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Energy-efficient distributed heterogeneous clustered spectrum-aware cognitive radio sensor network for guaranteed quality of service in smart grid

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Abstract

The development of a modern electric power grid has triggered the need for large-scale monitoring and communication in smart grids for efficient grid automation. This has led to the development of smart grids, which utilize cognitive radio sensor networks, which are combinations of cognitive radios and wireless sensor networks. Cognitive radio sensor networks can overcome spectrum limitations and interference challenges. The implementation of dense cognitive radio sensor networks, based on the specific topology of smart grids, is one of the critical issues for guaranteed quality of service through a communication network. In this article, various topologies of ZigBee cognitive radio sensor networks are investigated. Suitable topologies with energy-efficient spectrum-aware algorithms of ZigBee cognitive radio sensor networks in smart grids are proposed. The performance of the proposed ZigBee cognitive radio sensor network model with its control algorithms is analyzed and compared with existing ZigBee sensor network topologies within the smart grid environment. The quality of service metrics used for evaluating the performance are the end-to-end delay, bit error rate, and energy consumption. The simulation results confirm that the proposed topology model is preferable for sensor network deployment in smart grids based on reduced bit error rate, end-to-end delay (latency), and energy consumption. Smart grid applications require prompt, reliable, and efficient communication with low latency. Hence, the proposed topology model supports heterogeneous cognitive radio sensor networks and guarantees network connectivity with spectrum-awareness. Hence, it is suitable for efficient grid automation in cognitive radio sensor network–based smart grids. The traditional model lacks these capability features.

Keywords

Bit error rate, distributed heterogeneous cluster, equilateral triangulation, network connectivity degree, quality of service, smart grid, superframe structure order, variator, ZigBee cognitive radio sensor network

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Introduction

Background

Cognitive radio sensor networks (CRSNs) have recently been proposed for smart grid (SG) applications. This will help to improve the monitoring, control, and overall communication network in an SG

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Table 1. Comparisons of ZigBee WSNs and ZigBee CRSNs.

Features	ZigBee WSNs	ZigBee CRSNs
Channel access	Fixed channel access	Multiple and dynamic channel access
Organizing and self-healing	Moderate self-healing	Very high self-healing
Interference avoidance	Low	High
Network topologies	Star, Cluster-tree, and Mesh	Star, peer-to-peer/mesh, cluster, heterogeneous and hierarchical, mobile ad hoc, and DHC
Communication protocol stack	Physical, data link, network, and application layer	Physical, data link, network, transport, and application layer

DHC: distributed heterogeneous cluster.

ecosystem. This leads to reliable and efficient electric power services.[1,2] SG provides a bidirectional data exchange between utility and consumers. SG can greatly improve the utilization of some resources such as metre data management and available power, and avoid some failures caused by power resource scheduling.[3] The performance requirement such as delay for different types of data in the SG diverges greatly. This can pose a severe challenge in wireless communication; therefore, the integration of an improved quality of service (QoS) scheme for SG is very important.[4] For example, Fang et al.[5] proposed a QoS model that provides different QoS for different priority data in the communication system of wireless sensor network (WSN). However, real-time traffic applications such as SG applications can be effectively guaranteed in a CRSN with minimal packet transmission delay.[2,6] This is because the interference challenge in the unlicensed wireless communication (Industrial, Scientific and Medical (ISM)) band is mitigated in the CRSN wireless environment. CRSNs are networks of cognitive radios (CRs) that are equipped with sensor nodes. They have cognitive capability and reconfigurability and can adjust their transceiver parameters with respect to interactions with the environmental circumstance in which they operate.[2] CRs can help to mitigate excessive collisions in the network.[7]

Generally, CRSN topologies involve the deployment of a few to several hundred CR sensors within areas where monitoring activities are required. For example, deployment for monitoring activities can be carried out in specified areas of power generation, transmission, distribution, and consumer end points. The deployment can be carried out to cut across SG communication network hierarchical layers, as follows:

- Premises area networks comprising of HANs (Home Area Networks), BANs (Building Area Networks), CANs (Commercial Area Networks), and IANs (Industrial Area Networks);
- Neighborhood area networks (NANs);
- Field area networks (FANs);
- Wide area networks.

Each CR sensor node can connect to one or more CR sensor nodes in order to transmit data.[8] Obviously, CR sensor node deployment for full sensing coverage plays a vital role in allowing reliable transmission through an SG communication network. Basically sensor nodes including CR sensor nodes have energy and resource constraint issues.[9,10] The limitation of the energy or the battery life can adversely affect the overall sensor network lifetime. Good design topology and modeling will address the energy consumption of a CRSN as well as providing minimal end-to-end delay and appreciable throughput of the CR sensor node. In addition, efficient MAC protocols that will enable the coexistence of CRSNs with existing wireless infrastructure are essential.[11]

Mobile edge computing (MEC) can be used in a SG CRSN paradigm to address the issue of resource constraint sensor nodes – this is an emerging approach. For instance, a joint scheme of matrix completion technology and cache placement for dealing with the resource constraint edge nodes problem was proposed by Tan et al.[12] While conventional ZigBee WSNs make use of fixed channel access, CRSNs make use of multiple channel access from the available spectrum opportunistically through dynamic spectrum access (DSA). The fixed channel for conventional ZigBees can easily be choked during access allocation and as a result cause excess energy consumption, overhead and interference. Other features that illustrate the differences between ZigBee WSN and ZigBee CRSNs are given in Table 1. From Table 1, the topological differences between ZigBee WSNs and ZigBee CRSNs can be seen. The CRSN topologies are highlighted in the section on the overview of CRSN technologies.

The contribution of this article can be summarized as follows:

- Investigation of the potential differences, with particular emphasis on the network topologies of ZigBee WSNs and ZigBee CRSNs for SG applications.
- An energy-efficient CRSN model suitable for SGs, industrial networks, and Internet of Things (IoT) applications is developed.

- An energy-efficient distributed heterogeneous clustered spectrum-aware (EDHC-SA) network connectivity formation is presented together with its coordination for CRSN deployment in SGs.
- An EDHC-SA multichannel sensing coverage model based on the cross-layer algorithm is proposed.

Compliance requirements for communication infrastructure and CRSN integration in SG

CRSNs for other applications are different from the CRSNs for SG applications due to the following compliance requirements:

- CRSN deployment in SGs should be supported by key immunity-compliance requirements set by the International Electrotechnical Commission (IEC).[13] CRSNs for other applications do not have these key SG immunity compliance requirements.
- SG CRSNs must be able to overcome the electromagnetic interference (EMI) present in SGs. It has been established that EMI and environmental changes negatively impact SG wireless communication infrastructure.[13,14]
- Appropriate electromagnetic comparability (EMC) must be considered for implementation of CRSNs in SGs. 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.[15]

Existing work on CRSNs for other applications suffers from the impact of SG EMI. This work reported here considers the key immunity-compliance requirements for CRSNs when deployed in SGs.

Overview of CRSN technologies

In a CRSN, there are two types of users: primary and secondary. Primary users (PUs) are the licensed (authorized) users, which have the license to operate in an allotted spectrum band in order to access the primary base station (BS). Secondary users (SUs) or the CR users are unlicensed users. CRs use the existing spectrum through opportunistic access without causing harmful interference to the primary or licensed users. CRs look for the available portion of the unused spectrum (called spectrum hole or white space (WS)). The optimal available channel (AC) is then used by the secondary or CR sensor nodes if there are no PUs operating in the licensed bands.[8] The WS geolocation database handles the control of the usage of the spectrum holes by the SUs in order to guarantee usage by the PUs when the PUs need the channels. Hence, a CRSN possesses unique characteristics.

Unique characteristics of CRSN.

A CRSN has numerous unique characteristics that differentiate it from the conventional ZigBee WSN. Since it incorporates the cognitive capabilities of CR into WSN, it can differentiate itself from CRN and WSN. Hence, it has a unique feature wherein it possesses the dual characteristics of CRN and WSN. Other unique characteristics of CRSN include the following:

- Capabilities for sensing the current radio frequency (RF) spectrum environment;
- Policy with configuration repository—policies specify how the radio is to be operated, while the repository is usually formed from the sources used to constrain the operating process of the radio in order to remain within regulatory or physical limits;
- DSA capabilities with multiple channels availability;
- Spectrum handoff capabilities;
- Adaptive algorithmic mechanism—during the radio process, the CR is sensing its environment, and following the constraints of the policy and configuration by exchanging with sensor nodes to best employ the radio spectrum and meet user demands;
- Low traffic flow;
- Reconfigurability and distributed cooperation capabilities;
- Limited memory and power constraints.

Some of the unique characteristics stated above are based on the cognitive cycle functionalities which enable the SUs to have dynamic and opportunistic access to the unused channels. These functionalities are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. These four main DSA management functionalities of the CR are required to determine the accurate communication parameters of SG communication and adjust to the dynamic radio environments. Details of these DSA management functionalities are found in Akyildiz et al.[16]

Due to the presence of the unique CRSN features, optimization of the protocol stacks to achieve improved QoS performance that is used for conventional ZigBee WSN cannot be directly applied to CRSNs. Also, the existing protocols of the conventional WSN cannot be applied to a CRSN because of the dynamic availability of multiple channels in the CRSN, and to dynamic spectrum access in the presence of PU activity. Hence, while designing resource allocation schemes for CRSNs, their unique features should

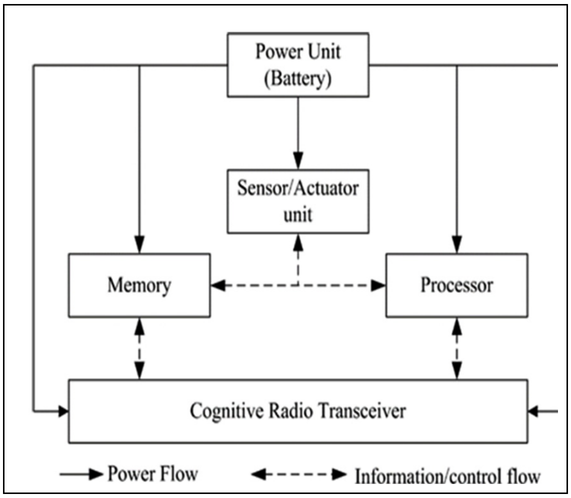

Figure 1. CRSN node structure.

be considered together with the PU activity consideration. Consequently, the work reported here considers these unique characteristics when designing the algorithms for QoS enhancement.

Structure of CRSN node hardware. A typical block diagram structure of a CRSN node is shown in Figure 1. It is composed of a sensor or the sensing unit which is used for sensing data and target signals. The processor processes and commands the activities of various units. The memory is used for storing data/information. The transceiver contains the cognitive engine and the RF component which enables the sensor node to dynamically adjust their communication network parameters and to transmit sensed data respectively. The battery or power unit supplies the necessary power to the rest of the units.

The rest of this article is organized as follows: In section "CRSN topologies and communication protocols," CRSN topologies and communication protocols are presented. Related works are highlighted in section "Related work." Section "Distributed heterogeneous clustered topology of CRSNs in SG" presents a distributed heterogeneous cluster (DHC) for energy-efficient CRSNs, including a multichannel sensing coverage model in an SG. Section "Simulation, analysis, and results" presents simulation, analysis, and results of the EDHC-SA models. Finally, Section "Conclusion and future work" concludes the article.

CRSN topologies and communication protocols

CRSN topologies

A CRSN has different network topologies which are based on the application requirement. Hence each topology is suitable for a particular application. The following network topologies have been identified. Table 2 gives some of the characteristics of the different Zigbee CRSN topologies.

Star topology. This is the simplest topology suitable for very small-scale sensor network. This topology has central BS infrastructure which handles spectrum sensing and resource allocation to the connected node, as shown in Figure 2(a).

Peer-to-peer topology. In this topology, the CR sensor nodes communicate with each other in peer-to-peer as well as in multi-hop manner and directly to the sink node. This topology has no BS infrastructure. Hence, spectrum sensing, resource provisioning, and sharing are done by each node separately or by cooperative communication. Large-scale deployment of this topology can lead to a mesh network with several multi-hops, as shown in Figure 2(b). This topology has no high computational complexity and overheads. However, there will be high latency delay due to so many hop count in the mesh network.

Clustered-based topology. This is a form of star topology, however, with more sophisticated features suitable for large-scale sensor network deployment. The clustered-based topology involves selection of cluster heads or coordinator which will be apportioned to carry out critical tasks such as spectrum sensing for channel

Table 2. Different topologies of ZigBee CRSN with their characteristics.

Topology type	Latency	Computational complexity	Distance covered	Scale of Application	Number of hops
Star	Low	Low	Short	Low scale	Very low
Peer-peer/mesh	High	Medium	Long	Large scale	High
cluster	Medium	Medium	Long	Large scale	low
Heterogeneous hierarchical	High	High	Long	Large scale	High
Distributed heterogeneous cluster	Medium	Medium	Very long	Very large scale	Medium
Mobile ad hoc	High	Medium	Very long	Very large scale	High

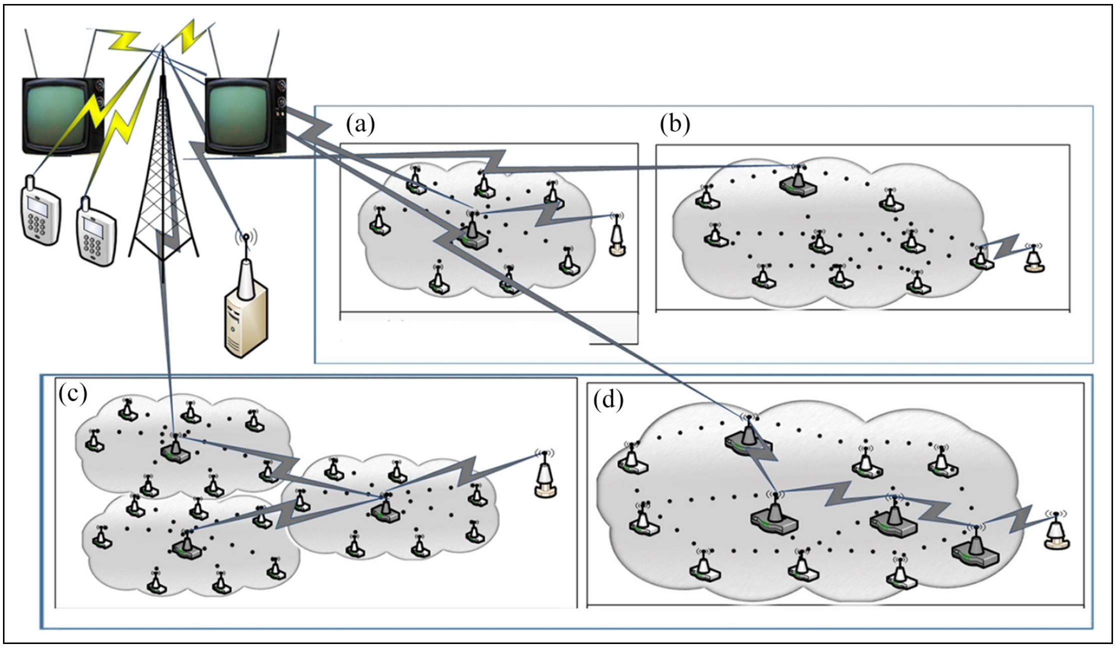

Figure 2. CRSN topologies: (a) star network topology, (b) peer-to-peer/mesh network topology, (c) cluster network topology, and (d) heterogeneous hierarchical network topology.

availability, and allocation of radio resources to other CR sensor nodes. This topology is illustrated in Figure 2(c). Consequently, cluster head (CH) selection and cluster network formation technique are essential in this topology for improved data communication network in SG application deployment.

Heterogeneous hierarchical topology. This involves the combination superior sensor nodes such as the actuator and multimedia CR sensor nodes, and the normal CR sensor nodes. The deployment of these mixed CR sensor nodes for various technologies is done in a hierarchical mesh network manner. Hence, this topology comprises heterogeneous CRSN nodes in a hierarchical mesh network, as shown in Figure 2(d).

DHC topology. This topology consists of heterogeneous CRSN nodes such as normal ZigBee CR nodes, actuator, and multimedia sensor nodes. Unlike heterogeneous hierarchical topology, the deployment here is done in a distributed clustered manner covering an extensive and long range area. The DHC topology is shown in Figure 3. This CRSN DHC topology is recommended for SG applications, because SGs require heterogeneous networks to support different QoS for the various applications. This topology has been adopted from the work of Ogbodo et al.,[17] which has now been improved with an energy-efficient spectrum-aware model, and a multichannel sensing coverage model. It is regarded as distributed clustered because multiple inter-clustered network are linked with relay CRSN nodes for extensive range coverage. This will help in reducing the number of multi-hops with minimal latency delay, unlike the heterogeneous hierarchical topology that has several hops with high latency delay.

Mobile ad hoc topology. This topology is somewhat similar to the peer-to-peer topology, except that mobility is integrated in the CRSN node to cover the deployment area. Some of the CRSN nodes are made to be mobile. For example, mobile ad hoc CRSNs can be deployed with environmental, proximity, and light monitoring CR sensors.

Communication protocols in ZigBee CRSN

An investigation of the communication layer protocols in a ZigBee CRSN is presented in this section. Obviously, the communication layer protocols have direct relationships and cooperation with the DSA management functionalities highlighted in the previous section. The protocols and cooperation with the DSA functionalities, as shown in Figure 4, will jointly enhance the communication in ZigBee CRSN nodes. The communication layer protocols are as follows:

- Physical (PHY) layer;
- Media access control (MAC) layer;
- Network layer;

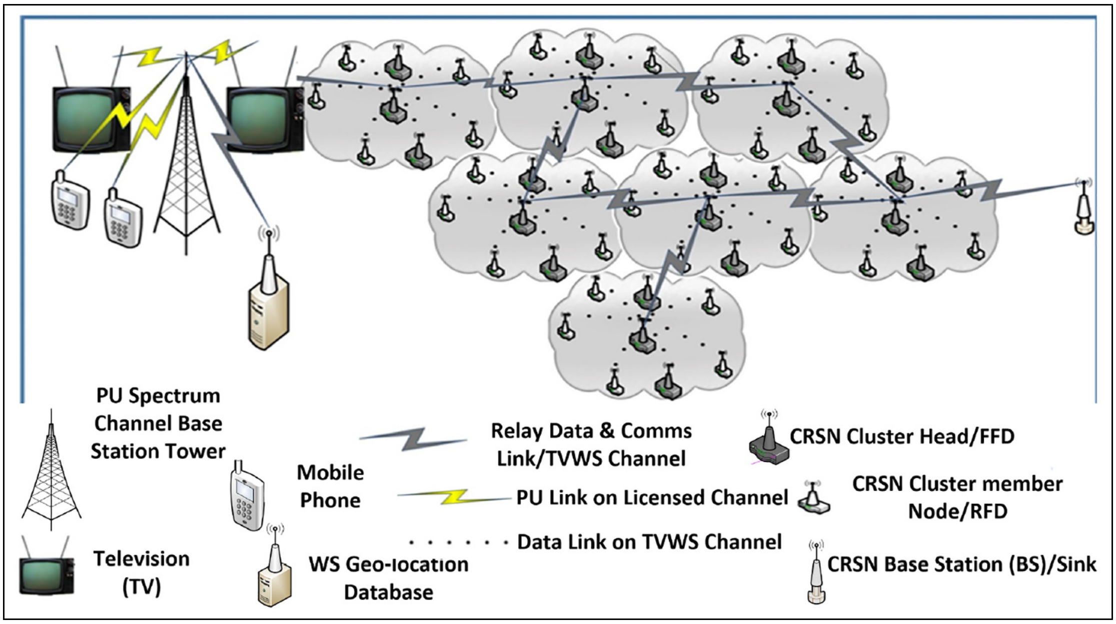

Figure 3. CRSN distributed heterogeneous cluster topology.

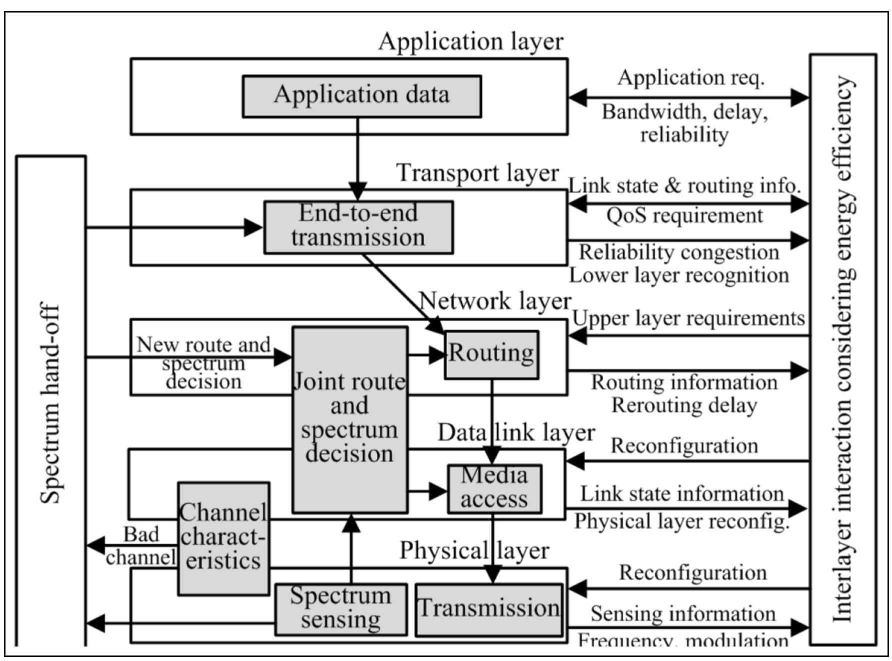

Figure 4. Interaction between the communication protocols and DSA functionalities.[16]

- Transport layer;
- Application layer.

Related work

The implementation of CRSNs for QoS improvement has been investigated by researchers from several perspectives. Gao et al.[18] presented a joint lifetime maximization and adaptive modulation framework for realizing high power efficiency in CRSNs. The framework to improve energy consumption of the sensor nodes is only on protocol optimization and not based on network topology. Naeem et al.[19] investigated energy-efficient power allocation including the maximization of ratio of throughput to power for CRSNs. Their work does not consider network topology for sensor nodes deployment and is not centered on SG. Aslam et al.[20] proposed a scheme that selects the optimal number of sensor nodes and efficient channel allocation mechanism, which improves the performance of clustered topology-based CRSNs. The work focuses on efficient channel allocation in CRSNs without considering integration in the SG environment. Zhang et al.[21] presented a centralized spectrum-aware clustering algorithm and a distributed spectrum-aware clustering (DSAC) protocol which maintained scalability and stability as well as low complexity with quick convergence of the dynamic spectrum variation. They did not consider bit error rate (BER) in their work. It is also not in the context of an SG.

Improvement of energy efficiency and end-to-end delay with a QoS guarantee for a CRSN when using in-network computation was investigated by Lin and Chen.[22] They also presented the maximization of throughput in the deployment of WSNs. However, their work is not in the perspective of an SG. Ren et al.[23] demonstrated how channel accessing schemes can significantly improve energy efficiency in CRSNs. Though again, the work is not in the context of an SG, Oto and Akan[24] investigated PU behavior and channel BER as the key critical parameters in determining the energy efficiency for CRSN, though this was still not in the context of an SG.

Other works addressed energy efficiency in sensor networks for monitoring applications using a hierarchical clustering topology approach. For instance, Heinzelman et. al.[25] proposed a low energy adaptive clustering hierarchy (LEACH) algorithm. This involves CHs which are randomly selected in order to increase the sensor network lifetime. Smaragdakis et al.[26] proposed a stable election protocol (SEP) for clustered heterogeneous WSN. SEP involves a heterogeneous-aware protocol to prolong the time interval before the death sensor node in order to conserve energy. Younis and Fahmy[27] proposed a hybrid energy-efficient distributed (HEED) clustering protocol. This periodically selects CHs based on the hybrid of the node residual energy and a node proximity to its neighbors. Saini and Sharma[28] proposed a threshold distributed energy-efficient clustering (TDEEC) protocol. This improves the energy use of the CHs by adjusting the threshold value of a node in a heterogeneous WSN. Arumugam and Ponnuchamy[29] proposed an energy-efficient LEACH (EE-LEACH) Protocol for data gathering in WSN. EE-LEACH helps to provide an optimal packet delivery ratio with lower energy consumption. Eletreby et al.[30] proposed Cognitive LEACH (CogLEACH), which is a spectrum-aware extension of the LEACH protocol. CogLEACH is a fast, decentralized, and spectrum-aware (including energy-efficient clustering) protocol for CRSNs.

The major drawback of the above-mentioned works, on energy-efficient hierarchical clustering topology approaches in sensor networks, is that they lack consideration of compliance requirements for sensor network integration in SGs. However, the energy-efficiency model reported in this article considers the compliance requirements for sensor network integration in SGs.

Studies involving energy-efficient clustering for data gathering in WSN, including underwater wireless sensor network (UWSN). have been conducted.[31,32] Huang et al.[31] addressed an autonomous underwater vehicle (AUV)-assisted data gathering scheme using clustering, and matrix completion to improve the data gathering efficiency in the UWSN was proposed. Jiang et al.[32] proposed a trust-based energy-efficient data collection for an unmanned aerial vehicle (TEEDC-UAV) scheme to prolong sensor nodes lifetime with a trustworthy mechanism. Although these studies are not in the context of SG, one of their main focuses is energy-efficient clustering using an optimized approach for monitoring, control, and data collections in WSN and IoT applications.

Another area of research attention is the sensing coverage problem in sensor networks. Several researchers have addressed this using deterministic sensing models.[33–35] Some researchers have investigated the sensing coverage problem using a probability coverage model.[36–38] Other researchers explored the sensing coverage problem using environmental impacts such as path loss, multi-path, and shadowing fading.[39–42] Most of these sensing coverage models ignore the consideration of compliance requirements for sensor network integration in SGs. They do consider multichannel sensing coverage of CRSNs or coverage probability with respect to BER and latency in their models. However, this article considers the multichannel sensing coverage of CRSNs, and coverage probability with respect to BER and latency for CRSN-based SG communication.

Implementation of CRSNs for enhanced QoS from an SG perspective is found in a few studies. For instance, Shah et al.[43] proposed a cross-layer design that ensures the QoS requirements for CRSN-based SGs. The authors handle the issues of heterogeneous traffic in a CRSN-based SG by defining different classes of traffic with different priority levels. This classification is significant in terms of separating the traffic with respect to the services and their network requirements, for example, latency, link reliability, and data rate. However, network topology for CRSN deployment, and BER and energy consumption, is not considered in their work.

Markov chain modeling of CRSNs in SGs was presented by Luo et al.;[44] the work aims at reducing transition delay during handoffs, though improvement using network topology is not considered in this work.

Aroua et al.[45] presented unselfish distributed channel allocation using a partially observable Markov decision process (POMDP) to improve spectrum utilization

Table 3. Symbols.

Symbol or term	Description
A	Required area of sensing coverage
$BU - CH$	Back up cluster head
CH	Cluster head
C_N	Number of cluster
COV_{Pr}	Probability of coverage
$E_{CONNECTED}$	CRSN node connection with available channel
E_{CBC}	CRSN node connection with CBC
EDD_{S_N}	Event-driven data sensor nodes
$E_{pldintra}$	Energy dissipation in the radio frequency (RF) amplifier within a C_N due to path loss
$E_{mpdshinter}$	Energy dissipation in the RF amplifier in single-hop inter-C_N action due to multi-path fading
$E_{shadmhinter}$	Energy dissipation in the RF amplifier in multi-hop inter-C_N action due to shadowing
p	Any point within the area where the phenomenon to be sensed or covered is situated
L	Length of the sensing area
NC	Network coverage
R_{min}	Minimum communication range
R_{max}	Maximum communication range
R_{ils}	S_i Least sensing range
R_{ifs}	S_i Furthest sensing range
R_{us}	Sensing range of S_u
S_i	RFD CRSN node
S_u	FFD CRSN node
S_N	Number of both RFD and FFD CRSN nodes that make a cluster or clusters
$S_{1,1}, S_{2,2} \ldots S_N$	The number of both RFD and FFD CRSN nodes up to the last CRSN node in a cluster
S_{Ns}	Sensor nodes
TDD_{S_N}	Time-driven data sensor nodes
TS	Total number of CRSN nodes required for full coverage in an area
V_R	Variator for varying available channels

CRSN: cognitive radio sensor networks; RF: radio frequency.

for smart microgrid-based CRSNs. Hassan et al.[46] proposed the use of unlicensed TVWS spectra for CR operators to guarantee QoS for SG applications.

However, even though there are few improvements for QoS through the implementation of CRSNs in SGs, as highlighted above, the implementation of CRSNs for guaranteed QoS in the context of network topology of the CR sensor nodes deployments in SG, including the evaluation of QoS metric in terms of BER, is rarely investigated. Hence, the focus here is performance improvement of CRSN-based SG which is achieve by utilizing a proposed CRSN topology for guaranteed QoS based on metric such as reduced BER, low end-to-end delay, and reduced energy consumption in SG. This will help for seamless delivery of sensed data in the SG ecosystem.

DHC topology of CRSNs in SG

In this section, DHCs are presented. It begins with a description of the composition of the system as well as the topology. Also presented is the EDHC-SA network connectivity formation model. EDHC-SA multichannel sensing coverage model is proposed. For better understanding of the terminologies and symbols used in this article, Table 3 presents a description of the symbols and terms, and further acronyms are listed in Table 4.

DHC system model

A DHC ZigBee CRSN topology system model is composed of heterogeneous devices, which consist of fully function devices (FFDs) such as ZigBee Pro and multimedia sensors, and reduced function devices (RFDs) such as ZigBee and actuators. In this system model, different tasks are assigned to the different sensor devices; for example, ZigBee sensors and actuators are responsible for sensing activities within the expected coverage. ZigBee Pro acts as the CH, which is responsible for communication channel sensing and allocation to the RFDs. The ZigBee Pro also acts as the coordinator for the RFDs, including transmission of collected sensed data as well as a relay for the collected data to the BS or sink. The multimedia sensors are responsible for video signals and surveillance activities. Each sector is designed to have two FFDs, primary and redundant or backup coordinators, in order to alleviate energy consumption and increase network lifetime. A number of clusters are meant to cover a specific area. The clusters are extended via the ZigBee Pro in a distributed relay manner for long-range coverage area. The DHC topology is shown in Figure 3.

EDHC-SA network model

In order to guarantee network coverage and connectivity, the deployment scheme of the heterogeneous ZigBee CRSNs was first presented.

Deployment scheme for the EDHC-SA model. There are two main sensor deployment schemes: (1) structured or deterministic sensor deployment and (2) unstructured or random sensor deployment. The latter is suitable for applications in remote and inaccessible areas. In this work, deterministic sensor networks are used for SG applications because it provides sufficient sensing coverage and guaranteed connectivity. This is because SG applications are mission-critical applications[47] and require guaranteed transmission of sensed data in a real-time manner. For scheme (2), random deployment is susceptible to sensor coverage holes or possessing some areas that are not covered in the actual field; hence, it is not suitable for SG applications.

Table 4. Acronyms and description of terms.

Acronym or Term	Description
AC	Available channels
AMI	Automatic metering infrastructure
AWGN	Additive white Gaussian noise
BAN	Building area network
BE	Backoff exponent
BER	Bit error rate
CAN	Commercial area network
CBC	Common backup channel, which serves as channel for communication when the available channels are in use by the PU
Control algorithms	Algorithms with mechanism for data/control signals
CR	Cognitive radio
CRAHNs	Cognitive radio ad hoc networks
CRN	Cognitive radio network
CRSN	Cognitive radio sensor network
CSMA/CA	Carrier sense multiple access and collision avoidance
DA	Distribution automation
DHC	Distributed heterogeneous cluster
DR	Demand response
DRM	Demand response management
DSA	Dynamic spectrum access
DSAC	Distributed spectrum-aware clustering
EDD	Event-driven data
EDHC-SA	Energy-efficient distributed heterogeneous clustered spectrum-aware
ETA	Equilateral triangulation algorithm
FDMA	Frequency division multiple access
FFD	Full function device
HAN	Home area network
IAN	Industrial area network
IoT	Internet of Things
ISM	Industrial scientific and medical
LPWAN	Low-power wide-area network
MAC	Medium access control
MAN	Metropolitan area network
MATLAB	Matrix laboratory
MGF	Moment generating function
MQAM	M-ary quadrature amplitude modulation
MRC	Maximum ratio combiner
NAN	Neighborhood area network
NIST	National Institute of Standards and Technology
Optimal available channel	Available channels with guaranteed link
OSA	Opportunistic spectrum access
PHY	Physical layer
PU	Primary user
QoS	Quality of service
RFD	Reduce function device
SG	Smart grid
SNR	Signal-noise-ratio
SO	Superframe structure order
SU	Secondary user
TDD	Time-driven data
WAN	Wide area network
WSN	Wireless sensor network

A square field area is considered. The phenomenon (target) to be sensed or covered is situated within the area. Hence the area is $A = L \times L$ where L is the length of the sensing area A. The heterogeneous sensors are non-identical and are denoted by S_i and S_u which are deployed cluster by cluster in the sensing area A. S_i and S_u represent the RFD and FFD, respectively. The number of CRSN nodes which is denoted as S_{Ns} can be written as $S_{1,1}, S_{2,2}, \ldots, S_N$. They make up a cluster, and are deployed in the target area A. Similarly, the number of clusters which is denoted as C_N can be written as $C_1, C_2, \ldots, C_N$. They make up the total number of clusters in the entire coverage area, and are deployed strategically.

Let the least distance from any point p within the sensing area to a sensor node S_i in the clustered network be denoted as the minimum communication range R_{min}. The farthest distance from any point p within the sensing area to a sensor node S_u in the clustered network is denoted as the maximum communication range R_{max}. The sensing range is based on the coverage sensing disk. S_i has least sensing range denoted by R_{ils} and farthest sensing range denoted by R_{ifs}. The sensing range of S_u is denoted by R_{us}. Hence a conditional property of a heterogeneous sensor network for initialize network coverage (NC) at any given point p in a sensing field area can be introduced. This is given as

$$NC = \begin{cases} R_{ils} \geqslant R_{min}(i,p) < R_{ifs} \\ R_{max}(u,p) \leqslant R_{us} \\ R_{ifs} = R_{us} \\ R_{min}(i,p) < R_{max}(u,p) \end{cases} \quad (1)$$

where $R_{min}(i,p)$ is the Euclidean or minimum communication range between point p and the RFD sensor node i; $R_{max}(u,p)$ is the maximum communication range between point p and the FFD sensor node i. However, due to the excessive number of points in the sensing area, it will be cumbersome to estimate the minimum and maximum communication range at any given point in order to establish if a network coverage will be fully covered. Hence, the Voronoi diagram[48,49] is used to address this challenge. The Voronoi diagram partitions the required area A into a set of regular polygons, such that each polygon has a corresponding sensor node; and for any point in the regular polygon, there is a minimum Euclidean distance or minimum communication range to the S_N. Three regular shapes are used with the Voronoi diagram: square, hexagon, and equilateral triangle. The method of the equilateral triangle is utilized as shown in Figure 5. This is because it gives minimal number of sensors with no errors or coverage hole in an ideal deployment scenario.[50] The deployment strategy is shown in Figure 6. Since the SG is prone to harsh

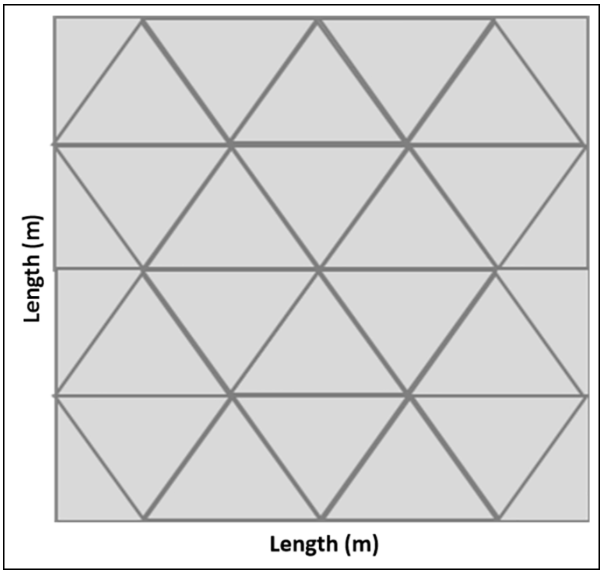

Figure 5. Voronoi diagram with equilateral triangle shape in a square field.

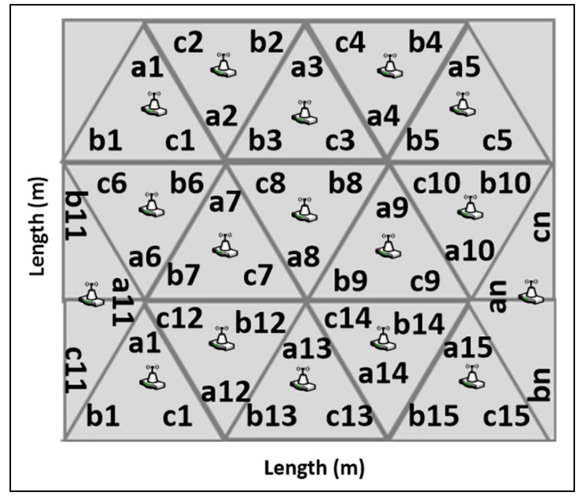

Figure 6. Equilateral triangulation pattern deployment strategy in a square field.

environmental conditions and multipath fading, there may exist a coverage hole; hence, a multichannel fading sensing signal model is integrated into the Voronoi equilateral triangle to address this challenge. The details of this sensing signal model is provided in the subsequent sections.

EDHC-SA network connectivity model. Link interruption will cause the loss of communication between two adjacent nodes in the SG communication network. Therefore, a stronger network connectivity will be devoid of link interruption. For instance, Chen et al.[51] demonstrated network connectivity using the connectivity degree; that communication loss is related to the node connectivity degree. Hence the stronger the connectivity degree the better the connected link. However, the EDHC-SA network connectivity method, is modeled by a equilateral triangulation pattern, denoted as $G = (V, E)$, where V represents the vertices of the triangle and E are the edges which is the communication links or line segments between the vertices. Hence, in order to maintain network coverage and connectivity, the following properties stipulated in Ogbodo et al.[17] are adopted:

- An S_N in any corresponding triangle can communicate with another S_N if any of the vertices of the associated S_N triangle is connected with the other vertices of the associated S_N triangle.
- If all vertices in a triangle are connected, then the triangle is covered by the associated sensor node; hence, the total triangles are covered, resulting to the full coverage and connectivity of the whole area.
- Coverage and connectivity can be maintained if and only if the minimum Euclidean distance or minimum communication range, $R_{min}(i,p) < R_{ifs}$ as well as the conditional property in equation (1). This can be estimated for the edge E of any triangle. The maximal actual distance D_{max} of the edge of a polygon is approximated in Cheng et al.[52] as

$$D_{max} = \sqrt{K} r_s \qquad (2)$$

where $K = 3, 4, 6$ to be used for triangle, square, or hexagon of a pattern-based lattice; r_s is the sensing range. Hence, the edge E of the equilateral triangulation can be expressed as

$$E = R_{ifs}\sqrt{3} \qquad (3)$$

- The probability of coverage of the equilateral triangulation pattern field can be computed using the sensor node that constitutes a lattice which is denoted as N_p. In a triangular lattice pattern, $N_p = 3$ as found in Cheng et al.[52] Hence the coverage probability for equilateral triangulation as shown in Figure 6 is the ratio of the sensing area A_{Et} of the triangle to N_p so that

$$COV_{Pr} = \frac{A_{Et}}{N_p} \qquad (4)$$

But the area of the equilateral triangle A_{Et} is

Table 5. Algorithm 1: ETA Algorithm for guaranteed S_{Ns} network connectivity.

```
1. G={V, E};
2. AC=[1, 2, 3, 4, 5, 6];
3. CBC=[7];
4. V={a1, b1, c1, a2, b2, c2,..... an, bn, cn};
5. E={a1,b1; a1,c1; b1,c1; a2,b2; a2,c2;
   b2c2; ......... an,bn; an,cn; bn,cn};
6. if AC = 1||2||3||4||5||6;
7. E_CONNECTED = AC (an, bn; an, cn; bn, cn);
8. else if AC=7;
9. E_CBC = CBC(an, bn; an, cn; bn, cn);
10. while E = E_CONNECTED;
11. send msg via AC
12. else
13. send control signal and msg via CBC; end if;
14. end
15. end
```

AC: available channels; CBC: common backup channel.

$$A_{Et} = \frac{(R_{ifs})^2\sqrt{3}}{4} \tag{5}$$

Therefore,

$$COV_{Pr} = \frac{3(R_{ifs})^2\sqrt{3}}{4} \tag{6}$$

- The total number of CRSN nodes TS that is required for full coverage and connectivity in the total area of the equilateral triangulation pattern field excluding the cut-off edges of the square field can be obtained as

$$TS = \frac{A}{COV_{Pr}} \tag{7}$$

where area of the square field $A = L^2$. Hence

$$TS = \frac{4L^2}{3(R_{ifs})^2\sqrt{3}} \tag{8}$$

Since TS are uniformly distributed, the total field area A is covered.

- Any point p is said to be connected to the clustered head (CH) if the Euclidean distance is within the sensing range of R_{ifs} or R_{us}.
- The total number of clusters CNs is estimated using

$$CNs = \sqrt{TS} \tag{9}$$

so that

$$CNs = \sqrt{\frac{4L^2}{3(R_{ifs})^2\sqrt{3}}} \tag{10}$$

However, there are two CHs in each cluster, the main CH and the backup CH ($BU - CH$) for energy efficiency and longer network lifetime. During the formation of cluster network, the primary CH and backup CH will advertise themselves as the CH and their header ID via the MAC protocol so that SNs within the proximity of the Euclidean distance can be associated with them for data frame exchange. However, immediately after this advertisement, the backup CH will go to an idle state until a certain threshold is met and for it to become the primary CH and resume association with the SNs. Since CH coordinates the opportunistic channel access from the PUs' network via dynamic spectrum access (DSA). It allocates the available unused channels to the CR sensor nodes at the MAC protocol layer through the CSMA/CA. Up to six channels in the 650–860 frequency band can be made available when is not in used by the PU. The SU or CRSN nodes automatically relinquishes the channels as soon as the authorized users arrive. These intermittently relinquish all the channels, especially when the ACs are all occupied by the PU. This can cause unnecessary delay to the sensor network so it is not suitable for mission-critical applications like SGs. To address this, the common backup channel (CBC) and equilateral triangulation algorithm (ETA) are introduced as shown by Algorithm 1 in Table 5. This guarantees connectivity of the EDHC-SA network in the presence of dynamic multichannel use. The CBC serves as the control channel and handles the control signaling of the SU and as a channel for communication when the ACs are in use by the PUs.

Algorithm 1 in Table 5 shows the connectivity and coverage in the equilateral triangulation. Any point p in the triangle is covered by the sensor for sensing coverage if the adjacent or nearest edge E is connected with an associated channel AC. Once the edge is connected, the sensor will then send a sensed data message via the connected channel. The process of connectivity and coverage for a sending sensed data message is shown in Algorithm 1 and involves the equilateral triangulation pattern graph which begins with the six ACs. The seventh channel is the CBC and the vertices are represented as a_1, b_1, c_1, a_2, b_2, c_2, ..., a_n, b_n, c_n, which indicate connections with channels. It then connects with any ACs. Once connected with a channel, the edges are connected. Otherwise, connection is with CBC if there is no AC. A message is via the AC while connection is with any channel, else a control signal is sent, and a message if connection is with CBC. If not, then end and begin again. Based on the earlier statement about the conditional properties, that if all vertices in a triangle are connected, then the triangle is covered by the associated S_N. With respect to this, relating to the ETA algorithm lines 7 and 8, the vertices are connected by the ACs or backup channel. Hence, the associated S_N or CH in the triangle can communicate and exchange messages or sensed data.

EDHC-SA energy model. In this section, the energy consumption that is involved in the entire process of cluster network formation and the data communication or transmission phase is presented. The energy expended in the CRSN node during transmission and reception is

$$E_{TX}(z,d) = \begin{cases} zE_C + zE_{pl}d_{intra}, & d \leq d_{intra} \\ zE_C + zE_{mp}d_{shinter}, & d \geq d_{shinter} \\ zE_C + zE_{sha}d_{mhinter}, & d \geq d_{mhinter} \end{cases} \quad (11)$$

$$E_{RX}(z) = zE_C \quad (12)$$

During transmission, a data frame of size z is transmitted by the transmitter over a distance d, denoted by $E_{TX}(z,d)$, and energy is expended in the S_N device circuit denoted by E_C and in the RF amplifier. Hence, during transmission there is a device circuit power loss and RF amplifier power loss. The RF amplifier power can be adjusted based on a certain distance threshold with respect to distance covered. If the distance is within a cluster the RF amplifier power loss encounters a path loss energy dissipation, denoted by E_{pl} with distance d_{intra}. If the distance is inter-cluster with a single hop, the RF amplifier power encounters a multi-path energy dissipation, denoted by E_{mp}, and distance $d_{shinter}$, and if the distance is inter-cluster, with multiple hops, it encounters shadowing energy dissipation, denoted by E_{sha} with distance $d_{mhinter}$. At the receiver, the energy expended in receiving a data frame of size z is denoted by $E_{RX}(z)$. This is the energy dissipated in the S_N device circuit.

Some S_N s are meant to monitor event-driven data such as object detection and real-time data delivery. Other S_Ns are meant to monitor time-driven data that are scheduled for periodic data reporting. In order to save energy and network lifetime, the S_N for the event-driven data and time-driven data are alternated based on their effective energy. During sensing activities, the SN uses a previously AC in the MAC protocol for the sensing. A CSMA/CA algorithm is employed for the alternation of the S_Ns based on adaptation of the back-off exponent (BE) parameter. In the CSMA/CA algorithm, the BE state is adjusted based on the threshold of the effective energy of the S_N device circuit. There is a low duration channel sensing in the CRSN nodes since each S_N obtains the ACs with the help of the CH CSMA/CA algorithm in beacon enable mode. Both the CH and cluster member S_N do not wait for channel in the event of non-AC since there is CBC, thereby eliminating period of waiting for an AC which is crucial to real-time delivery data. The S_N effective energy is expressed as

$$E_{Eff} = \frac{E_{current}}{E_{res}} \quad (13)$$

where E_{Eff} is the initial effective energy which can be either the maximum or the low energy state of the CRSN node circuit for transmission; $E_{current}$ is the energy currently dissipated in the S_N circuit for transmitting data packet, and E_{res} is the residual or remaining energy of the circuit after transmission.

The primary CH and the $BU-CH$ follow the technique of S_{Ns} alternation of equation (13); however, the effective energy threshold for the primary CH and $BU-CH$ is different from the cluster member S_Ns. Prior to transmission, the primary CH possesses maximum effective energy state, while the $BU-CH$ is made to be at a low energy state (this is an inactive or sleeping state of the $BU-CH$ node). Data transmission continues until the primary CH becomes 20% of the maximum energy state (this is the threshold for the primary CH to be set as low energy state and becomes the $BU-CH$. Once the threshold occurs the $BU-CH$ becomes the primary CH. This process continues until the end of the data transmission. The cluster member S_{Ns} for both time-driven data and event-driven data are meant to be delivering data to the CH. Energy is dissipated in the cluster member in transmitting data frame to the CH within the cluster, and it is expressed as

$$E_{CM} = zE_C + zE_{pl}d_{intra} \quad (14)$$

where E_{CM} is the energy expended in each of the cluster member and $zE_{pl}d_{intra}$ is the distance from the cluster member to the CH. Similarly, the CH expends energy in the receiving data frame from the cluster member, aggregates the data frame, and finally transmit the aggregated data frame to the sink or BS. This is

$$E_{CH-BU} = zE_C\left[\left(\frac{TS}{C_N}\right) - 2\right] + zE_{(DFA)}\left(\frac{TS}{C_N}\right) + zE_C + zE_{mp}d_{shinter} \quad (15)$$

$$E_{CH-BU} = zE_C\left[\left(\frac{TS}{C_N}\right) - 2\right] + zE_{(DFA)}\left(\frac{TS}{C_N}\right) + zE_C + zE_{sha}d_{mhinter} \quad (16)$$

where E_{CH-BU} is the energy expended in either the CH or in the $BU-CH$, $[(TS/C_N)-2]$ is the number of cluster member nodes in the cluster without the CH and the $BU-CH$. E_{DFA} is energy expended during data frame aggregation. E_{mp} with $d_{shinter}$ is the energy expended with distance from the CH to the BS if it is only a single hop to the BS, and E_{sha} with $d_{mhinter}$ is the energy expended when the distance to the BS has multi-hops.

Equations (15) and (16) are for the CH to transmit a single complete frame of the aggregated data frame for event-driven data. This is because event-driven data are mission-critical and requires real-time data delivery. The CH aggregates and transmits up to five complete frames to the BS for time-driven data. This is because time-driven data require a periodic data delivery. However, if there is any available aggregated complete frame of the event-driven data, the CH will transmit both the event-driven and time-driven data, even if the time-driven data have less than five frames. Hence, the expression for transmitting time-driven data or both sets of data frames to the BS is as follows

$$E_{CHTE} = \sum_{f=1}^{n} E_{CH-BU} \tag{17}$$

where E_{CHTE} is the energy expended in the CH for both time-driven and event-driven data frames and f represents the frame starting from frame 1 to frame 5; hence, $1 \leq n \leq 5$.

Algorithm 2 in Table 6 uses CSMA/CA algorithms for the alternation of S_N data frame transmission. The algorithm starts by initializing the Beacon period (BP), broadcasting available sensed channels and CH or $BU - CH$ identity. The S_N for sensing and delivering the event-driven data and time-driven data are in either active or inactive state. The BE is in the range of 0–5, while the effective energy is in the range of 2–10 J. The superframe structure order (SO) activates if channels 1–6 are available. However, if the channel is not equal to 0 and less than or equal to 6, the SO changes with the BE decrementing by 1. While the effective energy is between 5 and 10 J inclusive, the BE should be decremented by 1 and be incremented by 1 if the effective energy is less than 2 J. If the BE is 0 or 1, EDD_{SN} should be triggered to the active state which then sends a message, otherwise it should remain in the inactive state and ends and initializes again. If BE is between 2 and 5 J inclusive, the TDDSN is set to the active state and sends a message, or it remains in inactive state and ends to initialize again to begin the process, and then finally ends.

Table 6. Algorithm 2: CSMA/CA Algorithms for Alternation of S_N data frame transmission.

1. initialize → BP
2. EDD_{SN} = {Active state || Inactive state};
3. TDD_{SN} ={Active state || Inactive state};
4. BE = 0:5;
5. E_{Eff} = 5:10;
6. if AC=1:6;
7. activate superframe structure Order (SO);
8. else
9. while AC 0 &&<=6;
10. SO changes with → BE − 1;
11. while E_{Eff}>=5 &&<=10;
12. →BE →− 1;
13. else if E_Eff<5;
14. →BE → + 1;
15. if BE=0 || 1;
16. EDD_{SN}=Active state;
17. else
18. EDD_{SN} =Inactive state;
19. if EDD_{SN} =Active state;
20. send msg; end if;
21. if BE>=2 &&<=5;
22. TDD_{SN} = Active state;
23. else
24. TDD_{SN} = Inactive state;
25. if EDD_{SN} = Active state;
26. send msg; end if;
27. end;
28. end; end; end;

BP: beacon period; BE: backoff exponent; ACs: available channels; SO: superframe structure order.

EDHC-SA multichannel sensing coverage model

Signal model. CRSN-based SGs are examples of a situation where channel conditions fluctuate dynamically. Thus, ZigBee CRSN systems use an adaptive modulation schemes so as to take into account the difference in channel conditions.[53] The adaptive modulation varies transmission parameters such as power, data rate, and modulation technique. Hence, adaptive CR technologies will help to achieve interference-free networks as well as spectral efficiency[54,55] during data frame transmission. The SG-sensed data is modulated using MQAM through a single fading channel from the available multiple fading channels distribution conditions via DSA. The received signal at the respective CRSN nodes can be modeled as

$$y_i(t) = \sqrt{E_s} h_i(t) x_i(t) + n_i(t) \quad 1 \leq i \leq 6 \tag{18}$$

where $y_i(t)$ is the received signal, E_s is the transmit signal power, x_i is the transmitted signal, and $h_i(t)$ is Nakagami-q multi-path fading channel

$$h_i = h_i^I + j h_i^Q \tag{19}$$

and has a zero mean with complex Gaussian variables denoted as $(0,\sigma_x^2)$ and $(0,\sigma_y^2)$, $i \in (1,2,3,4,5,6)$ which is the ith number of available fading channels, $n_i(t)$ is the noise with complex Gaussian distribution CN $(0,N_0)$, and N_0 denotes the noise power spectral density of a single channel.

However, $q = \sigma_y/\sigma_x$, where $0 \leq q < 1$, $\gamma = \alpha^2 (E/N_o)$ and $\bar{\gamma} = 2\sigma^2(E_s/N_o)$, where γ is the received signal-noise-ratio (SNR), $\bar{\gamma}$ is the average received SNR for each channel, and σ denotes the shadowing distribution, E is the signal power, and E_s is the instantaneous transmit power. Hence, the average SNR can be expressed as

$$\bar{\gamma} = \frac{E_s}{N_0} \tag{20}$$

The higher the transmit power (E_s) the higher the energy expended in the CRSN node, leading to a corresponding high SNR. However, the higher the average SNR, the lower the BER; hence, the BER is inversely proportional to the average SNR so that

$$\text{BER} = \frac{K_{delay}}{\bar{\gamma}} \tag{21}$$

where K_{delay} is the delay resulting from latency, media access delay, retransmission delay, and so on. Hence, in order to save energy, it is good to avoid a high expended energy in the CRSN node resulting from high SNR. Therefore, it is necessary to devise a mechanism that will reduce the BER at a given SNR, which will maintain less errors as well as energy efficiency at an appreciable SNR. Consequently, a channel variator V_R is introduced to the fading channel components which will help to reduce the transmit power without noise amplification for energy efficiency. Recall that

$$h_i = 0, \sigma_x^2 + 0, \sigma_y^2 \tag{22}$$

Hence, the channel implementation is expressed as

$$h_{VRi} = V_R[0, \sigma_x^2 + 0, \sigma_y^2] \tag{23}$$

where

$$1 \leq V_R < N_R$$

and N_R is the maximum number of ACs; hence, $N_R \in [1, 2, 3, 4, 5, 6]$. V_R is adjusted to the number of ACs without amplification of the noise component; it then transmits based on the number of antennas of the CRSN node. In this case, it transmits on only a single channel since the CRSN node has only one antenna. The V_R factor varies to release only a single channel for transmission and reception via DSA. This helps with a moderate transmit power without noise amplification, thereby expending moderate energy for energy efficiency.

Probability of sensing coverage signal. Various sensing models such as the circular disk sensing model, deterministic model and random deployment model cannot give absolute sensing coverage. This is due to the fact that they do not take into account the error probability mechanism. Hence, the error probability of the sensing coverage was introduced to the Voronoi equilateral triangulation model. Therefore, the probability density function (PDF) is employed; this uses the moment generating function (MGF). This utilizes the average bit error MQAM probability over a single Nakagami-q fading channel, which was derived in earlier work[53] and is given as

$$\begin{aligned}\bar{P}_{MQAM} = \tfrac{a}{n}\left\{\tfrac{1}{2}M_\gamma q\left(-\tfrac{b}{2}\right) - \left(\tfrac{a}{2}\right)M_\gamma q(-b)\right. \\ + (1-a) \\ \sum_{i-1}^{n-1} M_\gamma q\left(\tfrac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_\gamma q\left(\tfrac{-b}{s_i}\right)\end{aligned} \tag{24}$$

where $\bar{P}_{MQAM}$ is the average probability of detection under MQAM modulation, and

$$a = 1 - \frac{1}{\sqrt{M}}, \quad b = \frac{3}{M-1}, \quad s_i = \frac{2sini\pi}{4n}, \quad M_\gamma q$$

The MGF of the received SNR over the Nakagami-q channels is

$$M_\gamma q(s) = \left(1 - 2s\bar{\gamma} + \frac{(2s2s\bar{\gamma})^2 q^2}{(1+q^2)^2}\right)^{\frac{-1}{2}} \tag{25}$$

In order to estimate the coverage probability of detection of the sensing signal, the sensing range R_S of the CRSN node is taken into consideration. The R_S depends on the transmit power of the sensing signal, the sensing received power (which is also the received signal strength (power), denoted as ρ), and the propagation path effect such as path loss, shadowing, and multi-path fading. Hence, the received signal power ρ is approximated in Kumar and Lobiyal[41] as

$$\rho = E_s * \eta\left(\frac{R_o}{R_s}\right)^\gamma \tag{26}$$

where E_S is the sensing transmit power, η is the path loss component, R_0 is the sensing reference distance which is equal to 1 for an outdoor CRSN, and γ is the SNR which is a function of shadowing and multi-path fading effects. The sensing range R_S is not the same for all the CRSN nodes due to the propagation effects. However, applying the error detection probability will account for the error caused by the propagation effects. Hence, the coverage probability of the sensing signal of a CRSN node within a sensing range R_S of a target over the MQAM Nakagami-q fading channel based on ETA is

Table 7. Simulation parameters.

Parameter	Value
EDHC-SA Energy model parameters	
Network field size	200×200 m^2
Total number of nodes	200
Initial effective energy of CH member	2 J
Number of Cluster	14
Initial effective energy of CH	5 J
Location of sink (BS)	(250, 200)
Data packet size	4000 Bits
EDHC-SA multichannel sensing coverage parameters	
Number of available channels	6
Simulation runs	10,000
Fading type	Nakagami-q
Modulation size	4QAM
SNR	0:18
V_R	1:6

EDHC-SA: energy-efficient distributed heterogeneous clustered spectrum-aware; CH: cluster heads; BS: base station; QAM: quadrature amplitude modulation; SNR: signal-noise-ratio.

$$\bar{P}_{C_{ETA}} = \int_0^{R_{ifs}} \frac{a}{n}\left\{\frac{1}{2}M_\gamma q\left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right)M_\gamma q(-b) + (1-a)\sum_{i-1}^{n-1} M_\gamma q\left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_\gamma q\left(\frac{-b}{s_i}\right)\right\}\left(\frac{3R_{ifs}^2\sqrt{3}}{4}\right)dR_S \tag{27}$$

where $0 \leqslant R_S \leqslant R_{ifs}$. Scaling the coverage probability of sensing signal for the total sensing coverage area A gives

$$\bar{P}_{C_{AETA}} = \frac{1}{A}\int_0^{R_{ifs}} \frac{a}{n}\left\{\frac{1}{2}M_\gamma q\left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right)M_\gamma q(-b) + (1-a)\sum_{i-1}^{n-1} M_\gamma q\left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_\gamma q\left(\frac{-b}{s_i}\right)\right\}\left(\frac{3R_{ifs}^2\sqrt{3}}{4}\right)dR_S \tag{28}$$

Hence, integrating between limits

$$\bar{P}_{C_{AETA}} = \frac{aR_{ifs}^3\sqrt{3}}{4An}\left\{\frac{1}{2}M_\gamma q\left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right)M_\gamma q(-b) + (1-a)\sum_{i-1}^{n-1} M_\gamma q\left(\frac{-b}{s_i}\right) + \sum_{i-1}^{2n-1} M_\gamma q\left(\frac{-b}{s_i}\right)\right\} \tag{29}$$

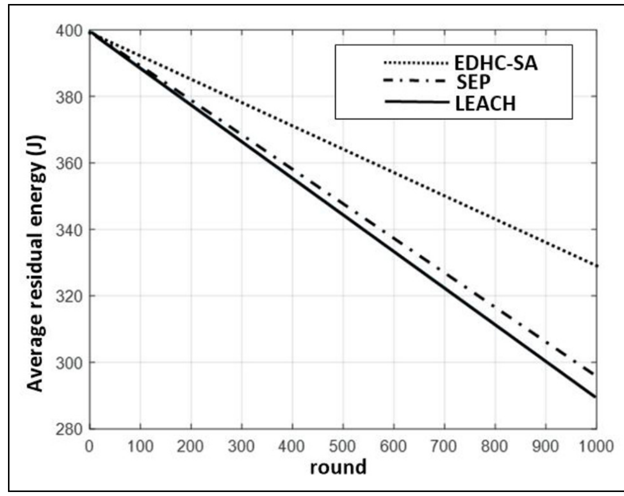

Figure 7. Average residual energy per round for EDHC-SA compared with the existing SEP and LEACH protocol.

Simulation, analysis, and results

In this section, the EDHC-SA energy model and EDHC-SA multichannel sensing coverage model are implemented and evaluated using MATLAB. The EDHC-SA energy model algorithm is run and the results compared with the stable energy protocol (SEP), and the LEACH protocol. The performance efficiency of the proposed energy model is evaluated based on average residual or remaining energy for the sensor nodes. The efficiency of the EDHC-SA multichannel sensing coverage model is tested and the results compared with existing ZigBee sensor network models. The proposed multichannel sensing coverage model is evaluated using the following metrics Coverage error probability or BER, SNR, and latency. Table 7 presents simulations parameters for the models.

Figure 7 shows the energy consumption analysis based on average residual energy per round of the EDHC-SA energy model. This is compared with the existing SEP and LEACH Protocol. The results confirm that the EDHC-SA energy model can effectively do the data aggregation from the sensor node sources to the sink with minimal energy consumption. Figure 7 shows a higher average residual energy than the existing SEP and LEACH energy protocols.

For the EDHC-SA multichannel sensing coverage model, the results in terms of BER with respect to SNR are obtained in two different scenarios. Scenario 1 is shown in Figure 8, and Scenario 2 in Figure 9. Scenario 1 is where all the six channels are available in the EDHC-SA CRSN model. It is compared with the conventional ZigBee WSN in order to obtain the BER and SNR. By inspection of Figure 8, it can be seen that the error rate at a given SNR in the EDHC-SA CRSN model is lower than the error rate in the conventional

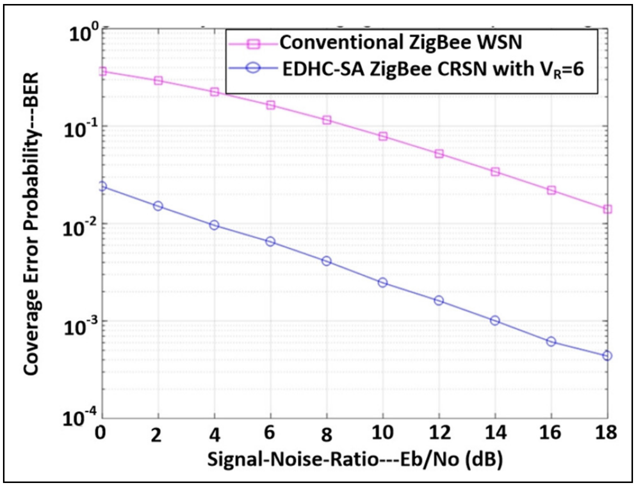

Figure 8. Scenario 1: error probability comparisons of conventional ZigBee WSN and EDHC-SA CRSN.

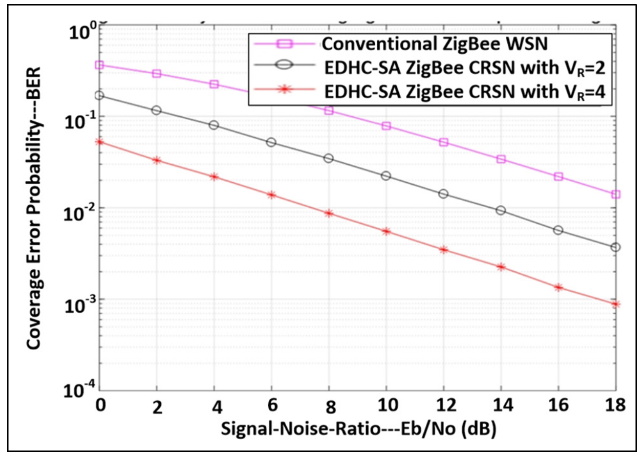

Figure 9. Scenario 2: error probability comparisons of conventional ZigBee WSN and EDHC-SA CRSN with further channel changes.

ZigBee WSN. For example, the EDHC-SA CRSN model exhibits a minimum error rate of approximately 10^{-4} at an SNR of 18 dB and maximum error rate of approximately 10^{-2} at an SNR of 0 dB. The conventional ZigBee WSN exhibit a minimum error rate of approximately 10^{-2} at an SNR of 18 dB and maximum error rate of approximately 10^{-1} at an SNR of 0 dB. This means that the conventional ZigBee WSN encounters more errors in excess of 100% at a given SNR than the EDHC-SA CRSN model.

At a given BER, the EDHC-SA CRSN model has a lower energy per bit-to-noise ratio (E_b/N_o) than the conventional ZigBee WSN. For example, at BER of 10^{-2}, the EDHC-SA CRSN model has an SNR of 4 dB whereas the conventional ZigBee WSN is over 18 dB for the same BER of 10^{-2}. This means that less energy is expended at a given BER in the EDHC-SA CRSN, whereas more energy is consumed in the conventional ZigBee WSN. It is obvious that it will take less energy to accomplish greater sensing coverage and data frame transmission with minimal BER in the EDHC-SA CRSN than in the conventional ZigBee WSN.

The EDHC-SA CRSN model is further simulated with $V_R = 2$ and $V_R = 4$ in order to validate the behavior of the EDHC-SA CRSN model with respect to changes in the ACs. It can be observed that as the ACs increases, the BER reduces, leading to an improvement of the network with increase in ACs. As the ACs reduce, the BER increases. However, in all cases, the EDHC-SA CRSN with opportunistic multichannels access has better sensing coverage than the conventional ZigBee WSN in terms of BER and energy per bit to noise ratio as shown in Figure 9. Therefore, it is easier to reduce the energy consumption of data frame transmission in the EDHC-SA CRSN model by using a lower SNR while simultaneously satisfying a certain minimal BER.

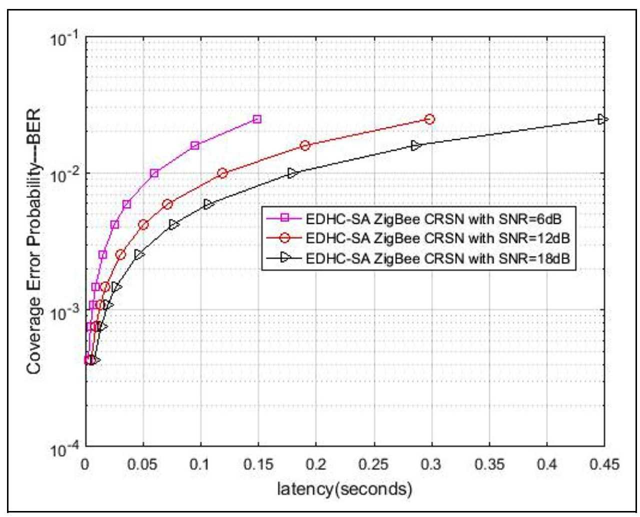

Figure 10. BER relationship with latency at three different SNR values for EDHC-SA CRSN model.

From the simulation results in Figure 9, equation (17) was implemented at a given SNR in order to obtained a relationship of BER with respect to delay as illustrated in Figure 10 for the EDHC-SA CRSN model. From Figure 10, it is obvious that both the SNR and latency reduce as the BER reduces. For example, with SNRs of 18, 12, and 6 dB, it has a maximum latency of 0.44, 0.29, and 0.14 s, respectively. This means that at any given SNR, there is a corresponding decrease in the latency or delay as the BER reduces; and corresponding increase in the latency as the BER increases. Hence, an optimal data frame transmission

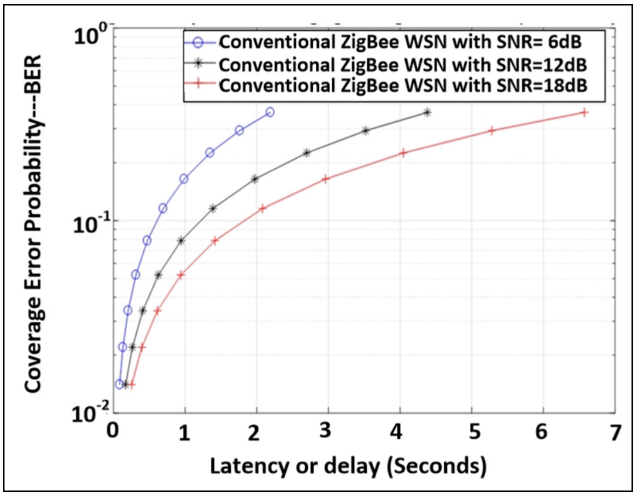

Figure 11. BER relationship with latency at three different SNR values for conventional ZigBee WSN.

can be made at a given SNR with minimal error rate and low latency. Therefore, the EDHC-SA CRSN model satisfies both energy efficiency and latency issues.

From Figure 11, the BER and the latency have the same trend as that of Figure 10, but with a higher error rate and latency at a given SNR. This means that the conventional ZigBee WSN exhibits high latency and is not energy-efficient when compared with the EDHC-SA CRSN model.

Conclusion and future work

In this article, a DHC topology for ZigBee CRSN in an SG has been presented. The potential differences between conventional ZigBee WSN and ZigBee CRSN, when suitable for SG applications, was evaluated. Furthermore, an EDHC-SA model was proposed. The model was supported by providing a novel algorithm called the ETA for guaranteed network connectivity in CRSN-based SGs. A CSMA/CA MAC protocol algorithm for the alternation of data frame transmission of both event-driven and data-driven CRSN nodes was incorporated in order to save the network lifetime. This was the variator mechanism for varying the opportunistic multichannel access with single data frame transmission. The mechanism was implemented with a derived coverage probability for sensing coverage under multi-path fading conditions.

The simulation results confirm that the EDHC-SA CRSN model outperforms existing and conventional ZigBee WSN protocols in terms of BER, end-to-end delay (latency), and energy consumption. The SG applications are mission-critical applications that require low latency for real-time satisfactory sensed data delivery. Thus, the EDHC-SA CRSN model supports heterogeneous CRSNs and spectrum-aware guaranteed network connectivity. This is suitable for harsh SG environmental conditions. The traditional model lacks these capability features for SG applications.

The spectrum-aware cross-layer algorithm framework in the EDHC-SA is mainly based on lower layer communication protocols. Spectrum-aware cross-layer algorithms in the upper communication layer protocols (transport and application layer) of CRSNs in SGs will be an interesting future research area.

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