

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

SULEIMAN ZUBAIR

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Universiti Teknologi Malaysia

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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.

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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-rintas untuk mendapatkan saluran kawalan sepunya sebagai pengisyratan bagi menentukan saluran data. ROR adalah reka bentuk protokol lapisan-rintas 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 memperoleh 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 Prior 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
	–	

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
\tilde{h}_{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 referred to as time to rendezvous (TTR). Thus, while considering the unique resource restraints 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 referred 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 referred 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.

REFERENCES

1. Akan, O. B., Karli, O. and Ergul, O. Cognitive radio sensor networks. *IEEE Network*, 2009. 23(4): 34–40.
2. Akyildiz, I. F., Lee, W.-Y. and Chowdhury, K. R. CRAHNs: Cognitive radio ad hoc networks. *Ad Hoc Networks*, 2009. 7(5): 810–836.
3. Vuran, M. C. and Akyildiz, I. F. XLP: A cross-layer protocol for efficient communication in wireless sensor networks. *IEEE Transactions on Mobile Computing*, 2010. 9(11): 1578–1591.
4. Commission, F. C. *et al.* Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies. *Et docket*, 2003. (03-108): 05–57.
5. Wang, B. and Liu, K. R. Advances in cognitive radio networks: A survey. *IEEE Journal of Selected Topics in Signal Processing*, 2011. 5(1): 5–23.
6. Ma, C., He, J., Chen, H.-H. and Tang, Z. Coverage overlapping problems in applications of IEEE 802.15. 4 wireless sensor networks. *2013 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2013. 4364–4369.
7. Shin, S. Y. Throughput analysis of IEEE 802.15. 4 network under IEEE 802.11 network interference. *AEU-International Journal of Electronics and Communications*, 2013. 67(8): 686–689.
8. Yuan, W., Wang, X., Linnartz, J.-P. M. and Niemegeers, I. G. Coexistence performance of IEEE 802.15. 4 wireless sensor networks under IEEE 802.11 b/g interference. *Wireless Personal Communications*, 2013. 68(2): 281–302.
9. Garroppo, R. G., Gazzarrini, L., Giordano, S. and Tavanti, L. Experimental assessment of the coexistence of Wi-Fi, ZigBee, and Bluetooth devices. *2011 IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE. 2011. 1–9.
10. Pollin, S., Tan, I., Hodge, B., Chun, C. and Bahl, A. Harmful coexistence between 802.15. 4 and 802.11: A measurement-based study. *3rd International Conference on Cognitive Radio Oriented Wireless Networks*

- and Communications, 2008. CrownCom 2008. IEEE. 2008. 1–6.*
11. Haron, M. A., Syed-Yusof, S., Faisal, N., Syed-Arifin, S. and Abdallah, A. Performance study of the coexistence of wireless sensor networks (WSN) and Wireless Local Area Networks (WLAN). *Second Asia International Conference on Modeling & Simulation, 2008. AICMS 08. IEEE. 2008. 475–479.*
 12. Bicen, A. O. and Akan, O. B. Reliability and congestion control in cognitive radio sensor networks. *Ad Hoc Networks*, 2011. 9(7): 1154–1164.
 13. Bicen, A. O., Gungor, V. C. and Akan, O. B. Delay-sensitive and multimedia communication in cognitive radio sensor networks. *Ad Hoc Networks*, 2012. 10(5): 816–830.
 14. Lo, B. F. A survey of common control channel design in cognitive radio networks. *Physical Communication*, 2011. 4(1): 26–39.
 15. Cesana, M., Cuomo, F. and Ekici, E. Routing in cognitive radio networks: Challenges and solutions. *Ad Hoc Networks*, 2011. 9(3): 228–248.
 16. Boukerche, A., Turgut, B., Aydin, N., Ahmad, M. Z., Bölöni, L. and Turgut, D. Routing protocols in ad hoc networks: A survey. *Computer Networks*, 2011. 55(13): 3032–3080.
 17. How, K. C., Ma, M. and Qin, Y. Routing and QoS provisioning in cognitive radio networks. *Computer Networks*, 2011. 55(1): 330–342.
 18. Zorzi, M. and Rao, R. R. Geographic random forwarding (GeRaF) for ad hoc and sensor networks: multihop performance. *IEEE Transactions on Mobile Computing*, 2003. 2(4): 337–348.
 19. Zuniga, M. and Krishnamachari, B. Analyzing the transitional region in low power wireless links. *First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. IEEE. 2004. 517–526.*
 20. Zubair, S., Faisal, N., Baguda, Y. S. and Saleem, K. Assessing routing strategies for cognitive radio sensor networks. *Sensors*, 2013. 13(10): 13005–13038.
 21. Shah, G. A. and Akan, O. B. Spectrum-aware cluster-based routing for cognitive radio sensor networks. *2013 IEEE International Conference on Communications (ICC). IEEE. 2013. 2885–2889.*
 22. Shah, G., Alagoz, F., Fadel, E. and Akan, O. A Spectrum-Aware Clustering for Efficient Multimedia Routing in Cognitive Radio Sensor Networks. *IEEE*

- Transactions on Vehicular Technology*, 2013.
23. Xu, N. A survey of sensor network applications. *IEEE Communications Magazine*, 2002. 40(8): 102–114.
 24. Pavai, K., Sivagami, A. and Sridharan, D. Study of routing protocols in wireless sensor networks. *International Conference on Advances in Computing, Control, & Telecommunication Technologies, 2009. ACT'09*. IEEE. 2009. 522–525.
 25. Cavalcanti, D., Schmitt, R. and Soomro, A. Achieving energy efficiency and QoS for low-rate applications with 802.11 e. *IEEE Wireless Communications and Networking Conference, 2007. WCNC 2007*. IEEE. 2007. 2143–2148.
 26. Howitt, I. and Gutierrez, J. A. IEEE 802.15. 4 low rate-wireless personal area network coexistence issues. *2003 IEEE Wireless Communications and Networking, 2003. WCNC 2003*. IEEE. 2003, vol. 3. 1481–1486.
 27. Zhou, G., Stankovic, J. A. and Son, S. H. Crowded spectrum in wireless sensor networks. *IEEE EmNets*, 2006. 6.
 28. Cavalcanti, D., Das, S., Wang, J. and Challapali, K. Cognitive radio based wireless sensor networks. *Proceedings of 17th International Conference on Computer Communications and Networks, 2008. ICCCN'08*. IEEE. 2008. 1–6.
 29. Shah, G. A. and Akan, O. B. Performance analysis of CSMA-based opportunistic medium access protocol in cognitive radio sensor networks. *Ad Hoc Networks*, 2013.
 30. Vijay, G., Bdira, E. and Ibnkahla, M. Cognitive approaches in wireless sensor networks: a survey. *25th Biennial Symposium on Communications (QBSC), 2010*. IEEE. 2010. 177–180.
 31. Vijay, G., Ben Ali Bdira, E. and Ibnkahla, M. Cognition in wireless sensor networks: A perspective. *IEEE Sensors Journal*, 2011. 11(3): 582–592.
 32. Saleem, K., Fisal, N., Baharudin, M. A., Ahmed, A. A., Hafizah, S. and Kamilah, S. Ant colony inspired self-optimized routing protocol based on cross layer architecture for wireless sensor networks. *WSEAS Transactions on Communications*, 2010. 9(10): 669–678.
 33. Ahmed, A. A. and Fisal, N. F. Secure real-time routing protocol with load distribution in wireless sensor networks. *Security and Communication Networks*, 2011. 4(8): 839–869.
 34. Glatz, P. M., Hormann, L., Steger, C. and Weiss, R. Implementing

- autonomous network coding for wireless sensor network applications. *18th International Conference on Telecommunications (ICT), 2011*. IEEE. 2011. 9–14.
35. Vuran, M. C., Gungor, V. C. and Akan, O. B. On the interdependency of congestion and contention in wireless sensor networks. *Proc. SENMETRICS05*. 2005. 136–147.
 36. Salim, S. and Moh, S. On-demand routing protocols for cognitive radio ad hoc networks. *EURASIP Journal on Wireless Communications and Networking*, 2013. 2013(1): 1–10.
 37. Chowdhury, K. R. and Akyildiz, I. F. CRP: A routing protocol for cognitive radio ad hoc networks. *IEEE Journal on Selected Areas in Communications*, 2011. 29(4): 794–804.
 38. Abbagnale, A. and Cuomo, F. Connectivity-driven routing for cognitive radio ad-hoc networks. *7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks (SECON), 2010*. IEEE. 2010. 1–9.
 39. Yick, J., Mukherjee, B. and Ghosal, D. Wireless sensor network survey. *Computer networks*, 2008. 52(12): 2292–2330.
 40. Sreesha, A. A., Somal, S. and Lu, I.-T. Cognitive radio based wireless sensor network architecture for smart grid utility. *2011 IEEE Long Island Systems, Applications and Technology Conference (LISAT)*. IEEE. 2011. 1–7.
 41. Ma, W., Hu, S. Z., Wang, Y. C. and Zhue, L. Cooperative spectrum sensing in OFDM based on MIMO cognitive radio sensor networks. *5th International Conference on Wireless Communications, Networking and Mobile Computing, 2009. WiCom'09*. IEEE. 2009. 1–4.
 42. Commission, F. C. *et al.* Second Report and Order and Memorandum Opinion and Order, in the matter of unlicensed operation in the TV broadcast bands (ET Docket No. 04-186) and additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz band (ET Docket No. 02-380), FCC 08-260, 2008.
 43. Willkomm, D., Machiraju, S., Bolot, J. and Wolisz, A. Primary users in cellular networks: A large-scale measurement study. *3rd IEEE symposium on New frontiers in dynamic spectrum access networks, 2008. DySPAN 2008*. IEEE. 2008. 1–11.
 44. Bacchus, R. B., Fertner, A. J., Hood, C. S. and Roberson, D. A. Long-term, wide-band spectral monitoring in support of dynamic spectrum access

- networks at the IIT spectrum observatory. *3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008*. IEEE. 2008. 1–10.
45. Akyildiz, I. F., Lee, W.-Y., Vuran, M. C. and Mohanty, S. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey. *Computer Networks*, 2006. 50(13): 2127–2159.
 46. Gao, S., Qian, L. and Vaman, D. R. Distributed energy efficient spectrum access in wireless cognitive radio sensor networks. *IEEE Wireless communications and networking conference, 2008. WCNC 2008*. IEEE. 2008. 1442–1447.
 47. Kumar, K. V., Phani, G. L., Sayeesh, K. V., Chaganty, A. and Murthy, G. R. Two Layered Hierarchical Model for Cognitive Wireless Sensor Networks. In: *Advances in Computing and Communications*. Springer. 19–24. 2011.
 48. Maleki, S., Pandharipande, A. and Leus, G. Energy-efficient distributed spectrum sensing for cognitive sensor networks. *IEEE Sensors Journal*, 2011. 11(3): 565–573.
 49. Khaleel, H., Penna, F., Pastrone, C., Tomasi, R. and Spirito, M. Distributed spectrum sensing and channel selection in opportunistic wireless personal area networks. *Proceedings of the Second International Workshop on Mobile Opportunistic Networking*. ACM. 2010. 185–187.
 50. Zhao, J., Zheng, H. and Yang, G.-H. Distributed coordination in dynamic spectrum allocation networks. *2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005*. IEEE. 2005. 259–268.
 51. Cormio, C. and Chowdhury, K. R. A survey on MAC protocols for cognitive radio networks. *Ad Hoc Networks*, 2009. 7(7): 1315–1329.
 52. Li, X., Wang, D., McNair, J. and Chen, J. Residual energy aware channel assignment in cognitive radio sensor networks. *2011 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2011. 398–403.
 53. Bo, S. and Kesen, C. A Multichannel QoS-MAC Protocol for Two-Layered WMSNs. In: *Mechanical Engineering and Technology*. Springer. 793–801. 2012.
 54. Chowdhury, K. R. and Akyildiz, I. F. OFDM-based common control channel design for cognitive radio ad hoc networks. *IEEE Transactions on Mobile Computing*, 2011. 10(2): 228–238.

55. Kondareddy, Y. R. and Agrawal, P. Synchronized MAC protocol for multi-hop cognitive radio networks. *IEEE International Conference on Communications, 2008. ICC'08*. IEEE. 2008. 3198–3202.
56. Shah, G. A. and Akan, O. B. CSMA-Based Bandwidth Estimation for Cognitive Radio Sensor Networks. *5th International Conference on New Technologies, Mobility and Security (NTMS), 2012*. IEEE. 2012. 1–5.
57. Lee, Y. and Koo, I. A distributed MAC protocol using virtual control channels for CRSNs. *Wireless personal communications*, 2013. 71(2): 1021–1048.
58. Lo, B. F., Akyildiz, I. F. and Al-Dhelaan, A. M. Efficient recovery control channel design in cognitive radio ad hoc networks. *IEEE Transactions on Vehicular Technology*, 2010. 59(9): 4513–4526.
59. Clancy, T. C. Achievable capacity under the interference temperature model. *26th IEEE International Conference on Computer Communications. INFOCOM 2007*. IEEE. 2007. 794–802.
60. Byun, S.-S., Balasingham, I. and Liang, X. Dynamic spectrum allocation in wireless cognitive sensor networks: Improving fairness and energy efficiency. *IEEE 68th Vehicular Technology Conference, 2008. VTC 2008-Fall*. IEEE. 2008. 1–5.
61. Sohn, S. H., Jang, S. J. and Kim, J. M. HMM-based Adaptive Frequency-Hopping Cognitive Radio System to Reduce Interference Time and to Improve Throughput. *KSII Transactions on Internet & Information Systems*, 2010. 4(4).
62. Liang, Z., Feng, S., Zhao, D. and Shen, X. Delay performance analysis for supporting real-time traffic in a cognitive radio sensor network. *IEEE Transactions on Wireless Communications*, 2011. 10(1): 325–335.
63. Hu, F. and Wang, S. Energy detection for spectrum Sensing in cognitive radio sensor network over fading channels. *5th International Conference on Wireless Communications, Networking and Mobile Computing, 2009. WiCom'09*. IEEE. 2009. 1–4.
64. Commission, F. *et al.* Notice of proposed rules (et docket no. 03-237) on termination of proceeding: Interference temperature operation. *Federal Communications Commission, Tech. Rep*, 2007.
65. Sharma, M., Sahoo, A. and Nayak, K. Channel modeling based on interference temperature in underlay cognitive wireless networks. *IEEE International Symposium on Wireless Communication Systems, 2008. ISWCS'08*. IEEE. 2008. 224–228.

66. Tao, Z., Yajuan, Q., Deyun, G., Junqi, D. and Hongke, Z. Hybrid Model Design and Transmission Rate Optimize with Interference Temperature Constraints in Cognitive Radio Sensor Networks. *7th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM), 2011*. IEEE. 2011. 1–4.
67. Zhao, Q., Tong, L., Swami, A. and Chen, Y. Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework. *IEEE Journal on Selected Areas in Communications*, 2007. 25(3): 589–600.
68. Liu, S., Srivastava, R., Koksal, C. E. and Sinha, P. Pushback: A hidden Markov model based scheme for energy efficient data transmission in sensor networks. *Ad Hoc Networks*, 2009. 7(5): 973–986.
69. Liang, Q., Liu, M. and Yuan, D. Channel estimation for opportunistic spectrum access: Uniform and random sensing. *IEEE Transactions on Mobile Computing*, 2012. 11(8): 1304–1316.
70. Liang, Z., Feng, S. and Zhao, D. Supporting Random Real-Time Traffic in a Cognitive Radio Sensor Network. *IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall), 2010*. IEEE. 2010. 1–5.
71. Shenai, K. and Mukhopadhyay, S. Cognitive sensor networks. *26th International Conference on Microelectronics, MIEL 2008*. IEEE. 2008. 315–320.
72. Kyasanur, P. and Vaidya, N. Protocol design challenges for multi-hop dynamic spectrum access networks. *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*. IEEE. 2005. 645–648.
73. Ding, L., Melodia, T., Batalama, S. N., Matyjas, J. D. and Medley, M. J. Cross-layer routing and dynamic spectrum allocation in cognitive radio ad hoc networks. *Vehicular Technology, IEEE Transactions on*, 2010. 59(4): 1969–1979.
74. Wang, Q. and Zheng, H. Route and spectrum selection in dynamic spectrum networks. *IEEE Consumer Communications and Networking Conference (CNCC)*. 2006. 342–346.
75. Oey, C. H., Christian, I. and Moh, S. Energy-and cognitive-radio-aware routing in cognitive radio sensor networks. *International Journal of Distributed Sensor Networks*, 2012. 2012.
76. Kamruzzaman, S., Kim, E., Jeong, D. G. and Jeon, W. S. Energy-aware routing protocol for cognitive radio ad hoc networks. *IET communications*,

2012. 6(14): 2159–2168.
77. Jin, Z. L., Kim, B. S., Guan, D. H. and Cho, J. S. A probabilistic routing protocol based on priori information for cognitive radio sensor networks. *Applied Mechanics and Materials*, 2013. 303: 210–214.
 78. Sun, S., Ju, Y. and Yamao, Y. Overlay cognitive radio OFDM system for 4G cellular networks. *IEEE Wireless Communications*, 2013. 20(2): 68–73.
 79. Sengupta, S. and Subbalakshmi, K. Open research issues in multi-hop cognitive radio networks. *IEEE Communications Magazine*, 2013. 51(4): 168–176.
 80. Gui, L., Zou, S. and Zhong, X. Distributed best-route selection for multipath routing in cognitive radio ad hoc networks. *Electronics Letters*, 2012. 48(25): 1630–1632.
 81. Panahi, N., Rohi, H. O., Payandeh, A. and Haghghi, M. S. Adaptation of LEACH routing protocol to cognitive radio sensor networks. *Sixth International Symposium on Telecommunications (IST), 2012*. IEEE. 2012. 541–547.
 82. Quang, P. T. A., Kim, S.-R. and Kim, D.-S. A throughput-aware routing for distributed industrial cognitive radio sensor networks. *9th IEEE International Workshop on Factory Communication Systems (WFCS), 2012*. IEEE. 2012. 87–90.
 83. Wu, C., Ohzahata, S. and Kato, T. Dynamic channel assignment and routing for cognitive sensor networks. *2012 International Symposium on Wireless Communication Systems (ISWCS)*. IEEE. 2012. 86–90.
 84. Yu, R., Zhang, Y., Yao, W., Song, L. and Xie, S. Spectrum-Aware Routing for Reliable End-to-End Communications in Cognitive Sensor Network. *2010 IEEE Global Telecommunications Conference (GLOBECOM 2010)*. IEEE. 2010. 1–5.
 85. Incel, O. D. A survey on multi-channel communication in wireless sensor networks. *Computer Networks*, 2011. 55(13): 3081–3099.
 86. Ren, P., Wang, Y., Du, Q. and Xu, J. A survey on dynamic spectrum access protocols for distributed cognitive wireless networks. *EURASIP J. Wireless Comm. and Networking*, 2012. 2012: 60.
 87. De Domenico, A., Strinati, E. C. and Di Benedetto, M. A survey on MAC strategies for cognitive radio networks. *IEEE Communications Surveys & Tutorials*, 2012. 14(1): 21–44.

88. Borms, J., Steenhaut, K. and Lemmens, B. Low-overhead dynamic multi-channel mac for wireless sensor networks. In: *Wireless Sensor Networks*. Springer. 81–96. 2010.
89. Ramakrishnan, M. and Ranjan, P. V. Multi channel mac implementation for wireless sensor networks. *International Conference on Advances in Computing, Control, & Telecommunication Technologies, 2009. ACT'09*. IEEE. 2009. 809–813.
90. Incel, O. D., van Hoesel, L., Jansen, P. and Havinga, P. MC-LMAC: A multi-channel MAC protocol for wireless sensor networks. *Ad Hoc Networks*, 2011. 9(1): 73–94.
91. Yu, Q., Chen, J., Fan, Y., Shen, X. and Sun, Y. Multi-channel assignment in wireless sensor networks: A game theoretic approach. *2010 Proceedings IEEE INFOCOM*. IEEE. 2010. 1–9.
92. Su, H. and Zhang, X. Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks. *IEEE Journal on Selected Areas in Communications*, 2008. 26(1): 118–129.
93. Su, H. and Zhang, X. CREAM-MAC: an efficient cognitive radio-enabled multi-channel mac protocol for wireless networks. *2008 International Symposium on a World of Wireless, Mobile and Multimedia Networks, 2008. WoWMoM 2008*. IEEE. 2008. 1–8.
94. Song, H. and Lin, X.-L. An auction-based MAC protocol for cognitive radio networks. *International Journal of Communication Systems*, 2012. 25(12): 1530–1549.
95. Ekbatanifard, G., Monsefi, R., Yaghmaee M, M. H. and Hosseini S, S. A. Queen-MAC: A quorum-based energy-efficient medium access control protocol for wireless sensor networks. *Computer Networks*, 2012. 56(8): 2221–2236.
96. Gupta, A., Gui, C. and Mohapatra, P. Exploiting multi-channel clustering for power efficiency in sensor networks. *First International Conference on Communication System Software and Middleware, 2006. Comsware 2006*. IEEE. 2006. 1–10.
97. Zhou, G., Huang, C., Yan, T., He, T., Stankovic, J. A. and Abdelzaher, T. F. MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks. *Infocom*. 2006, vol. 6. 1–13.
98. Lee, T., Qiao, C., Demirbas, M. and Xu, J. ABC-MC: A new multi-channel geographic forwarding scheme for wireless sensor networks. *Ad Hoc*

- Networks*, 2011. 9(5): 699–712.
99. Rahman, A. and Gburzynski, P. MAC-assisted topology control for ad hoc wireless networks. *International Journal of Communication Systems*, 2006. 19(9): 955–976.
 100. Liu, H., Zhang, B., Zheng, J. and Mouftah, H. T. An energy-efficient localized topology control algorithm for wireless ad hoc and sensor networks. *International Journal of Communication Systems*, 2008. 21(11): 1205–1220.
 101. Khaleel, H., Penna, F., Pastrone, C., Tomasi, R. and Spirito, M. A. Frequency agile wireless sensor networks: design and implementation. *IEEE Sensors Journal*, 2012. 12(5): 1599–1608.
 102. Xu, W., Trappe, W. and Zhang, Y. Channel surfing: defending wireless sensor networks from interference. *Proceedings of the 6th international conference on Information processing in sensor networks*. ACM. 2007. 499–508.
 103. Wu, Y., Stankovic, J. A., He, T. and Lin, S. Realistic and efficient multi-channel communications in wireless sensor networks. *INFOCOM 2008. The 27th IEEE Conference on Computer Communications*. IEEE. 2008.
 104. Liang, C.-J. M. and Terzis, A. Rethinking multi-channel protocols in wireless sensor networks. *Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors*. ACM. 2010. 1.
 105. Campbell, C. E.-A., Loo, K.-K. J., Gemikonakli, O., Khan, S. and Singh, D. Multi-channel distributed coordinated function over single radio in wireless sensor networks. *Sensors*, 2011. 11(1): 964–991.
 106. Arkoulis, S., Spanos, D.-E., Barbounakis, S., Zafeiropoulos, A. and Mitrou, N. Cognitive radio-aided wireless sensor networks for emergency response. *Measurement Science and Technology*, 2010. 21(12): 124002.
 107. Zhang, L. and Lu, W. A Novel Multi-channel MAC Protocol for Cluster Based Wireless Multimedia Sensor Networks. In: *Network Computing and Information Security*. Springer. 696–704. 2012.
 108. Huang, Y.-M., Su, B.-L. and Wang, M.-S. Localized and load-balanced clustering for energy saving in wireless sensor networks. *International Journal of Communication Systems*, 2008. 21(8): 799–814.
 109. Peiravi, A., Mashhadi, H. R. and Hamed Javadi, S. An optimal energy-efficient clustering method in wireless sensor networks using multi-objective genetic algorithm. *International Journal of Communication Systems*, 2013. 26(1): 114–126.

110. Gandhi, R., Wang, C.-C. and Hu, Y. C. Fast rendezvous for multiple clients for cognitive radios using coordinated channel hopping. *9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2012*. IEEE. 2012. 434–442.
111. Kamruzzaman, S., Kim, E. and Jeong, D. G. Spectrum and energy aware routing protocol for cognitive radio ad hoc networks. *2011 IEEE International Conference on Communications (ICC)*. IEEE. 2011. 1–5.
112. Xiao, Y. and Hu, F. *Cognitive radio networks*. CRC press. 2008.
113. Al-Rawi, H. A. and Yau, K.-L. A. Routing in distributed cognitive radio networks: A survey. *Wireless personal communications*, 2013. 69(4): 1983–2020.
114. Woo, A., Tong, T. and Culler, D. Taming the underlying challenges of reliable multihop routing in sensor networks. *Proceedings of the 1st international conference on Embedded networked sensor systems*. ACM. 2003. 14–27.
115. Zhao, J. and Govindan, R. Understanding packet delivery performance in dense wireless sensor networks. *Proceedings of the 1st international conference on Embedded networked sensor systems*. ACM. 2003. 1–13.
116. LaI, D., Manjeshwar, A., Herrmann, F., Uysal-Biyikoglu, E. and Keshavarzian, A. Measurement and characterization of link quality metrics in energy constrained wireless sensor networks. *IEEE Global Telecommunications Conference, 2003. GLOBECOM'03*. IEEE. 2003, vol. 1. 446–452.
117. He, T., Stankovic, J. A., Lu, C. and Abdelzaher, T. SPEED: A stateless protocol for real-time communication in sensor networks. *Proceedings of 23rd International Conference on Distributed Computing Systems, 2003*. IEEE. 2003. 46–55.
118. Misra, S., Reisslein, M. and Xue, G. A survey of multimedia streaming in wireless sensor networks. *IEEE Communications Surveys & Tutorials*, 2008. 10(4): 18–39.
119. Wiegand, T. and Sullivan, G. J. The H. 264/AVC video coding standard. *IEEE Signal Processing Magazine*, 2007. 24(2): 148–153.
120. Cheng, L., Chen, C., Ma, J. and Shu, L. Contention-based geographic forwarding in asynchronous duty-cycled wireless sensor networks. *International Journal of Communication Systems*, 2012. 25(12): 1585–1602.
121. Felemban, E., Lee, C.-G. and Ekici, E. MMSPEED: multipath Multi-SPEED

- protocol for QoS guarantee of reliability and. Timeliness in wireless sensor networks. *IEEE Transactions on Mobile Computing*, 2006. 5(6): 738–754.
122. Huang, H., Hu, G. and Yu, F. Energy-aware geographic routing in wireless sensor networks with anchor nodes. *International Journal of Communication Systems*, 2013. 26(1): 100–113.
 123. Moore, D., Leonard, J., Rus, D. and Teller, S. Robust distributed network localization with noisy range measurements. *Proceedings of the 2nd international conference on Embedded networked sensor systems*. ACM. 2004. 50–61.
 124. Simon, G. Prowler: Probabilistic wireless network simulator. *Institute for Software Integrated Systems, Nashville*, 2003.
 125. Simon, G., Volgyesi, P., Maróti, M. and Lédeczi, Á. Simulation-based optimization of communication protocols for large-scale wireless sensor networks. *IEEE aerospace conference*. 2003, vol. 3.
 126. Digham, F. F., Alouini, M.-S. and Simon, M. K. On the energy detection of unknown signals over fading channels. *IEEE Transactions on Communications*, 2007. 55(1): 21–24.
 127. Lee, W.-Y. and Akyildiz, I. F. Optimal spectrum sensing framework for cognitive radio networks. *IEEE Transactions on Wireless Communications*, 2008. 7(10): 3845–3857.
 128. Wellens, M., Riihijarvi, J. and Mahonen, P. Modelling primary system activity in dynamic spectrum access networks by aggregated on/off-processes. *6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops, 2009. SECON Workshops' 09*. IEEE. 2009. 1–6.
 129. Lien, S.-Y., Tseng, C.-C. and Chen, K.-C. Carrier sensing based multiple access protocols for cognitive radio networks. *IEEE International Conference on Communications, 2008. ICC'08*. IEEE. 2008. 3208–3214.
 130. Sundani, H., Li, H., Devabhaktuni, V. K., Alam, M. and Bhattacharya, P. Wireless sensor network simulators a survey and comparisons. *International Journal of Computer Networks*, 2011. 2(5): 249–265.
 131. Egea-Lopez, E., Vales-Alonso, J., Martinez-Sala, A., Pavon-Marino, P. and García-Haro, J. Simulation tools for wireless sensor networks. *Summer Simulation Multiconference-SPECTS*. 2005, vol. 2005.
 132. Zhang, Y., Simon, G. and Balogh, G. High-level sensor network simulations

- for routing performance evaluations. *Third International Conference on Networked Sensing Systems*. 2006.
133. Zungeru, A. M., Ang, L.-M. and Seng, K. P. Classical and swarm intelligence based routing protocols for wireless sensor networks: A survey and comparison. *Journal of Network and Computer Applications*, 2012. 35(5): 1508–1536.
 134. Ansari, J. and Mähönen, P. Channel selection in spectrum agile and cognitive MAC protocols for wireless sensor networks. *Proceedings of the 8th ACM international workshop on Mobility management and wireless access*. ACM. 2010. 83–90.
 135. Ramirez, D., Vía, J., Santamaria, I., López-Valcarce, R. and Scharf, L. L. Multiantenna spectrum sensing: Detection of spatial correlation among time-series with unknown spectra. *2010 IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP)*. IEEE. 2010. 2954–2957.
 136. Yucek, T. and Arslan, H. Spectrum characterization for opportunistic cognitive radio systems. *IEEE Military Communications Conference, 2006. MILCOM 2006*. IEEE. 2006. 1–6.
 137. Yin, S., Chen, D., Zhang, Q., Liu, M. and Li, S. Mining spectrum usage data: a large-scale spectrum measurement study. *IEEE Transactions on Mobile Computing*, 2012. 11(6): 1033–1046.
 138. Ding, G., Wang, J., Wu, Q., Song, F. and Chen, Y. Spectrum sensing in opportunity-heterogeneous cognitive sensor networks: how to cooperate? *IEEE Sensors Journal*, 2013.
 139. Zhang, Y., Fromherz, M. and Kuhn, L. Rmase: Routing modeling application simulation environment, 2009.
 140. Seada, K., Zuniga, M., Helmy, A. and Krishnamachari, B. Energy-efficient forwarding strategies for geographic routing in lossy wireless sensor networks. *Proceedings of the 2nd international conference on Embedded networked sensor systems*. ACM. 2004. 108–121.
 141. Vuran, M. C., Akan, Ö. B. and Akyildiz, I. F. Spatio-temporal correlation: theory and applications for wireless sensor networks. *Computer Networks*, 2004. 45(3): 245–259.
 142. *Mica2 Datasheet*. URL <http://www.xbow.com>.
 143. Zhang, Y. and Fromherz, M. Message-initiated constraint-based routing for wireless ad-hoc sensor networks. *First IEEE Consumer Communications and*

- Networking Conference, 2004. CCNC 2004.* IEEE. 2004. 648–650.
144. Perkins, C. E. and Royer, E. M. Ad-hoc on-demand distance vector routing. *Second IEEE Workshop on Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA'99.* IEEE. 1999. 90–100.
145. Ahmed, A. A. and Faisal, N. A real-time routing protocol with load distribution in wireless sensor networks. *Computer Communications*, 2008. 31(14): 3190–3203.
146. Zhang, Y., Kuhn, L. D. and Fromherz, M. P. Improvements on ant routing for sensor networks. In: *Ant Colony Optimization and Swarm Intelligence*. Springer. 154–165. 2004.