Radio Resource Allocation Improvements in Cognitive Radio Sensor Network for Smart Grid: Investigative Study and Solutions

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Abstract: Background: 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 conventional SG. Currently, an SG uses a static resource allocation technique to allocate resources to sensor nodes in the SG network. Static resource allocation is not efficient due to the heterogeneous nature of CRSN-based SGs. Hence, an appropriate mechanism such as dynamic Radio Resource Allocation (RRA) is required for efficient resource allocation in CRSNs for SGs.

Objective: The objective of this paper is to investigate and propose suitable dynamic RRA for efficient resource allocation in CRSNs-based SGs. This involves a proposal for an appropriate strategy that will address poor throughput and excessive errors in resource allocation.

Methods: In this paper, the dynamic RRA approach is used to allocate resources such as frequency, energy, channels and spectrum to the sensor nodes. This is because of the heterogeneity in a CRSN, which differs for SG applications. The dynamic RRA approach is based on optimization of resource allocation criteria such as energy efficiency, throughput maximization, QoS guarantee, etc. The methods include an introduced model called “guaranteed network connectivity channel allocation for throughput maximization” (GNC-TM). Also used is an optimal spectrum-band determination in RRA for improved throughput.

Results: The results show that the model outperforms the existing protocol of channel allocation in terms of throughput and error probability.

Conclusion: This study explores RRA schemes for CRSNs for SGs. The paper proposed a GNC-TM model, including demonstration of suitable spectrum band operation in CRSNs for SGs.

Keywords: Adaptive modulation, TVWS, CRSN, radio resource allocation, smart grid, Distributed Heterogeneous Clustered (DHC), dynamic radio, guaranteed network connectivity, probability of false alarm.

1. INTRODUCTION

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 bidirectional communication in SG. Wireless communication is a right communication technology option to drive SG due to the extensive coverage area required in SG. However, the wireless channels in 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 inefficiency 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 Cognitive Radio (CR) and Wireless Sensor Network (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.
Radio Resource Allocation Improvements

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]. For better understanding, Table 1 shows the acronym/descriptions of terms used in this paper. The realization of CRSN for the smart grid mainly requires efficient Radio Resource Allocation (RRA) strategies to manage the dynamic access of resources. 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 RRA scheme to effectively manage radio resources.

RRA involves strategies or schemes of allocating radio resources such as frequency bands, transceiver power, time slots, hand-off criteria, user fair allocation, modulation schemes, and antenna transmission to the channel state information. These are based on some optimization criteria. RRA can be static, in which resources are assigned statically, or dynamic, in which resources are assigned dynamically. Static RRA uses fixed spectrum-banding when allocating resources to the sensor nodes. The battery energy of a sensor node is easily exhausted through high energy consumption. For example, if the fixed spectrum-band is overwhelmed by frequent resource activities, there will be high transmission energy. This high transmission energy is due to many transmission attempts, thus leading to a poor network lifetime. This is not suitable for a SG network. On the other hand, dynamic RRA uses adaptable spectrum-banding to dynamically assign radio resources. In the event of high resource activity, the frequency-band is automatically adjusted thereby eliminating re-transmission attempts. This study focuses on dynamic RRA in CRSNs for SGs. CRSN has the potential advantages of re-configurability and Dynamic Spectrum Access (DSA) capabilities. To exploit these potential advantages of CRSN, a dynamic efficient RRA among the sensor nodes is essential in harsh smart grid propagation environments.

As mentioned, the focus of this paper is to investigate and provide solutions for RRA in a CRSN-based SG, thus leading to the following contributions in this paper:

- A comprehensive survey of RRA in a CRSN-based SG is presented.
- An SG Architectural Framework, including criteria for CRSNs deployment for SG applications, is presented.
- The overview, functionalities, and unique characteristics of a CRSN in a SG are discussed.
- A guaranteed network connectivity channel allocation for throughput maximization (GNC-TM) in CRSNs for SGs is presented.
- Optimal spectrum band determination in RRA for improved throughput criteria to establish suitable spectrum band operation in CRSNs for SGs is demonstrated.
- The protocol architecture for a CRSN in a SG is highlighted.

<table>
<thead>
<tr>
<th>Acronym/Terms</th>
<th>Descriptions</th>
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<tbody>
<tr>
<td>CPG</td>
<td>Central Power Generation</td>
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<tr>
<td>CR</td>
<td>Cognitive Radio</td>
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<td>CRN</td>
<td>Cognitive radio network</td>
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<td>CRSN</td>
<td>Cognitive radio sensor network</td>
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<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<td>CA</td>
<td>Collision Avoidance</td>
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<td>DA</td>
<td>Distribution automation</td>
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<td>DER</td>
<td>Distributed Energy Resources</td>
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<tr>
<td>DREG</td>
<td>Distributed Renewable Energy Generation</td>
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<td>DES</td>
<td>Discrete Event Simulation</td>
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<td>DSM</td>
<td>Demand Side Management</td>
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<td>EV</td>
<td>Electric Vehicle</td>
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<td>EMC</td>
<td>Electromagnetic Comparability</td>
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<td>EMI</td>
<td>Electromagnetic Interference</td>
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<td>GSM</td>
<td>Global System for Mobile Communication</td>
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<td>HAN</td>
<td>Home Area Network</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<td>IPO</td>
<td>Independent Power Operator</td>
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<td>ISM</td>
<td>Industrial scientific and medical</td>
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<td>LPWAN</td>
<td>Low Power Wide Area network</td>
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<td>MAC</td>
<td>Medium access control</td>
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<td>MDMS</td>
<td>Meter data management system</td>
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<td>NAN</td>
<td>Neighbourhood Area Network</td>
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<td>NETSIM</td>
<td>Network Simulator</td>
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<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>PHY</td>
<td>Physical Layer</td>
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<td>PLC</td>
<td>Power Line Communication</td>
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<td>PMU</td>
<td>Phasor management unit</td>
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<td>PU</td>
<td>Primary user</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RRA</td>
<td>Radio Resource Allocation</td>
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<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
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<td>SU</td>
<td>Secondary User</td>
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<tr>
<td>TV</td>
<td>Television</td>
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<td>TVWS</td>
<td>TV white space</td>
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<tr>
<td>CWS</td>
<td>Cellular white space</td>
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<tr>
<td>UDP</td>
<td>User datagram protocol</td>
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<tr>
<td>UHF</td>
<td>Ultra-high frequency</td>
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<td>VHF</td>
<td>Very high frequency</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecoms service</td>
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<td>WAN</td>
<td>Wide Area Network</td>
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<td>WIFI</td>
<td>Wireless Fidelity</td>
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<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
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<td>WLAN</td>
<td>Wireless local area network</td>
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<td>WSN</td>
<td>Wireless Sensor Network</td>
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Radio resources optimization criteria in a CRSN based SG are discussed in this paper.

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.

The remainder of this paper is structured as follows in the following sections: SG background, including description of the overview, functionalities, and unique characteristics of a CRSN in a SG are presented. Related works are discussed. 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 paper ends with conclusions.

2. SMART GRID AND CRSN BACKGROUND

2.1. SG Architectural Framework

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

![Smart grid architectural framework](image)

Fig. (1). Smart grid architectural framework.

2.1.1. Power System Layer

Power system layer consists of the Central Power Generation (CPG), Distributed Renewable Energy Generation (DREG), transmission, and distribution by utilities, with power supplied to the consumers.

2.1.2. Control Layer

This subsystem consists of control systems such as the Meter Data Management Systems (MDMSs), Supervisory Control and Data Acquisition (SCADA), monitoring applications and the MDMS server at the control/substation/data Centre. It enables the control and management functions in the SG.

2.1.3. 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.

2.1.4. Application Layer

This delivers numerous SG applications such as DER, Automatic Metering Infrastructure (AMI), Demand Side Management (DSM), etc., to customers as well as utilities.

2.1.5. Intelligent Layer

This consists of Intelligent Electronic Devices (IEDs) and sensors for monitoring and control in SCADA, MDMSs, and communications.

2.1.6. 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 SG architectural framework will deduce that the communication network layer is the key enabler for delivering 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 due to its cognitive capability than WSN. Another emerging area in M2M communication that is also advantageous for a SG and internet of things (IoT) implementation is the LPWA devices. However, LPWA is not the focus of this work.

Another essential component is the power systems layer. The Central Power Generation (CPG) alone is not sufficient to yield optimal returns in a SG. For a SG to be fully realized, it is expected to comprise an interconnected network of small-scale and self-contained microgrids (MGs) [4]. These MGs contain Renewable Energy Sources (RESs) which will play an important role at the power generation level. This includes the potential for environmental friendliness. However, due to unpredictable massive loads and RESs, there is a need for economical operation of the MGs. For instance, [4] proposed a Nondominated Sorting Genetic Algorithm II (NSGA-II) that jointly supports economical and environmentally friendly operation of smart MGs. The distributed MGs and huge loads produce large volumes of data which will require real-time analysis and high processing. This leads to the use of high cost dedicated communication network connections and big data processing in the SG. To address these
problems, a cloud computing-based SG was proposed [5, 6]. This will ultimately provide a low-cost, reliable and highly efficient SG.

An effective operation of a DSM that is based on accurate Machine Learning prior knowledge about the energy load patterns is required for efficient SG operation [7]. This machine learning-based DSM will help effectively control energy supply that will commensurately serve the increasing machine learning-based DSM will help effectively control load patterns is required for efficient SG operation [7]. This rate Machine Learning prior knowledge about the energy This will ultimately provide a low-cost, reliable and highly complex system which has higher computational complexity. 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.

2.2. 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:

2.2.1. Intermittent Channel Availability for a SU Network

Primary User (PU) activities can cause intermittent channel availability to a Secondary User (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 CRNs for adequate resource allocation.

2.2.2. 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 or miss 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.

2.2.3. 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 the further analysis was carried out in order to establish a suitable spectrum band with white space for CRNs in a SG.

2.2.4. Problem of 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. 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.

2.2.5. Problems of Communication Infrastructure in SG with Regards to the Requirements for SG Deployment

The communication equipment is susceptible to challenges associated with a SG environment. For example, power-frequency electromagnetic fields and Radiofrequency (RF) noise exists in the SG environment due to corona and partial discharges, solid-state and substation switching devices, and circuit breaker switching, including commutating processes [8]. These can result in Electromagnetic Interference (EMI) issues which are known to cause interference and failure of electronic devices and communication infrastructure [8]. 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 [9]. Impulse noise has been investigated in HV substations, including its influence on the performance of wireless channels and modulations [10]. EMI impacts SG wireless communication equipment and this was studied in [11]. 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.

Consequently, RRA in CRNs for other applications is different from the RRA in CRNs for SG applications. That makes this survey quite different from other related surveys on CRNs. Hence, RRA in CRNs 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 compatibility (EMC) for the CRSN to operate effectively in a varying EMI SG environment.
2.3. 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, and 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.

Hence:

• 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 some of the protocol layers will interact. For example, the Physical, MAC, and Application layer protocols will 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 [12]. 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 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 [13]. 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 [14]. 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 [15] 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 is scarce. None of the protocol architecture for a CRSN in a SG supports a cross-layer framework that cuts across the PHY layer, MAC layer, and application layer protocols together. Hence, a reliable cross-layer framework approach that jointly interacts with the Physical, MAC, 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.

2.4. Overview, Functionalities, and Unique Characteristics of a CRSN in an SG

2.4.1. Overview of CRSN

In a CRSN, there are two types of users: primary and secondary. Primary Users (PUs) are the 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 they 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 pre-determined 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 in 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.

The SU uses the optimal available channel only if there is no PU operating in the licensed bands [16]. The problem of the inability of the SUs to access channels in the overlay method has been addressed in previous work [17]. In this 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.

### 2.4.2. 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 [18]. 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 [19].

#### 2.4.2.1. Spectrum Sensing

Spectrum sensing is the process of discovering the available spectrum bands and detection of the spectrum holes in the PUs [20]. 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 [16, 21]. 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 [19]. 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 to switch 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.

#### 2.4.2.4. 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 [14]. 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 [19]. 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.

2.4.3. Unique Characteristics of CRSN

CRSNs have numerous unique characteristics that differentiate them from 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. The CRN provides the ability to adapt operating parameters to wireless devices such as WSN, Wi-Fi, etc., in order to overcome spectrum scarcity problems [25]. 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 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.
- Re-configurability and distributed cooperation.
- 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. Hence, while designing resource allocation schemes for CRSNs in SG, their unique features should be considered. The harsh environmental conditions of the SG as well as the primary user activity, should also be considered.

Table 2 shows the special conditions to be considered in CRSN-based SG applications when compared with CRSNs for other applications.

3. 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 [26-33]. However, these works are not in the context of a SG. However, there are some advantages in these works, which are (i) Prediction and scheduling resources in a centralized CRN for energy efficient communication; (ii) Improved RRA techniques in a cooperative CRN; (iii) Elongation of the lifetime of the energy-constrained cooperative spectrum sensing in a sensor network; and (iv) Improved sensing time and power control for an energy efficient CRSN. Only a very few articles have surveyed the RRA from a CRSN perspective. Their emphasis is not on the

<table>
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<tr>
<th>Special Conditions to be Considered in for CRSNs Deployment</th>
<th>CRSNs for SG Applications</th>
<th>CRSNs for Other Applications</th>
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<tbody>
<tr>
<td>Key immunity compliance requirement of communication infrastructure in SGs.</td>
<td>Key immunity compliance is a mandatory general requirement for communication networks and systems for SG utility automation [11]</td>
<td>Key immunity compliance requirement is optional. May be required depending on the applications.</td>
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<tr>
<td>CRSN Protocols for SGs applications</td>
<td>Currently generic protocols for sensor network are used for CRSN in SGs. New protocols for optimal communication in CRSN for SG have been proposed, which include CRB-MAC, Distributed control algorithm (DCA), and RPL (routing protocol for low power and lossy networks) [12 - 15].</td>
<td>CRSNs for other applications are based on generic protocols for sensor network. New SG protocols are not mandatory.</td>
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<tr>
<td>Spectrum sensing in CRSNs for SG</td>
<td>An optimized DSA is required for spectrum sensing in CRSNs for SG [19]. Improved spectrum mobility scheme is required to prevent buffer overflows and minimize communication contention delay in CRSNs for SG [19].</td>
<td>Generic DSA is used for spectrum sensing in CRSNs for other applications. Generic scheme is used for spectrum mobility in CRSNs for other applications.</td>
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<tr>
<td>Spectrum mobility in CRSNs for SG</td>
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Table 2. Criteria for CRSNs deployment for SG applications compared with other application.
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intersection of a CRSN in a SG for the RRA. Refs. [34-36] survey works on RRA in WSN and CRN. The authors in [34] study routing protocols for WSN. In [35] a survey on CRN was presented while [36] present a survey on cross-layer solutions for WSNs. The survey in [37] addresses RRA in a CRSN. In their 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 that are not mainly concerned with the survey of resource allocation but highlight some aspects of resource allocation strategies are found in [38-46]. A novel weighted cluster-based co-operative spectrum sensing scheme was put forward in [38]. This could reduce the probability of a false alarm in a CRN spectrum resource allocation. Reference [39] shows that resources in cognitive radio networks (CRNs) should dynamically be allocated according to the sensed radio environment.

Le and Hossain, in [40] presented the optimal allocation of the radio resources based on three schemes, minimizing the total outage probability, maximizing the total throughput, and maximizing the total diversity gain in a device to device communication (D2D). The authors in [41] demonstrated efficient resource allocation in Orthogonal Frequency Division Multiple Access (OFDMA)-based Hybrid Cooperative Cognitive Radio Network (HCCRN), their work shows improved QoS by increasing the number of subcarrier allocation in a sub-channel.

The work reported [42] addressed the energy efficiency aspect of spectrum sharing including power allocation in heterogeneous cognitive radio networks with femtocells.

A correlation-based admission control strategy was put forward in [43]. This allowed for efficient resource utilization in CRN. [44] proposed a distributed lightweight protocol for reduction of energy and communication overhead in CRSN. The work in [45] presents throughput maximization for machine to machine communication using an electromagnetic energy harvesting based CRSN. [46] discussed issues regarding dynamic spectrum management in a CRSN.

The authors in [47-49] demonstrated resource allocation in WSN as well as in ZigBee (IEEE 802.15. 4) for SG. In [47] the researchers carried out investigative studies on WSN for SG. The performance of ZigBee based wireless sensor network deployed in different Non-Line of Sight (NLOS) SG environments was investigated in [48]. This involved a systematic analysis of the average end-to-end delay with respect to the packet interval, throughput, energy consumption, packet reception rate and network lifetime. The work in [49] analyses and compares the network throughput, average end to end delay and successful data delivery ratio in beacon and beaconless mode of operations in different harsh environments of SGs at different data rates.

Resource allocation was generally discussed in the above works, but the survey of resource allocation strategies in the context of CRSN for SG was not their major target.

References [50-54] carried out experimental work on RRA for CRN. The experimental results validate improvements in some optimization criteria for resource allocation in a CRN. However, these studies were not carried out from the perspective of a CRSN based SG.

Experimental work on a CRN was carried out in [55]. This addressed the problem of 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 did not involve RRA in a CRSN based SG nor evaluation of frequency spectrum for throughput improvement in a CRSN based SG.

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. The authors in [56] carried out experimental work for RRA based on a CRN for IoT sensor network. Though their work did not address a CRSN based SG. Authors in [57] proposed channel selection strategies in a CRN with Energy Harvesting for Internet of Everything. Authors in [58] 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. Authors in [59] 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 [60] in which proposed energy efficient opportunistic spectrum allocation in a CRSN. However, this work did not involve RRA in a CRSN based SG.

The works in [61-68] demonstrate resource optimization with respect to adaptive-based energy efficiency and congestion control strategies in Ad-hoc networks. Though these schemes did not consider the CR paradigm, the advantages are high. This is because the adaptive energy efficient resource optimization will help to increase the network lifetime of sensor networks. Also, the adaptive congestion control optimization will help to improve throughput in Ad-hoc and sensor networks.

An efficient fuzzy based energy efficient load distribution scheme was studied in [61]. This was located in a congested Mobile Ad-hoc Networks (MANETs). This scheme offers lesser energy consumption, appreciable throughput, and elongated network lifetime in MANETs. In [62] an effective fuzzy-based energy efficient load distribution scheme was proposed. This scheme properly handles energy consumption considering congestion as a parameter in ad-hoc networks. An effective cross-layer adaptive transmission strategy to adequately control the congestion in mobile wireless ad-hoc networks was proposed in [63]. Reference [64] investigated the application of a Cross-Layer-based Adaptive Data Scheduling Policy (CL-ADSP) to Multi-Path Transmission Control Protocol (MPTCP) in a mobile ad-hoc network. This scheme effectively handles dissimilar path characteristics and unreasonable congestion window growth adaptations. The authors in [65] proposed a novel adaptive congestion-aware Fibonacci sequence-based data scheduling policy.
(A-CAFDSP) in MANETs. This scheme takes care of dis-similar characteristics of each individual path and schedules the data accordingly to achieve congestion free and a better throughput network.

Studies of CRSNs for SGs that highlight some aspects of resource allocation can be found in [16], and [69-74]. The investigators discussed spectrum sensing but they did not highlight resource allocation extensively, such as including frequency band, QoS, fairness, priority, and power allocation schemes, etc. Resource allocation schemes were not the main focus. They did not consider the evaluation of the frequency spectrum for throughput improvement in a CRSN based SG. However, the major advantages of these studies include the potential for new spectrum assignment, routing and MAC protocols, as well as an energy-efficiency driven spectrum discovery scheme for a CRSN in an SG.

The study in [69] presents survey on CR-based spectrum sensing with their major classifications. This includes a survey on CR-based routing and MAC protocols, including a description on interference mitigation schemes. In [70] a new spectrum resource sharing paradigm for CRSNs in SG was developed. The solution involves distributed and balanced spectrum sharing among SG sensor nodes, including CRSN deployment scenarios in SG areas. A SG network was proposed in [71] which utilised a CRSN for implementation in remote areas of Pakistan. This deployment method can be used in developing countries to realise cost-effective SGs for remote areas. The results show significant energy saving and reliability in supporting data transmissions in the SG.

From the above discussion, some of the works focus on RRA only in CRNs or CRSNs, or other aspects of wireless networks without addressing the SG. None has surveyed the integration of resource allocation in a CRSN into a SG. The survey that involves 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.

<table>
<thead>
<tr>
<th>References in Cognitive Radio Related Survey</th>
<th>CRN</th>
<th>CRSN</th>
<th>CRN-based SG</th>
<th>CRSN-based SG</th>
<th>Involving Resource Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tragos et al. [27]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Naeem et al. [28]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Ahmad et al. [37]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Md. Anamul et al. [38]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Xie et al. [39]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Akan et al. [46]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Aroua et al. [70]</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Yu et al. [50]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Khan AA et al. [69]</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hosseini et al. [43]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Zubair et al. [44]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Khan ZA et al. [71]</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

4. RADIO RESOURCE ALLOCATION IN CRSN BASED SG

4.1. 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:

### 4.1.1. 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 including SG have been widely studied in [73-92]. 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.

### 4.1.2. 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 [13, 14, 81], and [93-99]. Reference [13] 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 [100].

### 4.1.3. 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 [15, 82, 95, 96, 101-107].

### 4.1.4. 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. Interference avoidance and minimization criterion improve 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 [15, 92, 106].

### 4.1.5. Fairness Scheduling Criterion

Fairness among SU's in opportunistic spectrum access and scheduling and fairness in transmission power allocation to SU's 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 criterion in a SG is reported in [73]. They considered QoS guaranteed for heterogeneous traffic in SG applications such that each traffic type has associated fairness. Resource allocation strategies that utilize fairness criteria are also found in [15, 78, 108-113].

### 4.1.6. 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 [114]. A typical traffic type is the control commands having small packet size [114]. 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 [13, 112].

### 4.1.7. 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 overhead as well as supplemental energy consumption that results in the event of adapting or switching to another modulation type [55] 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.

### 4.1.8. 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 [73, 75, 78, 83]. 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. [51] investigated a resource allocation scheme involving reduced spectrum handoff for CRSN applications. Ref. [78] presented a dynamic spectrum access scheme that accomplishes the reduction in the number of spectrum handoff. The resource allocation algorithm in [51] 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 contexts 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, re-
source 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.

4.2. 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.

4.2.1. 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 Fig. (2). 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 devices 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 [15, 73, 75-80, 82, 86, 116, 119]. There are several advantages to a centralized scheme. The main advantages include simplified energy efficiency management and conflict avoidance in the transmission and reception link. Because the sink node coordinates every sensor node. However, the main disadvantages of this scheme include (i) The network cannot support large density sensor nodes. (ii) There is high signaling overhead leading to high energy consumption.

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

<table>
<thead>
<tr>
<th>Resource Optimization Criterion</th>
<th>CRSN</th>
<th>CRN Based SG</th>
<th>CRSN Based SG</th>
<th>References for Various Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>[24, 73, 75, 76, 78, 82, 86, 116, 119]</td>
</tr>
<tr>
<td>QoS guarantee</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>[74, 79, 80, 82, 92-95, 105]</td>
</tr>
<tr>
<td>Throughput</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>[78, 81, 84, 85, 86, 92, 93, 105]</td>
</tr>
<tr>
<td>Interference mitigation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>[23, 24, 75, 78, 81, 87, 93, 102, 121, 122]</td>
</tr>
<tr>
<td>Fairness</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>[75, 78, 93]</td>
</tr>
<tr>
<td>Priority scheduling</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>[15, 103, 122]</td>
</tr>
<tr>
<td>Adaptive modulation</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>[79, 126]</td>
</tr>
<tr>
<td>Spectrum handoff</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>[75, 80, 83, 120]</td>
</tr>
</tbody>
</table>

![Centralized resource allocation architecture for a CRSN based SG.](image1)

![Cluster resource allocation architecture for a CRSN based SG.](image2)
The notable RRA schemes that utilize centralized architecture, as drawn from the literature review, 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 [77]. 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 sensor node.

- **A Home Area Network Gateway (HGW) assisted cross-layer cognitive spectrum sharing mechanism was proposed in [73].** 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 involved was presented in [78]. 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 [73].** 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 [79]. Adaptive modulation helps to improve 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:** [85] 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 [13]. 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.

### 4.2.2. 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 [87, 94, 96, 97, 104, 106], and [120-122]. 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 to 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.

From the literature, there are notable RRA schemes that utilized the cluster architecture. These 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. [106] 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 [87]. 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 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 [90], 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 [123]. 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 [124] 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 [110], 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 [121]. 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 $\lambda_p$, and their service time is exponentially distributed with rate $\mu_p$. Likewise, CRSN secondary users follow a Poisson distribution with rate $\lambda_s$ and exponential service rate $\mu_s$. 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 is essential in energy and spectrum efficiency. In [16], 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.

4.2.3. 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 render distributed resource allocation to a weak optimal solution. Distributed architecture resource allocation in CRSN related applications has been studied in [74, 92, 97, 98, 100, 105, 120, 125]. An example of a distributed resource allocation architecture for a CRSN based SG is shown in Fig. (4).
Notable RRA schemes that utilize a distributed architecture are:

- Spectrum discovery schemes were presented in [74]. The schemes comprise of non-cooperative spectrum discovery and cooperative spectrum discovery. The objective of these schemes is to reduce the total energy 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 [86]. 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 [99], 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 [100]. 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 the 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 [106]. 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 [125].

Table 5 summarizes the schemes with multiple optimization criteria considerations 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.

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

<table>
<thead>
<tr>
<th>References for Various Resource Allocation Schemes</th>
<th>CRSN</th>
<th>CRN Based SG</th>
<th>CRSN Based SG</th>
<th>Scheme with Multiple Optimization Criteria</th>
<th>Cross Layer Framework Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu et al. [73]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Byun et al. [75]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Zhaoyang et al. [77]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sun et al. [81]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Gao et al. [79]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Ayala et al. [80]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Nacem et al. [86]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Shah et al. [14]</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Khalil et al. [100]</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Lin et al. [108]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Izumi et al. [116]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Zhang et al. [78]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Han et al. [87]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hareesh et al. [99]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Liang et al. [94]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Alagöz et al. [97]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Seneviratne et al. [101]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Phuong et al. [108]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Hu et al. [116]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Luo et al. [120]</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Aslam et al. [90]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Ergul et al. [72]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Lee et al. [104]</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

**Fig. (5).** Distributed Heterogeneous Clustered (DHC) resource allocation architecture. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

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 Fig. (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 [42, 120, 127]. Xie proposed the energy efficiency aspect of spectrum sharing including power allocation in heterogeneous CRNs using a Stackelberg game with femtocells [42]. 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. [127] proposed a probability of detection mechanism using a moment generating function and a Maximum Ratio Combiner (MRC) for performance improvement of RRA in a multichannel CRSN based SG.

5. SG 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 SGs. 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.

5.1. Guaranteed Network Connectivity Channel Allocation for Throughput Maximization in CRSN-based SG

Equilateral triangulation pattern graph is employed in the Guaranteed network connectivity for throughput maximization (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 are the communication links or line segments between the vertices. A SU base-station or Cluster Head (CH) coordinates the communication links or line segments between the vertices which indicate $a_1, b_1, c_1, a_2, b_2, c_2, \ldots, a_n, b_n, c_n$, 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 [126]:

$$\bar{\gamma} = \frac{E_s}{N_0}$$

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 $P_e$ of the MQAM signal under Rayleigh fading channel is given by [127]:

$$P_e = \frac{a}{n} \left[ \frac{1}{b^2 + 2} - \frac{a}{b^2 + 1} \right] + \sum_{i=1}^{n} \frac{b_i^2 + S_i}{b_i^2 + S_i}$$

where $a = 1 - \frac{1}{M}; b = \frac{3}{M - 1}; S_i = 2 \sin \left( \frac{i \pi}{4n} \right)$; and $M$ is the constellation order ($M = 4$); and $n$ is the number of iterations. The relationship of SNR and throughput gives the maximized throughput so that:

![Fig. (6). Algorithm 1.](image-url)
\[
\text{Thoughput} = CB \times \log_2(1 + \text{SNR})
\]  
(3)

where \(CB\) is the channel bandwidth

### 5.1.1. Simulation Experimental Setup for GNC-TM Channel Allocation

In this section, the GNC-TM algorithm is 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 are compared with the existing protocol. The performance efficiency of the GNC-TM model is evaluated based on the error probability and throughput matrices.

#### Table 6. GNC-TM model simulation parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation runs (n)</td>
<td>10,000</td>
</tr>
<tr>
<td>Multi-path fading</td>
<td>Rayleigh fading</td>
</tr>
<tr>
<td>SNR</td>
<td>0:3:24 dB</td>
</tr>
<tr>
<td>Modulation size</td>
<td>4 QAM</td>
</tr>
<tr>
<td>Channel Bandwidth (CB)</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Shadow Fading</td>
<td>Log-Normal Shadowing</td>
</tr>
</tbody>
</table>

### 5.1.2. Simulation Results and Analysis of GNC-TM Channel Allocation in CRSN for SG

Fig. (7) shows the throughput maximization analysis of the channel allocation based on the 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. Fig. (7) shows the GNC-TM minimal error probability starting with less than \(10^{-2}\) and ending with \(10^{-5}\). Existing protocol error probability starts at about \(10^{-1}\) and ends at \(10^{-4}\). 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 compared to existing protocols for channel allocation in CRSN-based SGs.

### 5.2. Optimal Spectrum Band Determination in RRA for Throughput Improvement Criteria in CRSN Based SG

#### 5.2.1. Concepts and Simulation Experimental Setup for Optimal Spectrum Band Determination

PU activities can impact 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 as well as high bandwidth is adequate for the enhancement of the throughput of the SUs [128].

Hence, when the SU is operating at a higher frequency band UHF: 470-868 MHz or higher, it gives rise to more channel creations during certain PU activities. This improves the throughput performance of the SU. However, when the SU is operating at a lower frequency band (VHF: 54-216 MHz) under the same conditions during PU activities, it will have a negative impact on the throughput performance of the SU. This is due to the limited number of spectrum holes and fewer channels when operating on a lower frequency band.

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 [129, 130]. Table 7 shows

#### Table 7. CRSN configuration parameters.

<table>
<thead>
<tr>
<th>CRSN Base Station Parameters</th>
<th>CRSN Module Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Name Base Station</td>
<td>Device Name CRSN Module</td>
</tr>
<tr>
<td>Min/Max Frequency</td>
<td>UDP</td>
</tr>
<tr>
<td>Coding rate</td>
<td>(1/2)</td>
</tr>
<tr>
<td>Distance (Range)</td>
<td>1 km</td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>4 QAM</td>
</tr>
<tr>
<td>Pathloss</td>
<td>30 dB</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>5 mW</td>
</tr>
<tr>
<td>Frequency (varies with each scenario)</td>
<td>54-80 MHz/54-216 MHz/54-802 MHz</td>
</tr>
</tbody>
</table>

---

Fig. (7). Throughput evaluation of channel allocation in CRSN for SG.
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 8. SG Application parameter.

<table>
<thead>
<tr>
<th>Device Name</th>
<th>SG Application Server</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application Method</td>
<td>Broadcast</td>
</tr>
<tr>
<td>Application Type</td>
<td>Custom</td>
</tr>
<tr>
<td>Application Name</td>
<td>DRM</td>
</tr>
<tr>
<td>Source ID</td>
<td>SG Application Server</td>
</tr>
<tr>
<td>Destination ID</td>
<td>CRSN Modules</td>
</tr>
<tr>
<td>Start Time (s)</td>
<td>0 s</td>
</tr>
<tr>
<td>End time (s)</td>
<td>100 s</td>
</tr>
<tr>
<td>Packet size (byte)</td>
<td>1460</td>
</tr>
</tbody>
</table>

5.2.2. Simulation Results and Analysis of Throughput Based on Spectrum-band Determination in CRSNs for SG

The results of the CRSN link moving average throughput were obtained and are shown in Figs. (8-10). Fig. (8) 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 the attainment of below 0.15 Mbps throughput throughout the transmission duration. Fig. (9) 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.

Fig. (10) shows Scenario 3. Moving average throughput attainment of 0.23 Mbps at the initial phase of the transmission. This continues steady with negligible throughput fluctuation and maintains 0.23 Mbps throughout the transmission duration. Overall, the higher frequency spectrum with more channel availability gives a steady throughput. This gives rise to appreciable optimal throughput of the CRSN in a SG. Whereas the lower 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, 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.

![Fig. (8). Scenario 1: 54 MHz – 88 MHz.](image)

![Fig. (9). Scenario 2: 54 MHz – 216 MHz.](image)
6. RECOMMENDATIONS AND FUTURE RESEARCH DIRECTION

A SG 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 allocate resources to the sensor node and communication devices statically. However, the CRSN paradigm uses 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 uses 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 lack 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 is 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 some 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, 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.

CONCLUSION

In this paper, CRSN based SGs, as a new paradigm for a modern SG, has been introduced. 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 [126] has been adopted in this work as a
recommendation for CRSN-based SG deployment. The RRA architecture in a CRSN-based SG, has been presented in this paper. A guaranteed network connectivity channel allocation for throughput maximization (GNC-TM) algorithm is demonstrated. Also, an optimal spectrum band determination in RRA for improved throughput criteria in CRSNs for SGs, has been conducted. The results show that the new model outperforms the existing protocol in terms of throughput and error probability.

CONSENT FOR PUBLICATION

Not applicable.

STANDARD OF REPORTING

By inspection of the PRISMA Checklist as published it is found that the review work in this paper follows the checklist requirements in the standard of reporting. The authors are independent of any work reviewed in the paper. The sources were obtained using several international databases. The sources were critically reviewed, comparisons made and conclusions drawn. Some of the work was tested in the paper for efficacy and clarification.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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