CHANNEL ACQUISITION AND ROUTING SYSTEM FOR REAL-TIME COGNITIVE RADIO SENSOR NETWORKS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy in (Electrical Engineering)

Faculty of Electrical Engineering
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JANUARY 2015

This thesis is first dedicated to my late beloved father, Alhaji Ismaila Zubair. We lost him while I was in the fifth semester of my PhD work. This thesis is a testimony to his effort of how he prayed and struggled for us to get the best things of both worlds. May Allah ta'aala forgive and have mercy on him. It is also dedicated to my beloved, patient and struggling Mother, Hajiya Zainab Aliyu Zubair. She has always been in the forefront of love, concern, dua, advice and guidance to make sure we achieve the best of both worlds. May Allah preserve her in goodness. Also dedicated to my Thurayyah, my patient, lovely wife, Mariam Bello, that has been a supporting pillar of encouragement, love and dua. May Allah preserve her in goodness. Also to my lovely children, Khadijah Ummu Ammarah, Fatimah Zahrah ummu Hakim and Ibrahim Khalil. I will never forget their support, patience and understanding. May Allah preserve them in goodness. And finally to my lovely and dear Sisters and brothers; Ramatu, Asma'u, Fatimah, Wali, Ismail, Zainab and Abdurahman, for their concern, encouragement and support. May Allah preserve them in goodness and give all, the best of this world and the hereafter.

ACKNOWLEDGEMENT

First, all praise belong to Allah by whose blessings this work was completed. This feat would not have been achieved without the guidance, mercy, forgiveness and subtleness of Allah. The tongue is short of rendering to Him the deserved praises and I seek His forgiveness for this shortfall.

I would like to thank my supervisor Prof. Dr. Norsheila bnt Fisal for not only being a supervisor, but a mother. May Allah reward you in many fold for your patience, support and invaluable advises.

I would also like to thank the Education Trust Fund (ETF) for sponsoring my studies and the Federal University of Technology Minna for their support throughout the course of this study.

I also appreciate the support of all my family members.

This appreciation would not be complete without extending it to all the members of the UTM-MIMOS lab. for being supporting companions.

I would also like to thank the developers of the utmthesis LaTeX project for making the thesis writing process a lot easier for me.

Finally, ***Alhamdu-lillahi-Rabbil-A'lamin***.

Suleiman Zubair, Skudai, Johor

ABSTRACT

The need for efficient spectrum utilization and routing has ignited interest in the Cognitive Radio Sensor Network (CRSN) paradigm among researchers. CRSN ensures efficient spectrum utilization for wireless sensor network. However, the main challenge faced by CRSN users have to deal with is the issue of service quality in terms of interference when using channels and degradation in multi-hop communication. This thesis proposes to overcome the interference due to contention and routing issues through the design of an efficient Channel Acquisition and Reliable routing System (CARS). CARS is designed to reduce carrier sense multiple access contention and enhance routing in CRSNs. CARS comprises of Lightweight Distributed Geographical (LDG), and Reliable Opportunists Routing (ROR) modules. LDG is a medium access control centric; cross-layer designed protocol to acquire a common control channel for signalling to determine the data channel. ROR is a network-centric cross-layer designed protocol to decide on a path for routing data packets. The result shows that LDG significantly reduces the overhead of media access contention and energy cost by at an average of 70% and 80% respectively compared to other approaches that use common control channel acquisition like Efficient Recovery Control Channel (ERCC) protocol. In addition, LDG achieves a 16.3% boost in the time to rendezvous on the control channel above ERCC and a 36.9% boost above Coordinated Channel Hopping (CCH) protocol. On the other hand, the virtual clustering framework inspired by ROR has further improved network performance. The proposed ROR significantly increases packet received at the sink node by an average of over 20%, reduces end-to-end latency by an average of 37% and minimizes energy consumption by an average of 22% as compared to Spectrum-aware Clustering for Efficient Multimedia routing (SCEEM) protocol. In brief, the design of CARS which takes the intrinsic characteristics of CRSNs into consideration helps to significantly reduce the energy needed for securing a control channel and to guarantee that end-to-end, real-time conditions are preserved in terms of latency and media content. Thus, LDG and ROR are highly recommended for real-time data transmission such as multimedia data transfer in CRSN.

ABSTRAK

Keperluan untuk penggunaan spektrum dan laluan yang cekap telah menyuntik minat di kalangan para penyelidik dalam paradigma CRSN. Rangkaian peranti Pengesan Radio Kognitif (CRSN) memastikan penggunaan spektrum yang cekap untuk rangkaian peranti pengesan tanpa wayar. Tetapi, cabaran utama yang dihadapi oleh pengguna-pengguna CRSN adalah isu kualiti perkhidmatan daripada segi gangguan apabila menggunakan saluran dan kemerosotan dalam komunikasi multi-hop. Tesis ini dikemukakan untuk mengatasi gangguan yang disebabkan oleh isu-isu pertembungan dan laluan melalui reka bentuk satu Sistem Pemerolehan saluran dan Laluan yang cekap dan Boleh Dipercayai (CARS). CARS direka untuk mengurangkan pertembungan capaian berbilang penderiaan pembawa dan meningkatkan laluan dalam CRSNs. CARS terdiri daripada modul-modul Geografi Ringan Teragih (LDG), dan laluan Oportunis yang Boleh Dipercayai (ROR). LDG adalah kawalan capaian perantara yang berpusat; reka bentuk protokol lapisan-rentas untuk mendapatkan saluran kawalan sepunya sebagai pengisyaratan bagi menentukan saluran data. ROR adalah reka bentuk protokol lapisan-rentas rangkaian berpusat untuk membuat keputusan mengenai laluan untuk paket-paket data. Keputusan menunjukkan LDG dengan ketaranya mengurangkan overhed bagi pertembungan kawalan capaian perantara dan kos tenaga dengan nilai purata masing-masing 70% dan 80% berbanding pendekatan lain yang menggunakan pemerolehan saluran kawalan sepunya seperti protokol Pemulihan Saluran Kawalan yang Cekap (ERCC). Di samping itu, LDG mencapai 16.3% peningkatan dalam masa untuk bertemu di saluran kawalan mengatasi ERCC dan 36.9% peningkatan mengatasi protokol Lompatan Saluran Terkoordinat (CCH). Sebaliknya, rangka kerja kelompok maya yang diilhamkan oleh ROR telah meningkatkan lagi prestasi rangkaian. ROR yang dicadangkan dengan ketaranya telah meningkatkan paket yang diterima pada nod sink dengan purata melebihi 20%, mengurangkan pendaman hujung-ke-hujung secara purata sebanyak 37% dan mengurangkan penggunaan tenaga secara purata sebanyak 22% berbanding dengan protokol Kelompok Spektrum-sedar untuk Laluan Multimedia Berkesan (SCEEM). Ringkasnya, reka bentuk CARS yang mengambil kira ciri-ciri intrinsik CRSNs membantu mengurangkan tenaga yang diperlukan secara berkesan bagi memperolehi satu saluran kawalan dan memberi jaminan bahawa hujung-ke-hujung, keadaan masa sebenar dipelihara daripada segi pendaman dan kandungan media. Oleh itu, LDG dan ROR adalah sangat disyorkan untuk penghantaran data masa sebenar seperti pemindahan data multimedia dalam CRSN.

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LIST OF ABBREVIATIONS

ACK	–	Acknowledgement
AODV	–	Ad Hoc On-Demand Distance Vector
A-POMDP	–	Approximated Partially Observable Markov Decision Process
AWGN	–	Additive White Gaussian Noise
BE	–	Best Effort
CA	–	Channel Availability
CBR	–	Constant Bit Rate
CMs	–	Cluster Members
CC	–	Cluster Common Channel
CCC	–	Common Control Channel
CCH	–	Coordinated Channel Hopping
CCL	–	Control Channel Update List
CH	–	Cluster Head
CL	–	Channel List
CLA	–	Channel Learning Algorithm
CR	–	Cognitive Radio
CRAHN	–	Cognitive Radio Ad Hoc Network
CRP	–	a Routing Protocol for Cognitive Radio Ad Hoc Networks
CRSN	–	Cognitive Radio Sensor Networks
CSMA/CA	–	Carrier-Sense Multiple Access with Collision Avoidance
DBMR	–	Distributed Best-Route Selection for Multipath Routing
DC	–	Duty Cycle
DCCC	–	Dedicated Common Control Channel
DSA	–	Dynamic Spectrum Access
ECR	–	Energy- and Cognitive-Radio-Aware Routing
ERCC	–	Efficient Recovery Control Channel
FCC	–	Federal Communications Commission
FF	–	Flooded Forward Ant Routing

FFT – Flooded Piggyback Ant Routing
FSMC – Finite-State Markov Chain
HMA – Homogeneous Spatial Spectral Area
HMM – Hidden Markov Model
HTA – Heterogeneous Spatial Spectral Area
IEEE – Institute of Electrical and Electronics Engineers
IoT – Internet of Things
ISM – Industrial, Scientific and Medical
LDG – Lightweight Distributed Geographical
LL – Link Layer
LMR – Local Minimum Resolution
MAC – Medium Access Control
MADM – Multiple Attribute Decision Making
MCF – Message-Initiated Constrained Flooding
MCT – Adaptive Spanning Tree Meta-Strategy Routing
MGT – Modified Game Theory
NAD – Network Area Discovery
OFDM – Orthogonal Frequency-Division Multiplexing
ORTPC – Opportunistic Routing With Transmit Power Control
OSA – Opportunistic Spectrum Access
OSDRP – Opportunistic Service Differentiation Routing Protocol
PDA – Personal Digital Assistant
PRP – Probabilistic Routing Protocol Based on Priori Information
Prowler – Probabilistic Wireless Network Simulator
PS – Periodic Frequency Switching
PU – Primary User
QoE – Quality of Experience
QoS – Quality of Service
RBRD – Reverse Backoff and Representative Drop
RMASE – Routing Modeling Application Simulation Environment
RNV – Receiver Noise Variance
ROR – Reliable Opportunistic Routing
RREP – Route Reply
RREQ – Route Request
RTLD – Real-Time Load Distribution Routing Protocol

rts – request to send

SCA – Scan Ant Routing

SCEEM – Spectrum-aware Clustering for Efficient Multimedia Routing in Cognitive Radio Sensor Networks

SER – Spectrum and Energy-Aware Routing

SIFS – Short Inter-Frame Space

SINR – Signal Interference Noise Ratio

SN – Sensor Networks

SNR – Signal to Noise Ratio

SOPs – Spectrum Opportunities

SU – Secondary User

TDMA – Time Division Multiple Access

TS – Triggered Switching

TTR – Time To Rendezvous

TV – Television

UNII – Unlicensed National Information Infrastructure

VC – Virtual Contention

VCG – Virtual Contention Group

VIF – VCG based Initiative Determination Forwarding

WiMAX – Worldwide Interoperability for Microwave Access

WPANs – Wireless Personal Area Networks

WSN – Wireless Sensor Networks

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LIST OF SYMBOLS

ι – Channel access delay gets to a limit

δ – DC parameter

ρ – Density

α – Fading model parameter

γ – Interference level

τ_{off} – Probability of channel switching to OFF state

τ_{on} – Probability of channel switching to ON state

λ_{pu} – Decision threshold

$A(d\psi)$ – Probability that there is a node inside the area

ξ_{th} – Signal-to-noise ratio threshold

$\hbar_{sk},$ – Distance from node to sink

ω_h – Assigned weights for the hop count

ω_s – Assigned weights for the channel switching count

ϑ – Network traffic

τ_{cs} – Period for sensing the carrier

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CHAPTER 1

INTRODUCTION

1.1 Background

The need for efficient spectrum utilization has recently brought about the new paradigm of *cognitive radio sensor networks* (CRSNs) [4]. The two major drives toward this paradigm are the underutilization of the spectrum below 3 GHz and the congestion problem in both licensed and unlicensed bands. As challenging as this paradigm may appear, the effort of recent studies such as [1, 5] are gradually making this paradigm a reality.

Meanwhile, as the world gradually develops into an *internet of things* (IoT), the ubiquity of *wireless sensor networks* (WSNs) is accordingly becoming imperative. As a result, this further complicates the issue of the congestion of the *industrial, scientific and medical* (ISM) spectrum and the *unlicensed national information infrastructure* (UNII), as evidenced by [6, 7, 8]. Notwithstanding the predicted ubiquity of WSNs, other wireless systems such as WiMAX, Bluetooth and Wi-Fi also operate in these bands, along with cordless phones and microwaves. The normal IEEE 802.15.4 standard defines sixteen channels, each with a bandwidth of 2 MHz, in the 2.4-GHz ISM band, among which only four are not overlapping with the IEEE 802.11 22-MHz bandwidth channels. If the Wi-Fi deployment uses channels other than 1, 6 and 11, then overlapping will occur. Furthermore, a recent and practical study performed on the co-existence issue showed that, in reality, only three of these channels are actually non-overlapping [9]. In extreme cases where all networks, for example, medical sensor networks, security networks, disaster communications, PDAs, Bluetooth devices and many more applications envisioned in the very near future, compete for these three channels, the congestion issue becomes more urgent. The authors of [10] and [11] have shown that IEEE 802.11 degrades the performance of 802.15.4 when they operate in overlapping bands, and in [9] a highly variable IEEE 804.15.4 performance drop of approximately 41% was demonstrated. Furthermore, as computing/networking heads toward ubiquity, various WSNs will form a great percentage of this phenomenon. The concept of CRSN aims to address this spectrum utilization challenge by offering sensor nodes temporary usage of vacant *primary user* (PU) spectra via *dynamic spectrum access* (DSA) with the condition that they will vacate that spectrum once the presence of the incumbent is detected [1].

With the successful implementation of DSA via *cognitive radio* (CR), other advantages are exploited by the WSN. The most enticing of these advantages are that the node energy can be significantly conserved by the reduction of collisions, which invariably results in the reduction of retransmission of lost packets. Energy conservation can also be achieved by employing nodes that dynamically change their transmission parameters to suit channel characteristics, thus providing full management control of these valuable resources. This practice, in effect, can also enable the coexistence of various WSNs deployed in a spatially overlapping area in terms of communication and resource utilization [1].

Notwithstanding the potential of this concept, the CRSN comes with its own unique challenges. For example, the practical development/implementation of a CR sensor node is still an unsolved issue. Additionally, because the DSA characteristic affects the entire communication framework of a conventional WSN [1], previous protocols proposed for classical WSNs cannot be directly applied to a CRSN, nor can the communication protocols for ad-hoc networks perfectly fit this context due to the resource constraints. Incorporating the idea of DSA into a WSN changes not only the MAC and PHY layers, but also affects all of the communication. However, the fact that WSNs still remain the launch pad for protocol design in CRSNs necessitates a performance study of WSN routing strategies vis-à-vis CRSN requirements [1, 12, 13]. Thus, there is a need for specially adapted communication protocols to fulfill the needs of both DSA and WSNs in a CR context.

Alongside the aforementioned, the increase in demand for more data content that satisfies the end user has made the transfer of multimedia across wireless links a major issue. This has specifically given birth to a new evaluation metric called quality of experience (QoE) [9, 13] which is a more customer centric metric unlike the quality of service (QoS) metric which is vendor centric. Most works in wireless multimedia networks often utilize only the QoS metric because of the low data rate characterised with Sensor networks. However, recent trends has shown the need for more data content at the sink to make analysis and corresponding action more accurate especially in emergency or critical mission situations. Thus guaranteeing both QoS and QoE in light of the spectrum congestion discussed above becomes an urgent issue in communication multimedia data packets over WSNs.

The network layer which offers routing services is fundamental in any network and is significantly affected by the dynamic radio environment created by CR because it addresses the peer-to-peer delivery through other nodes in a multi-hop fashion to the correct recipients in due time. The sending node must address both its dynamic radio environment and that of the next hop node. This phenomenon is otherwise referred to as the *deafness problem* and introduces a challenging scenario requiring innovative algorithms that consider the intrinsic nature of the sensor nodes. Although the *deafness problem* is local to the media access control (MAC) layer, it is fundamental to note that the deafness issue has introduced unique issues across all communication layers [2]. For example, any routing protocol in CR networks is dependent on a *common control channel* (CCC) for neighbour discovery, transmitter-receiver handshake, topology change and channel access negotiation which are the major facilitating components of any routing protocol. Hence, the design of any routing protocol for CRSNs has to be done in line with the underlying CCC establishment scheme in mind because the effectiveness of the latter defines how efficient the former will be. During routing operation, the deafness problem is usually solved by assuming the availability of a dedicated common control channel, or a separate design for a common control channel is made [2].

At this point, it is pertinent to acknowledge that a number of researchers have proposed common control channel design schemes [14] and routing schemes for cognitive radio ad-hoc networks [15, 16]. However, due to the differences in constraints between classical ad-hoc networks and WSNs, these solutions cannot be directly imported to solve the problem of routing in CRSNs [1]. In addition, the issue of reliable routing in all cognitive radio ad-hoc network (CRAHN) is still an open issue which needs to be looked into [15, 17].

Based on our studies, specific attention has not been given to the two areas, namely; control channel design and reliable routing as it relates to the network layer of CRSNs. Hence, there is the need for urgent research effort to focus on these areas.

1.2 Problem Statement

In order to effectively route real-time packets over CRSN in emergency or mission critical situations, two fundamental issues have to be addressed, namely; (i) how timely the nodes can acquire a common control channel for control signalling and (ii) how the most reliable route to the sink can be established. In line with these issues, the problem statement of this work are as follows;

- Unlike classical sensor networks in which sensor deployment is pre-planned and resources are allocated only after the deployment field is evaluated, the CR paradigm introduces the *deafness* issue which is a lack of common coordination amongst communicating nodes. Likewise, from the perspective of CRSN, proposed common control channel (CCC) designs for classical CRAHNs are characterised as too heavy in terms of communication and energy overhead. Hence, there is the need for a unique common control channel design for CRSN that takes into consideration, the unique characteristics of CRSN. Specifically, such a design should be characterised as lightweight in terms of communication and energy cost of securing the control channel at a considerable time refereed to as time to rendezvous (TTR). Thus, while considering the unique resource restrains of CRSN, what is the best way of implementing control channel acquisition that ensures network wide connectivity while reducing communication and energy cost at a considerable time refereed to as time to rendezvous (TTR)?
- In addition to the above, based on joint route and spectrum selection geographical forwarding schemes, in searching for the next hop node selection in CRSN, the choice between two criteria usually arise: (i) the stipulation of the closest node to the transmitting node criterion; or (ii) the stipulation of the closest node to the sink criterion. Although the choice of the first criteria has the capability of assuring node-to-node quality links, it cannot be classified as an efficient solution for resource-constrained CRSN, because, this means a greater number of hops will be required to transmit a packet to the sink. The implications of this choice include amplified end-to-end delays and additional energy incurred for the multiple hop-to-hop communication to the sink. On the other hand, if the closest node to the sink criterion is made, which is the typical greedy forwarding scenario, the existence of unreliable links, which is referred to as the *weakest link* problem, is encountered. For this strategy, at each hop, the neighbors that are closest to the destination (also likely to be farthest from the forwarding node) may have poor links with the current node. These “weak links“ will usually

result in a high rate of packet drops, resulting in drastic reduction of the delivery rate or increased energy wastage if re-transmissions are employed. Thus, the question arises: in order to ensure real-time conditions, what is an efficient and reliable way of implementing geographical forwarding for CRSNs?

1.3 Objectives of the Thesis

The main objective of the thesis is to develop an efficient framework that can ensure quality of service in CRSNs. The specific objectives of the work include:

- To develop a channel acquisition protocol in the MAC layer to ensure an efficient channel selection.
- To develop a routing protocol for CRSN that is able to ensure QoS in multi-hop communication.

The two protocols are carefully designed for a single system which is refereed to as *channel acquisition and routing system* (CARS). In this case, the fundamental real-time metrics that will direct this design will be towards reducing contention due to packet collision, ensuring reliable links, reducing packet loss, reducing end-to-end delay and energy consumption.

1.4 Scope of the Thesis

The work is divided into two parts, firstly, the control channel acquisition and secondly, routing having functions that primarily reside in the MAC layer and the Network layer respectively. A major point of significance is, since geographic forwarding schemes are usually the scheme of choice in WSNs and CRAHNs because of their simplicity and scalability, the presented protocols are designed for *lossy link* aware geographic forwarding schemes [18, 19]. In addition, all nodes are assumed to be stationary.

For the design of the CCC, the considered communication layers shall be restricted to the medium access control (MAC) and link layer for real-time applications. In the link layer, a CR based on dynamic spectrum access is employed to mitigate the congestion issue in ISM band. While at the MAC, the acquisition protocol will be addressed. Although, the control channel acquisition protocol shall be MAC centric, identification of local minima nodes which is a crucial issue for simplifying routing at the network layer shall be considered in the design. In geographical forwarding schemes, a node is said to be local minima when it cannot directly reach the sink or it is the only node closest to the sink with respect to its neighbours. Furthermore, while adhering to relevant IEEE 802.15.4 standard, the physical medium is accessed through a modified carrier sense multiple access with collision avoidance (CSMA/CA) protocol.

For the routing protocol, the protocol will consider application layer rate stipulation for route search. Also, same as in the CCC protocol, while adhering to relevant IEEE standard 802.15.4, the physical medium is accessed through a modified carrier sense multiple access with collision avoidance (CSMA/CA) protocol. The probabilistic wireless network simulator (PROWLER) will be used for designing the protocols. Finally, resulting solutions shall be evaluated and compared with previous works mathematically and through simulation.

1.5 Research Contributions

With respect to the aforementioned issues, the main contribution of the *channel acquisition and routing system* (CARS) presented in this work are as follows:

The development of the proposed *lightweight distributed geographical* (LDG) protocol, which is an efficient protocol for acquiring CCC in CRSN. LDG is a distributed channel selection algorithm for geographical forwarding in multimedia CRSNs to simplify channel selection overhead for the dynamic spectral nature of CR environment. In addition to LDG being a novel algorithm for dynamic virtual clustering in CRSN, it is also the first approach that leverages multichannel MAC on location awareness to further simplify geographical forwarding schemes. This contribution is fully documented in the Chapter 3.

The development of a proposed *reliable opportunistic routing* (ROR) protocol for geographical forwarding cognitive radio sensor networks using virtual clusters. The applicability of ROR is not restricted to CRSN alone; rather, it extends to CRAHNs generally. This is because, the need of implementing reliable data transfer in cognitive radio ad-hoc networks is still an open issue in the research community. Previously proposed protocols for routing in cognitive radio ad-hoc routing favorably use the common control channel to negotiate a communication channel which are usually selected based on the primary user activity and channel interference metrics. However, this does not adequately address the issue of reliability in the presence of lossy links, which is best addressed if choice of the next hop is made at the point of data transfer when the common *weak link* issue is considered. In this respect, ROR is a novel geographical forwarding technique that does not restrict the choice of the next hop to the nodes in the selected route. This is achieved by the creation of virtual clusters based on spectrum correlation around the nodes in the chosen route of the *ad hoc on-demand distance vector* (AODV) based route reply operation. Thus during data-transfer phase, the next hop is chosen from the virtual cluster members based on the best link that makes the most progress to the sink. The design which considers the resource constrained nature of CRSN nodes maximizes the use of idle listening and receiver contention prioritization for energy efficiency, avoidance of routing hot spots and stability. The validation result, which closely follows the simulation result, shows that the developed scheme can make more advancement to the sink as against the usual decisions of the AODV route select operation, while ensuring channel quality. Further simulation results show the enhanced reliability, lower latency and energy efficiency of the ROR scheme when compared to recent relevant proposals. This makes ROR the first *lossy link* aware geographical forwarding scheme for CRSNs that is able to service real time applications.

1.6 Significance of the Research

Ensuring reliability in cognitive radio based networks has been a pressing open issue of research. The ROR strategy can guarantee an effective implementation of reliable communication in industrial networks, smart-grid networks, medical networks, emergency and critical mission situations. Apart from its simplicity, it also lays a foundation for future improvements in reliable multi-hop routing in CR based communication and internet of things (IoT).

Furthermore, the LDG protocol has the capacity of greatly simplifying cognitive radio based communication managements. For example, in vehicular ad-hoc networks (VANETs), this is possible in that the protocol can help a vehicle maintain a reliable control channel with dynamic neighbours on real-time basis. Likewise, the routing protocol can greatly reduce the deployment cost of CRSN in industrial networks and can make smart grid communication more reliable. Finally, the energy conservation centric design principle adopted in the protocols readily finds a place for encouraging green communication.

1.7 Thesis Outline

This thesis consists of six chapters that are organized as follows:

Chapter 2 studies and reviews the background knowledge and previous works related to this research. It presents a quantitative analysis of the WSN routing strategy vis-à-vis CRSN environment in order to clearly present the research gaps in terms of routing in CRSN. In this respect, the work presents the first performance evaluation of WSN routing strategies in a cognitive radio environment and lays a proper analytical reason for developing CRSN routing solutions and to establish a basis for future work in this area [20]. Then, a critical review of relevant literature with respect to CCC design and routing in CRSN. Finally, reviewed literature were systematically categorised and the most relevant works were critically discussed vis-à-vis the proposed works in each case.

Chapter 3, presents an overview of the proposed system model used throughout the thesis and the methodology used in achieving the outlined objectives. First, the design concept of CARS which consist of LDG and ROR is explicitly presented. For each protocol, all functional modules are discussed with their functions along with relevant state diagrams. The network model considered in the development was then mentioned and finally, the major performance metrics investigated throughout the work were outlined.

Chapter 4 proposes the LDG protocol for acquisition of a efficient channel that can be used for control signalling in a CRSN. All operational components of LDG along with an all-inclusive implementation method are first presented. A cross-layer mathematical formulation of LDG is then presented. Afterwards, the performance evaluation results of LDG which includes, best operating values for LDG, effect on MAC layer collisions, effect on time to rendezvous and comparison results with similar protocols were presented.

Chapter 5 proposes the ROR protocol to ensure reliable routing in CRSNs. The operational building blocks are presented alongside appropriate in-depth discussions to make clear the adopted strategies. It also presents a detailed simulation study of ROR and explains how the results were gotten. It then discusses the performance evaluation of ROR and compares ROR performance with the SCEEM [21, 22] protocol. Finally, another variant of ROR which is specifically adapted for providing streaming service in a CRSN is presented.

Chapter 6 summarizes the thesis, re-stating the contributions, and suggests directions for future research.

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