing (PS) scheme: this scheme was proposed for a WiMAX based CR system network to manage co-channel band interferences during usual communication in power distribution sub-station monitoring. Ref. [94] grouped the PS data into time and frequency domains such that the interference is classified into various types. It then uses this classification to execute a corresponding management method in order to minimize the interference. This will help to avoid the in-band interference that results from other communication devices operating at the same frequency with the SCADA in the SG environment.
- Energy efficient channel management: a cluster-based energy efficient channel management framework for CRSN applications has been proposed in [75]. This scheme is based on partially observable Markov decision process framework. The work involves a small network connected in star topology and with a CH and multiple cluster members. channel sensing and channel switching are considered in this work. The scheme manages energy efficiently by making the CRSN to operate on a channel tagged operating channel that is not occupied by the primary network while maintaining another vacant channel. as a backup.
- Joint node selection and channel Allocation: in [78], a scheme that selects the optimal number of sensor nodes with an efficient channel allocation mechanism was proposed. This scheme improves the performance of a cluster architecture based CRSN. In this work, clustering is achieved using the K-means clustering mechanism [111]. The problem of node selection is formulated as a knapsack problem, whereby a CH in each cluster controls the optimal number of sensors and selects the suitable sensors. After which, the Hungarian algorithm [112] is used for efficient channel allocation between the sensors thereby prolonging the network lifetime and giving appreciable data transmission in the sensor nodes.
- Energy efficient spectrum sensing: in [98], an energy efficient spectrum sensing node selection for cooperative channel sensing was proposed. The scheme involves energy conservation and precise spectrum sensing under a network of limited energy availability. In this scheme, the sensor nodes liaise and form coalitions for collaborative sensing. In each coalition or cluster, one sensor node is chosen as the cluster head which makes sensing decisions in a centralized manner at the cluster

level. Between the sensor nodes of each coalition, the cluster head selects only the most suitable nodes for cooperative sensing.

- Markov chain modeling of a CRSN in SG: this scheme was presented in [109]. It aims at reducing transition delay during handoffs. The authors use examples of Markov chain models. The primary networks have prioritized access to the spectrum compared to the CRSN users, and are unaware of the CRSN user usage of the spectrum. Thus, the primary user arrivals follow a Poisson distribution with rate λ_p, and their service time is exponentially distributed with rate μ_p. Likewise, CRSN secondary users follow a Poisson distribution with rate λ_s and exponential service rate μ_s. A CRSN user is forced to immediately relinquish a channel due to the arrival of any primary network and instantaneously transition into other available spectrum resources.
- Energy efficient spectrum aware clustering: in a cluster architecture CRSN, the selection of a suitable CH together with the determination of an optimal number of clusters are essential in energy and spectrum efficiency. In [12], an energy efficient clustering scheme is considered. This work is centered on finding the optimal number of clusters to reduce transmission power consumption and on avoiding interference to the primary network. In this work, two types of communication are considered: intra-cluster and inter-cluster communication. In intra-cluster communication, the sensor nodes transmit their collected information to the matching CH, whereas in inter-cluster communication, the CH compresses the aggregated collected data and sends it to the neighboring relaying CH for subsequent transmission to the sink node.

3.3.3. Distributed architecture

In a distributed architecture scheme, each CRSN node makes its transmission decision in an independent manner. In addition, neighboring sensor nodes can cooperate with each other for transmission decisions. There is no central or base station node among the sensor nodes to coordinate the communication. Distributed resource allocation schemes can either have a cooperative distributed resource allocation or non-cooperative distributed resource allocation.

These schemes can quickly adjust to changes, and are robust to time changing wireless environments. For example, if an area of the network is disturbed, only the sensor nodes in the affected area will need to update their transmission mechanism which is a relatively faster process; whereas in the case of a centralized architecture, the resource allocation for all the sensor nodes will be updated.

In addition, the distributed schemes have lower signaling overhead as well as a faster decision process. The advantages of distributed schemes are similar to cluster schemes; however, with an additional advantage of reduced energy consumption at every sensor node.

The major disadvantage is that connectivity cannot be assured since each node makes decisions on local information which may include error or malicious activity spread by the neighboring nodes which renders distributed resource allocation to a weak optimal solution. Distributed architecture resource allocation in CRSN related applications has been studied in [62], [108], [80], [85]–[86], [88], [93], [113]. An example of a distributed resource allocation architecture for a CRSN based SG is shown in Figure 4.

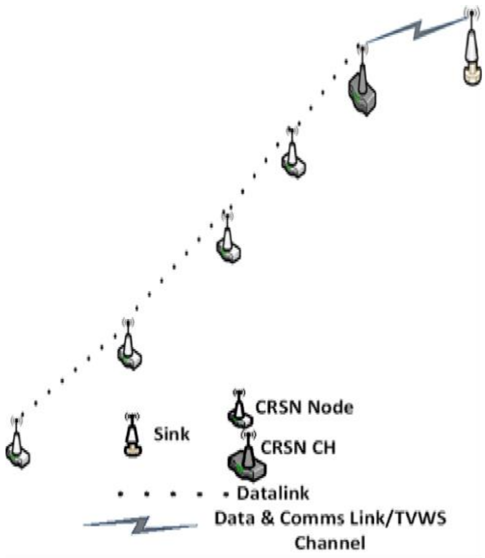

Figure 4. Distributed resource allocation architecture for CRSN SG.

Notable RRA schemes that utilize a distributed architecture are:

- Spectrum discovery schemes were presented in [62]. The schemes comprise of non-cooperative spectrum discovery and cooperative spectrum discovery. The objective of these schemes is to reduce the total energy of consumption of the sensor nodes during sensing using a home gateway (HGW). The schemes involve setting the threshold of the detection probability and the threshold of the false alarm probability, respectively. The thresholds represent the guarantee of sensing performance. Hence, an energy minimization problem in a scenario with two channels was formulated.
- Energy efficient spectrum access: distributed energy efficient power allocation and a sub-carrier selection framework for a multi-carrier CRSN was proposed in [80]. This distributed framework allocates power and a subcarrier to each CR sensor node based on the data rate requirement and power flow. This increases the energy efficiency of the network as well as avoiding any destructive interference to the primary network and the existing sensor nodes. Hence, it reduces the energy consumption of all the subcarriers allocated to the sensor nodes, thereby maximizing the network lifetime, and giving an appreciable QoS support.
- Robust distributed power control: a distributed power control algorithm was presented in [74]. The algorithm maximizes the throughput and energy efficiency of industrial CRSNs. In this work, the sensor nodes transmit data to the CRSN base station with the aim of maximizing the total rate of all the sensors at the base station. The scheme ensures that the SINR of each sensor is above a threshold such that the cumulative interference caused to each primary network by all the sensor node transmissions is brought below a predefined threshold.
- Energy efficient packet size optimization: in [87], a framework where each sensor node autonomously determines the optimal packet size before transmission was proposed. The main aims of this work are to minimize energy consumption, improve transmission efficiency, offer protection to a primary network, and increase event detection reliability. The energy efficiency of a CRSN can be enhanced by shaping the energy efficient packet size. Energy efficient packet size shaping is an active area of research for wireless networks.
- Channel packing scheme (CPS): a novel non-cooperative sensing scheme called a channel packing scheme (CPS) was proposed in [88]. This scheme integrates the role of optimal channel sensing into the analysis of the heterogeneous CRSN system performance to alleviate the problem encountered in serial search (SS) or random search (RS) sensing in heterogeneous CRSN based SG

networks. That is, unnecessary secondary user blocking. CPS consists of two steps. The first step involves the incoming sensor node or user with less bandwidth requirement, which identifies a channel that includes sub channels already occupied by other sensor nodes or users of the same type. For the second step, the first available sub channel in sequence is allocated for this new sensor node or user. It is assumed that each channel is composed of *r* sub channels.

- Spectrum-aware and cognitive sensor networks (SCSNs) were presented in [94]. These have a distributed scheme architecture. The schemes aim to overcome varying spectrum characteristics and severe environmental conditions for SG applications in a sensor network. The distributed spectrum-aware sensor nodes monitor critical SG equipment such that sensed data will be dynamically sent over available spectrum bands in a multi-hop manner to meet the application-specific requirements [113].

Table 5 summarizes the schemes with multiple optimization criteria consideration as well as cross layer framework consideration in different CRSN contexts. From the table, with respect to the references, it is obvious that many RRA schemes have been applied to CRSN applications in general whereas only very few are applied to CRN based SGs and CRSN based SGs. Schemes with multiple optimization criteria, that is, schemes having two or more resource optimization criteria, are very few with regards to CRSN based SGs. In addition, only one scheme with a cross layer framework is applied to a CRSN based SG. Utilizing a cross layer framework in RRA will improve communication in a SG. This is because the protocol stack in the bottom and upper layers of the sensor nodes and wireless device will exchange information seamlessly through a common control channel without delay and complexity. In general, a scheme with multiple optimization criteria and a cross layer framework will improve radio RRA in a CRSN based SG.

3.3.4. Distributed Heterogeneous Clustered (DHC) Architecture

The DHC architecture from a recent work [114] can be adopted for a CRSN based SG deployment in order to leverage multiple performance improvement criteria. The architecture consists of heterogeneous CRSN nodes such as normal ZigBee CR nodes, actuator, and multimedia sensor nodes. It is responsible for providing network operation services such as spectrum allocation, power/energy control, node localization, link/modulation adaptation and routing among the sensor nodes. A logical topology for this architectural approach is illustrated in Figure 5. The allocation of radio resources here is done in a distributed clustered manner covering an extensive and long range area. This scheme is suitable for a SG application, based on the fact that a SG requires heterogeneous networks in supporting different QoS for the various SG applications. Since this architecture is a newly introduced scheme, only very few schemes utilize this architecture for RRA in a CRSN based SG. The main importance of the DHC architecture is that it circumvents the disadvantages in centralized and distributed architecture while leveraging all the benefits of other architectures.

DHC architectures consider the EMC in order to operate optimally in a varying EMI SG environment. These schemes can quickly adjust to changes, and are robust to time varying wireless and EMI environments. Notable schemes are found in [38], [108], [115]. Ref. [38] proposed the energy efficiency aspect of spectrum sharing including power allocation in heterogeneous CRNs using a Stackelberg game with femtocells. Though this scheme is not specifically for the SG environment. Ref. [108] proposed a queuing theoretic model of the important components of a CRSN using the bandwidth of a heterogeneous network, including service rate heterogeneity and proactive priority for primary users. Ref. [115] proposed a probability of detection mechanism using a moment generating

Table 5. Summary of cross-layer framework with respect to various RRA schemes for CRSN based SG.

References for various resource allocation schemes	CRSN	CRN based SG	CRSN based SG	Scheme with multiple optimization criteria	Cross layer framework consideration
Yu et al. [61]	No	Yes	No	Yes	Yes
Byun et al. [63]	Yes	No	No	Yes	No
Zhaoyang et al. [65]	Yes	No	No	Yes	Yes
Sun et al. [69]	Yes	No	No	Yes	No
Gao et al. [70]	Yes	No	No	No	No
Ayala et al. [71]	Yes	No	No	No	No
Naeem et al. [76]	Yes	No	No	No	No
Shah et al. [11]	No	No	Yes	Yes	Yes
Khalil et al. [91]	No	No	Yes	No	No
Lin et al. [96]	No	Yes	No	No	No
Izumi et al. [107]	Yes	No	No	No	No
Zhang et al. [65]	No	Yes	No	No	No
Han et al. [78]	Yes	No	No	No	No
Hareesh et al. [87]	Yes	No	No	No	No
Liang et al. [85]	Yes	No	No	Yes	No
Alagoz et al. [88]	Yes	No	No	Yes	No
Seneviratne et al.	Yes	No	No	Yes	No
[89]	Yes	No	No	Yes	No
Phuong et al. [96]	Yes	No	No	No	No
Hu et al. [104]	No	No	Yes	Yes	No
Luo et al. [111]	Yes	No	No	No	No
Aslam et al. [80]	Yes	No	No	No	No
Lee et al. [77]	Yes	No	No	No	No

function and a maximum ratio combiner (MRC) for performance improvement of RRA in a multichannel CRSN based SG.

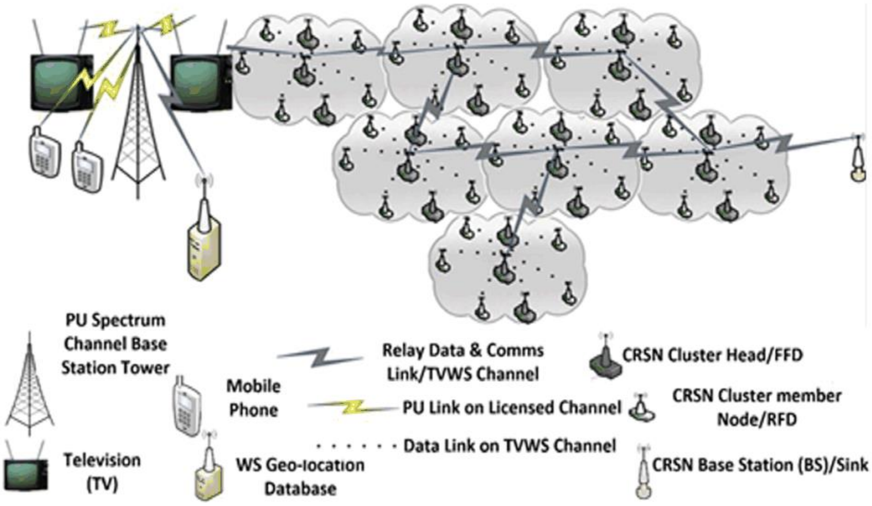

Figure 5. Distributed Heterogeneous Clustered (DHC) Resource Allocation Architecture

4. Channel Allocation for Improved Throughput in CRSN based SG

The available channels or spectrum holes are dynamically allocated by the SU base-stations to each SU for communication. However, high bit error probability or blocking probability in the SU network is a major problem associated with channel allocation in CRSNs for SG. This problem ultimately causes poor throughput. Hence, it is important to mitigate against the problem of blocking probability, in order to obtain maximised throughput of the channel allocation.

4.1 *Guaranteed Network Connectivity Channel Allocation for Throughput Maximization in CRSN-based SG*

The algorithm below, which involves guaranteed network connectivity channel allocation for throughput maximization (GNC-TM) algorithm has been introduced in a CRSNs for SG. An equilateral triangulation pattern graph is employed in the GNC-TM algorithm. The equilateral triangulation pattern graph is denoted as $G = (V, E)$, where V represents the vertices of the triangle and E the edges which is the communication links or line segments between the vertices.

The SU base-station or cluster Head (CH) coordinates the opportunistic channel access from the PU networks via DSA. It allocates the readily available unused channels to the sensor nodes at the MAC protocol layer through the CSMA/CA. Up to six channels in the 650-860 MHz frequency band can be readily available when it is not used by the PUs. The SU or CRSN nodes automatically hand over the channels as soon as the PU arrives. This intermittent arrival and relinquishing of the channels can cause unnecessary delay or blocking probability to the CRSNs. To address this, a common backup channel (CBC) and GNC-TM algorithm can be introduced as shown in Algorithm 1. The CBC serves as the control channel and handles the control signaling of the SUs as the communication channel when the available channels are in use by the PUs. The GNC-TM algorithm commences with the six available channels (AC*)*. The seventh channel is taken to be the *CBC*; and the vertices are represented as *a1, b1, c1, a2, b2, c2, …….an, bn, cn,* which indicate connections with channels. Relating to Algorithm 1, lines 7 and 8, the vertices can be connected by the available or CBC channel. Once connected, channels are then allocated to the associated sensor node for communication and exchange of messages or sensed data.

The allocated channel signals can be modulated with lower constellation order M, for (M = 4) of quadrature amplitude modulation (QAM) under Rayleigh fading channel distribution conditions. Hence, the average received signal-to-noise ratio (SNR) signal denoted as $\bar{\gamma}$ for each channel, can be expressed as

$$\bar{\gamma} = E_s/N_0 \tag{1}$$

$$\bar{P}_E = a/n \left\{ \frac{1}{b\bar{\gamma}+2} - \frac{a}{2} \times \frac{1}{b\bar{\gamma}+1} + (1-a) \sum_{i=1}^{n-1} \frac{S_i}{b\bar{\gamma}+S_i} + \sum_{i=1}^{2n-1} \frac{S_i}{b\bar{\gamma}+S_i} \right\} \tag{2}$$

where E_s denotes the average transmission power or energy per symbol in the channel, and N_0 denotes the Gaussian noise power per bandwidth of a channel. To obtain an appreciable or higher received average SNR, the error or blocking probability should be minimal. But the error or blocking probability, $\bar{P}_E$ of the MQAM signal under Rayleigh fading channel is given by [114]:

Algorithm 1

GNC-TM: Guaranteed network connectivity channel allocation for throughput maximization

```
BEGIN
G = {V, E};
AC = [1, 2, 3, 4, 5, 6];
CBC = [7];
V = {a1, b1, c1, a2, b2, c2, …….an, bn, cn};
E = {a1,b1; a1,c1; b1,c1; a2,b2; a2,c2; b,c2; ……… an,bn; an,cn; bn,cn};
if AC = 1 || 2 || 3 || 4 || 5 || 6;
    $E_{CONNECTED}$ = AC (an,bn; an,cn; bn,cn);
else if AC = 7;
    $E_{CBC}$ = CBC ( an,bn; an,cn; bn,cn);
    while E = $E_{CONNECTED}$;
        Send msg via AC
else
    send control signal and msg via CBC; end if;
end
End
```

where $a = 1 - \frac{1}{\sqrt{M}}$; $b = \frac{3}{M-1}$; $si = 2\sin i\pi/4n$; M is the constellation order ($M = 4$); and n is the number of iterations.

The relationship of SNR and throughput is given to obtain the maximized throughput so that

$$\text{Throughput} = CB \times \log_2(1 + SNR) \tag{3}$$

where CB is the channel bandwidth

4.1.1 Simulation experimental setup for GNC-TM channel allocation

In this section, the GNC-TM algorithm was implemented with error probability and signal throughput in the MATLAB environment. Table 6 shows the simulation parameters. The GNC-TM model is run and the results compared with existing protocol. The performance efficiency of the GNC-TM model is evaluated based the following metrics: error probability and throughput.

4.1.2. Simulation Results and Analysis of GNC-TM channel allocation in CRSN for SG

Figure 6 shows the throughput maximization analysis of the channel allocation based on bit error rate for the GNC-TM model compared with the existing Protocol. The results confirm that the GNC-TM model can effectively do throughput maximization in channel allocation with minimal error rate and high throughput. Figure 6 shows the GNC-TM minimal error probability starting with less than 10^{-2} and ending with 10^{-5}. Existing protocol error probability starts st about 10^{-1} and ends at 10^{-4}.

Table 6. GNC-TM model simulation parameters

Parameters	Value
Simulation runs (n)	10,000
Multi-path fading	Rayleigh fading
SNR	0:3:24 dB
Modulation size	4 QAM
Channel Bandwidth (CB)	6 MHz
Shadow Fading	Log-Normal Shadowing

In a similarly manner, the maximum throughput in the GNC-TM is 85 Mbps, while that of the existing protocol is 28 Mbps. Therefore, the results validate both the throughput maximization and error reduction in the GNC-TM model where the throughput and error rate are improved compared to existing protocols for channel allocation in CRSN-based SGs. `

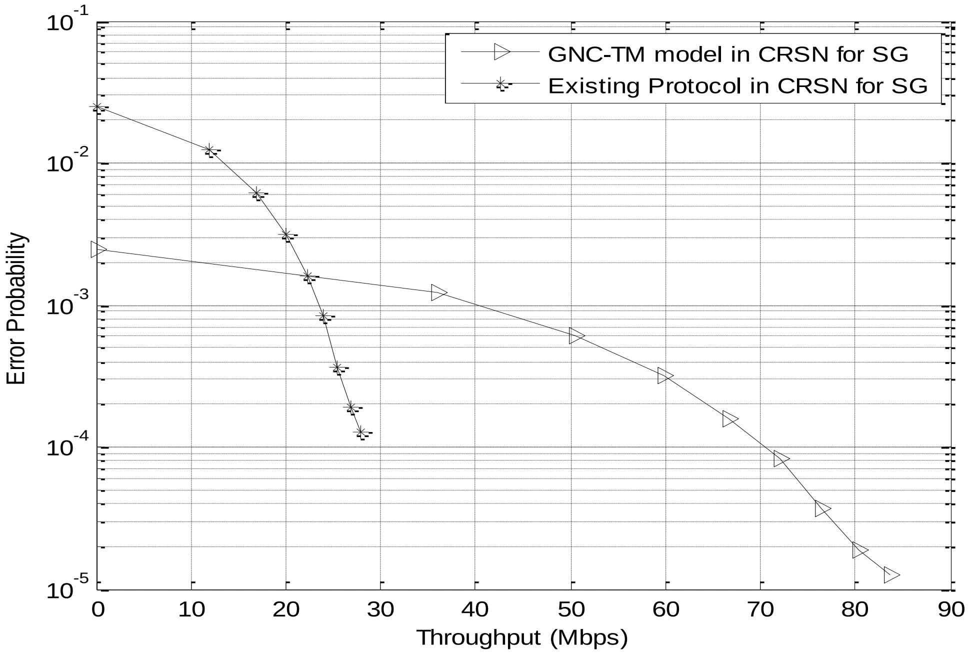

Figure 6. Throughput evaluation of channel allocation in CRSN for SG

4.2. *Optimal spectrum band determination in RRA for throughput improvement criteria in CRSN based SG*

4.2.1. Concepts and simulation experimental setup for optimal spectrum band determination

PU activities can impact on the performance of the SUs or CRSN users. Frequent PUs activities will lead to fewer spectrum holes. However, multiple SU spectrum channels will lead to more spectrum holes or white space. Multiple channels and high bandwidth is adequate for the enhancement of the throughput of the SUs [116]. Hence, making CRSN users operate at a higher frequency band (UHF: 470-868 MHz or higher) during certain PU activities will create more channels thus improving the throughput performance of the CRSN users. Whereas a lower frequency band (VHF: 54-216 MHz) for the CRSN users, operating with the same conditions as the PU activities, will adversely impact on the throughput performance of the CRSN users due to limited spectrum holes and fewer channels.

An investigation was carried out using NetSim simulation and modelling software for the performance analysis of the SU or CRSN throughput in order to establish a suitable spectrum band for the CRSNs in a SG network. NetSim is a network Discrete Event Simulation (DES) software package for protocol modelling and simulation. It allows for analyses of networks with unmatched depth [117]-[118].

Table 7 shows the network parameters used for modelling a CRSN base station and CRSN module users in three spectrum bands: 54-80 MHz; 54-216 MHz; and 54-802 MHz respectively. The experiment was modelled with a SG custom application. The SG application is generated from the SG application server with a packet size of 1460 bytes, which is then used by twenty CRSN modules for the SG data services. Table 8 shows the SG application parameters.

Table 7. CRSN configuration parameters

CRSN Base station parameters	
Device Name	Base Station
Min/Max Frequency	54/862 MHz
Coding rate	(1/2)
Distance (Range)	1 km
Channel Bandwidth	6 MHz
Modulation	4 QAM
Pathloss	30 dB
Transmission Power	5 mW
Frequency (varies with each scenario)	54-80 MHz/54-216 MHz/54-802 MHz
CRSN Module parameters	
Device Name	CRSN Module
Transport Layer protocol	UDP
Pathloss	30 dB
Transmitter power	5 mW

Table 8. SG Application parameter

Device Name	SG Application Server
Application Method	Broadcast
Application Type	Custom
Application Name	DRM
Source ID	SG Application Server
Destination ID	CRSN Modules
Start Time (s)	0 s
End time (s)	100 s
Packet size (byte)	1460

4.2.2 Simulation results and analysis of throughput based on spectrum band determination in CRSNs for SG

The simulation was conducted in Netsim under the same severe propagation conditions (30 dB) of SG in three different spectrum bands: 54-80 MHz; 54-216 MHz; and 54-802 MHz respectively. The aim of the simulation experiment is to analyse the throughput of the CRSN link in different spectrum bands with severe SG environmental conditions. There are the same PU activities in the three scenarios in order to ascertain a suitable frequency spectrum for an optimal throughput. A data packet of 1460 bytes for the SG application was transmitted to be received by the CRSN nodes. The results of the CRSN link moving average throughput were obtained and are shown in Figures 7 to 9.

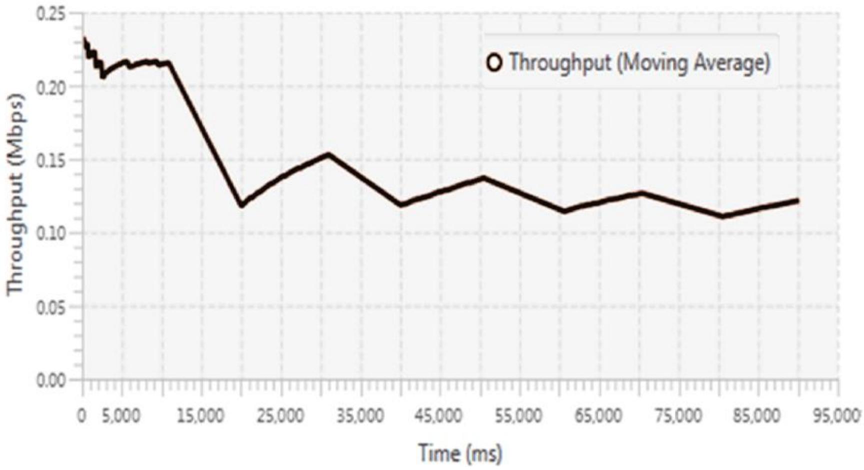

Figure 7. Scenario 1: 54 MHz – 88 MHz

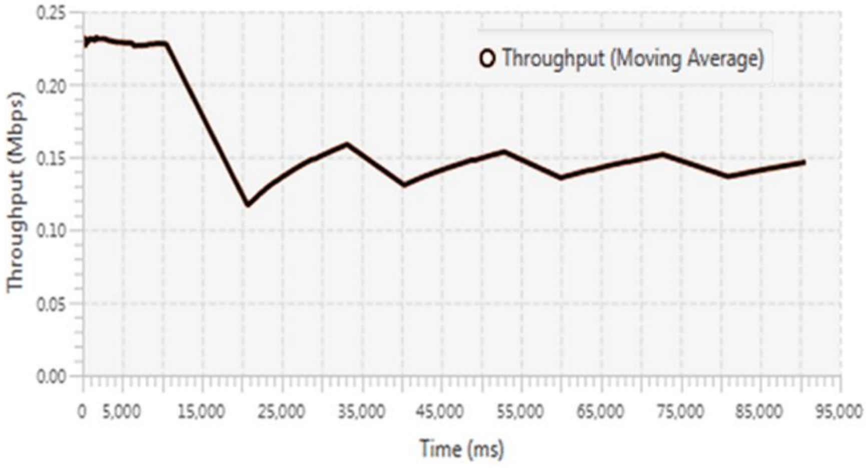

Figure 8. Scenario 2: 54 MHz – 216 MHz

Figure 7 shows Scenario 1. A moving average throughput of 0.23 Mbps is obtained at the initial phase of the transmission. This reduces then levels off up to about 10000 ms. It then reduces to 0.12 Mbps at 17500 ms. It increases again to about 0.15 Mbps at 31000 ms and decreases. It then continues erratically with attainment of below 0.15 Mbps throughput throughout the transmission duration.

Figure 8 shows Scenario 2. A moving average throughput of 0.23 Mbps is initially obtained and this starts reducing at about 10000 ms and resumes at about 20000 ms. A throughput of 0.15 Mbps is attained at 30000 ms. It then starts reducing again at 33000 ms. It continues erratically with an attained throughput that is about 0.15 Mbps throughout the transmission duration.

Figure 9 shows Scenario 3. A moving average throughput attainment of 0.23 Mbps at the initial phase of the transmission. This continues steady with negligible throughput fluctuation, and maintains 0.23bMbps throughout the transmission duration.

Overall, the higher frequency spectrum with more channel availability gives a steady throughput. This gives rise to optimal appreciable throughput of the CRSN in a SG. Because the throughput is necessary for network connectivity in the CRSNs radio resources such as a spectrum channel to be efficiently allocated to CRSN nodes. Whereas, the lower the frequency spectrum, which usually has less available channels, has lower throughput attainment with unsteady conditions. This latter case is not suitable for SG applications that are mission critical. The higher spectrum bands are associated with more channels compared with lower frequency bands which are usually associated with less available channels.

Hence, a CRSN for SG communications should be developed to accommodate higher spectrum bands with multiple available channels of over 800 MHz bands in order to leverage spectrum hole from both digital TV and some 4G/LTE frequency bands.

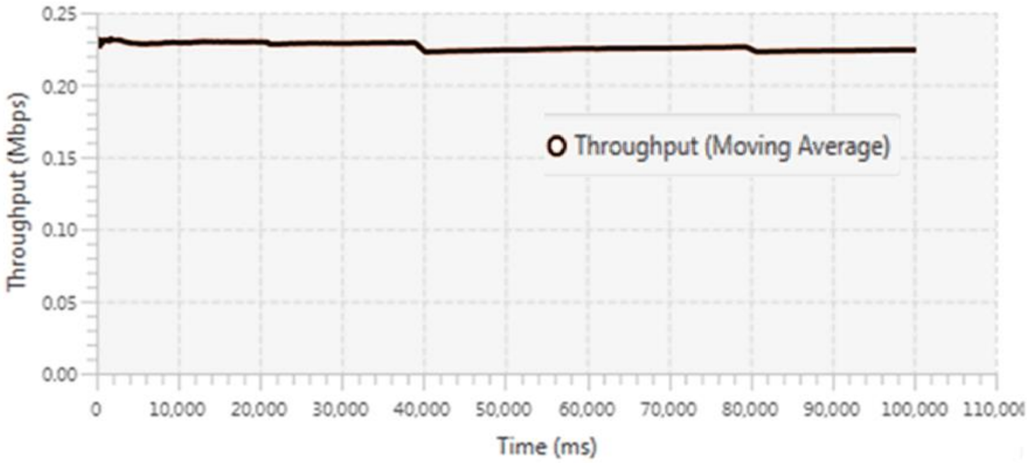

Figure 9. Scenario 3: 54 MHz – 802 MHz

5. Recommendations and Future Research Direction

A smart grid requires reliable and timely delivered sensed data to meet the expectation of various SG applications with satisfactory service delivery. The traditional or conventional SG uses probable WSN for monitoring and control in delivering the sensed data. WSN makes use of static resource allocation to statically allocate resources to the sensor node and communication devices. However, the CRSN paradigm makes use of dynamic resource allocation due to the presence of a dynamic spectrum access (DSA) capability. The CRSN paradigm works well in terms of dynamically allocating radio resources to sensor nodes and communication devices in a SG ecosystem. Hence, a CRSN makes use of dynamic resource allocation schemes to allocate resources optimally between multiple resource competitive sensor nodes.

It can be seen from the preceding section that the dynamic resource allocation schemes improve energy efficiency in the communication devices. For example, it helps to extend the battery power life of a sensor node. Unfortunately, the energy efficiency schemes in terms RRA are lacking in a CRSN based SG. Also, Table 5 shows that schemes for adaptive modulation and throughput maximization are lacking in a CRSN based SG. In addition, schemes that incorporate multiple resource optimization criteria, including a cross layer framework, as shown in Table 6, are lacking in the CRSN based SG domain.

It has been pointed out that distributed heterogeneous cluster architecture should leverage multiple improvement criteria. Thus, the authors believe that designing a holistic cross layer scheme that accommodates energy efficiency, throughput maximization and adaptive modulation, while leveraging multiple optimization criteria, such as interference avoidance, handoffs reduction, fairness, priority, and QoS support, etc., will go a long way in yielding optimal results in CRSN based SG monitoring and control.

Many SG applications such as distribution automation, demand response, SCADA, surveillance and multimedia applications, including security of automatic metering infrastructure (AMI), are mission critical. Hence, robust and reliable communication that can withstand harsh environmental SG conditions are required to meet the demand of these mission critical applications.

Based on this, research attention should be drawn to the direction of design and optimization of a cross layer framework for seamless exchange of signaling and control information across the protocol stack of the sensor nodes and communication devices for a CRSN based SG. It is pertinent to note that work is needed in the development of unified solution schemes that accommodate three or all of the resource optimization criteria for a CRSN based SG. Specifically, research should be directed towards energy efficient adaptive modulation, energy efficient throughput maximization, energy efficient spectrum access, and handoffs reduction. In fact, the energy efficiency issue is an open research direction in the CRSN based SG domain.

Hybrid energy harvesting that utilizes radio frequency alongside other mechanisms for harvesting energy perpetually for the power constraint sensor nodes remains an open research issue in the domain of SGs generally.

An energy efficient spectrum aware cross layer framework approach that interacts with the Physical, MAC, Routing, Transport, and Application layer protocols in CRSN based SG communication is an interesting research area.

Research should be directed towards the design of CRSNs for SG communications that will accommodate higher spectrum bands with multiple available channels from 54 MHz to 1000 MHz in order to support both digital TV and some 4G/LTE frequency bands.

6. Conclusions

In this paper, CRSN based SGs, as a new paradigm for a modern SG, has been introduced. These are different from the traditional power grid and also different from the conventional SG that uses static resource allocation techniques to allocate resources to sensor nodes and communication devices. RRA together with DSA capability to dynamically allocate radio resources to the sensor nodes and communication devices in a CRSN based SG environment has been explored.

The overview was put forward for a CRSN which introduces their unique characteristics, and functionalities. Radio resource optimization criterion, which is an important consideration for resource allocation in a CRSN based SG, has been highlighted. In addition, an improved RRA architecture called DHC architecture for a CRSN based SG [114] has been adopted in this work as a recommendation for CRSN based SG deployment. The various resource allocation schemes, i.e., RRA architecture in a CRSN based SG, have been presented in this paper. A guaranteed network connectivity channel allocation for throughput maximization (GNC-TM), including optimal spectrum band determination in RRA for improved throughput criteria in CRSNs for SGs, have been presented. The results show that the introduced model outperforms the existing protocol in terms of throughput and error probability. Recommendations have been made in order to improve communication device connectivity and seamless communication between multiple resource competitive sensor nodes in the CRSN based SG ecosystem.

A future research direction which includes design and optimization of a cross layer framework, including new protocol architecture for RRA in a CRSN based SG, has been highlighted. Finally, energy efficiency and hybrid energy harvesting schemes for perpetual power supply to the battery power constraints sensor node have also been pointed out as open research area in a CRSN based SG.

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