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An Efficient Multichannel Wireless Sensor Networks MAC Protocol based on IEEE 802.11 Distributed Co-ordinated Function

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Abstract

This research aimed to create new knowledge and pioneer a path in the area relating to future trends in the WSN, by resolving some of the issues at the MAC layer in Wireless Sensor Networks. This work introduced a Multi-channel Distributed Coordinated Function (MC-DCF) which takes advantage of multi-channel assignment. The backoff algorithm of the IEEE 802.11 distributed coordination function (DCF) was modified to invoke channel switching, based on threshold criteria in order to improve the overall throughput for wireless sensor networks.

This work commenced by surveying different protocols: contention-based MAC protocols, transport layer protocols, cross-layered design and multichannel multi-radio assignments. A number of existing protocols were analysed, each attempting to resolve one or more problems faced by the current layers.

The 802.15.4 performed very poorly at high data rate and at long range. Therefore 802.15.4 is not suitable for sensor multimedia or surveillance system with streaming data for future multichannel multi-radio systems.

A survey on 802.11 DCF - which was designed mainly for wireless networks –supports and confirm that it has a power saving mechanism which is used to synchronise nodes. However it uses a random back-off mechanism that cannot provide deterministic upper bounds on channel access delay and as such cannot support real-time traffic. The weaknesses identified by surveying this protocol form the backbone of this thesis

The overall aim for this thesis was to introduce multichannel with single radio as a new paradigm for IEEE 802.11 Distributed Coordinated Function (DCF) in wireless sensor networks (WSNs) that is used in a wide range of applications, from military application, environmental monitoring, medical care, smart buildings and other industry and to extend WSNs with multimedia capability which sense for instance sounds or motion, video sensor which capture video events of interest.

Traditionally WSNs do not need high data rate and throughput, since events are normally captured periodically. With the paradigm shift in technology, multimedia streaming has become more demanding than data sensing applications as such the need for high data rate protocol for WSN which is an emerging technology in this area. The IEEE 802.11 can support data rates up to 54Mbps and 802.11 DCF was designed specifically for use in wireless networks.

This thesis focused on designing an algorithm that applied multichannel to IEEE 802.11 DCF back-off algorithm to reduce the waiting time of a node and increase throughput when attempting to access the medium. Data collection in WSN tends to suffer from heavy congestion especially nodes nearer to the sink node. Therefore, this thesis proposes a contention based MAC protocol to address this problem from the inspiration of the 802.11 DCF backoff algorithm resulting from a comparison of IEEE 802.11 and IEEE 802.15.4 for Future Green Multichannel Multi-radio Wireless Sensor Networks.

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To the most understanding person of my life who I dedicate this thesis to, my one and only loving daughter, Donique Rodd, she has been there with me from the start; she has been through all the struggles with me. Love you daughter, I appreciate you so much for understanding, do know you are very special to me.

Finally, I offer my regards to all of those who supported me in any respect during the completion of the project.

Carlene E-A Campbell

January 2011, London, UK

I have fought the good fight, I have finished my course, I have kept the faith and now I have achieved the crown of victory.

~2 Timothy 4:7~

Dedicated to my family:

Especially

My Mother, Cathreta Campbell

My Father, Guy Campbell and

My Daughter, Donique Rodd
'YOu have been so understanding...Love you daughter!'

Author's Declaration

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Campbell

Carlene E-A Campbell

January 2011, London, UK

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List of Notations

C	The Channels
E	The Edge of the graph
G	The Graph
I	The number of radios
i	The number of available edges
L	The Links
l	The number of links
N	The Nodes
n	The number of non-overlapping channels
R	The Radio
V	The vertex of the graph
X	The number of sending nodes to sink

List of Abbreviations

ACK	Acknowledgement
aCWmax	Control Window maximum
aCWmin	Control Window minimum
AKA	Also known as
AP	Access Point
ARQ	Automatic Repeat Request
BE	Backoff Exponent
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BLE	Battery Life Extension
BSS	Basic Service Set
CAP	Contention Access Period
CBR	Constant Bit Rate
CCA	Clear channel assessment
CCTV	Close Circuit Television (TV)
CDMA	Code Division Multiple Access
CODA	Congestion Detection and Avoidance
CRCN	Cognitive Radio Cognitive Network
CS	Carrier Sense
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to send
CW	Control Window
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space
DSM	Distribution System Medium
ED	Energy Detection
ESRT	Event-to-Sink Reliability Transport
FAMA	Floor Acquisition Multiple Access
FAMA-NCS	Floor Acquisition Multiple Access non-persistent carrier sensing

FAMA-NPP	Floor Acquisition Multiple Access non-persistent packet
FAMA-NPS	Floor Acquisition Multiple Access non-persistent packet sensing
FDMA	Frequency Division Multiple Access
FIFO	First In First Out
GHz	Gigahertz
GUI	Graphics User Interface
HCF	Hybrid Coordination Function
IBSS	Independent Basic Service Set
ICD	Intelligent Congestion Detection
ICN	Implicit Congestion Notification
ID	Identification Number
IEEE	Institute of Electrical and Electronics Engineers
IFS	Interframe Space
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
Kbps	Kilobits per second
LMAC	Lightweight Medium Access Protocol
LR-WPAN	Low Rate Wireless Personal Area Networks
MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance
Mbps	Megabits per second
MC-DCF	Multi-Channel Distributed Coordinated Function
MCMR	Multichannel multi-radio
MCPS-SAP	MAC Common Part Sublayer Service Access Point
MCSR	Multichannel Single Radio
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MLME	MAC Sublayer Management Entity
MLME-SAP	MAC Sublayer Management Entity Service Access Point
MMSN	Multi-Frequency Media Access Control for Wireless Sensor Network
MPDU	MAC Protocol Data Unit
NACK	Negative Acknowledgement

NAP	National Agenda Project
NAV	Network Allocation Vector
NB	Number of Backoff
NIC	Network Interface Card
NS	Network Simulator
OSI	Open System Interconnection
PAMAS	Power Aware Multi-Access with Signaling
PAN	Personal Area Network
PCCP	Priority-based Congestion Control Protocol
PCF	Point Coordination Function
PD-SAP	PHY Data Service Access Point
PHY	Physical layer
PIB	PAN Information Base
PIFS	Point (Coordination Function) Interface Space
PLME-SAP	Physical Layer Management Entity Service Access Point
PMD	Physical Medium Dependent
POS	Personal Operating Space
PRA	Priority-based Rate Adjustment
QoS	Quality of Service
RBC	Reliable Bursty Convergecast
RF	Radio Frequency
RMST	Reliable Multi-Segment Transport
RTS	Request to send
RTT	Round Trip Time
SACK	Selective Acknowledgement
SAP	Service Access Point
SIFS	Short Inter-Frame Space
STA	Station
STCP	Sensor Transmission Protocol
Std	Standard
TCL	Tool Command Language
TCP	Transmission Control Protocol

TDMA	Time Division Multiple Access
TMMAC	TDMA Multi-channel MAC
UDP	User Datagram Protocol
UK	United Kingdom
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSNs	Wireless Sensor Networks

List of Contributed Publications

Journals:

1. **C. E-A Campbell**, K.K. Loo, D. Singh, Multi-channel Multi-radio using 802.11 based Media Access for Sink Nodes in Wireless Sensor Networks, *Sensors* 2011 (under review).

2. **C. E-A Campbell**, K.K. Loo, H. A. Kurdi, S. Khan, Comparison of IEEE 802.11 and IEEE 802.15.4 for Future Green Multichannel Multi-radio Wireless Sensor Networks, IJCNIS Vol. 3, No. 1, 2011, pp. 96-103.

3. **C. E-A Campbell**, K.K. Loo, O. Gemikonakli, D. Singh, Multi-channel Distributed Coordinated Function over Single Radio in Wireless Sensor Networks, *Sensors* 2010, pp. 964-991 (SCI-E).

4. **C. E-A Campbell**, I. A. Shah, K.K. Loo, Medium Access Control and Transport protocol for Wireless Sensor Networks: An overview, International Journal of Applied Research on Information Technology and Computing (IJARITAC), 2010, pp. 79-92.

5. I. Shah, S. Jan, **C. Campbell** and H. Al-Raweshidey, "Selfish Flow Games in Non-Cooperative Multi-Radio Multi-Channel Wireless Mesh Networks With Interference Constraint Topology" submitted to International Journal on Advances in Telecommunications ISSN: 1942-2601 (under review).

Conference:

1. C. Campbell, K. Loo, R. Comley, A New MAC Solution for Multi-Channel Single Radio in Wireless Sensor Networks, ISWCS 2010, pp. 907-911.

CHAPTER 1

Introduction

1.1 Motivations

Recent advances in Access Networks have made voice, data and multimedia communications ubiquitous and have knowingly/unknowingly changed life styles. However, important challenges still stand in the way of widespread use of wireless applications; power consumption, lack of spectrum, end user acceptance and interoperability. In fact, the complexity of mobility and traffic models, together with the dynamic topology and the unpredictability of link quality that characterise wireless networks made every application has different characteristics and requirements such as data type, rate of data transmission and reliability. Wireless Sensor Networks [1-9] are an emerging fast growing technology where the growing interest can be contributed to new applications enabled by large scale networks. The demand for using this medium is increasing with wide range of deployment for monitoring and surveillance systems as well as for military, Internet and scientific purposes. Packets from all nodes in the network converge at nodes near the sink as such the need to prioritised medium access control (MAC) protocol. There have been a number of proposed MAC protocols [10-12] to improve network performance in WSNs. A survey study has been carried out on the contention based protocols of WSNs and also the traditional ones such as 802.11 DCF.

From observation it can be easily seen that wireless networks are growing increasingly less structured. However, the dynamic interactions arising in these networks make it difficult to analyse and predict performance, inhibiting the development of wireless technologies. Thus, in order to deal with such challenging demands, a constant and thorough research is required for improving existing protocols, developing new standards and technologies.

A comparison between 802.11 and 802.15.4 was carried out to consider the future medium for wireless sensor networks operating in a multichannel environment at high data rate with streaming data. Both 802.11 and 802.15.4 use the CSMA/CA mechanism for contention based network and operate in the 2.4GHz frequency band.

The research presented in this thesis is motivated by the following issues:

1. WSNs that are rapidly gaining increasing attention on the experimentation level as well as the application-deployment level.WSN is a preferred choice due to its relative economic efficiency, ease of deployment, and its relatively superior monitoring capabilities[4]. These networks, however, suffer from severe congestion, packet loss, unfair utilization of bandwidth and unreliable data delivery to destination. The research presented in this thesis address solutions for enhancing the MAC contention-based protocol to reduce the congestion, packet loss and the unreliable data delivery.
2. Owing to the revolution of new technology, wireless sensor networks should be able to cope with multimedia traffic and delivery of data in keeping with technological trends. Currently, neither IEEE 802.11 contention based protocol nor the 2.4 GHz frequency band has the capability for high data rate transmission. This research determined the feasibility in having 802.11 being considered as a future medium for WSNs to operate high data rate with streaming data in the 2.4 GHz frequency band that requires timely and efficient delivery.
3. Multi-channel MAC protocols have recently obtained considerable attention in wireless networking research because they promise to increase capacity of wireless networks significantly by exploiting multiple frequency bands. Multi-channel allows wireless networks to assign different channels to different nodes in real-time transmission. IEEE 802.11 standard play a vital role for contention-based networks and divide the wireless spectrum into spectral bands called ‘channels’. The research address issues relating to simultaneous communications, limits interference between nodes while allowing the coexistence of multiple wireless networks on different channels.
4. The research proposes an original model that addresses shortage of spectrum which limits current capability to introduce new wireless services and improve

existing ones. This research introduces a model that allows different wireless systems to share multiple channels and switch channels without causing excessive harmful interference to other neighbours. This system will increase the amount of communications that can take place in a given network, which would defiantly lead to a revolution in the world of wireless services and applications, resulting in less expensive networks transmitting higher data rate than currently exist.

1.2 Aims and Objectives

The aims and objectives of the research presented in this thesis are to introduce multichannel and channel switching assignment in the IEEE 802.11 DCF contention-based MAC protocol. The research aims and objectives are summarised by the following points:

1. To review the area of MAC protocols to identify related paradigms for contention-based MAC protocols.
2. To compare IEEE 802.11 and IEEE 802.15.4 MAC protocol to determine the feasibility of IEEE 802.11 being utilised in the future as a medium for wireless sensor networks operating in a high data rate multichannel environment with streaming data.
3. To use the backoff algorithm of the 802.11 DCF for multichannel assignment and channel switching when a set criterion is met to reduce contention for a single medium, collision and congestion.
4. To design an efficient and distributed algorithm that overcomes the severe degradation at the sink node when using single radio to switch to multiple channels.
5. To utilise simulation experiments in order to investigate and analyse the performance of the proposed MC-DCF protocol of multi-channel communication in wireless sensor networks using an NS2 platform.

1.3 Contribution to Knowledge

This thesis contributes to knowledge by designing a contention-based protocol for multichannel WSN with the options to do channel switching when a channel is busy. This is aiming at reducing the unnecessary delays by nodes sending data to the sink node over a single radio interface.

Furthermore, the thesis presented a round robin cycle solution to aid delivery from sources to the sink node(s) when the radio interface switching between receiving nodes on the same channel to retrieve data packets.

The key contributions are summarised as follows:

1. Comparison of IEEE 802.11 and IEEE 802.15.4 for Future Green Multichannel Multi-radio Wireless Sensor Networks. This comprises:
    a. Details of the IEEE 802.15.4 MAC protocol determined to aid an understanding of CSMA/CA and PAN coordinator.
    b. Details of the IEEE 802.11 MAC protocol aimed at giving an understanding of CSMA/CA and DCF.
    c. Investigating and evaluating the performance of both IEEE 802.15.4 and IEEE 802.11 MAC protocol through simulation results conducted in NS2 to make a rational decision which protocol is feasible for future WSN operating with multimedia or surveillance system in a multichannel multi-radio environment.
    d. The simulation is based on CBR streaming data with 100kbps and 2Mbps at 10 and 50m range respectively.
2. Multi-channel Distributed Coordinated Function over Single Radio in Wireless Sensor Networks, which aims at having the design of multi-channel communication based on the 802.11 DCF over a single radio for WSNs in order to improve its communication performance namely throughput, end-to-end delay and channel access delay.
    a. Multi-channel protocols utilise bandwidth better and thus may perform favorably in cases of applications demanding high data rates.
    b. The 802.11 standards provide up to 12 non-overlapped channels, respectively, in 2.4 GHz and 5 GHz spectrums.

   c. Nodes within the transmission range of each other can operate on different non-overlapped channels so as to avoid interference.
   d. Node interface will be able to switch between channels.
   e. The approach will have all nodes aware of the channels in use but each node interface can only tune into one channel at a given time.
   f. At initialisation, a random assigner that employs uniform distribution will be applied to distribute node interfaces to channels.
   g. Channel switching among sending nodes will only occur after a set threshold has been reached during the backoff period.

3. Multi-channel Multi-Radio using 802.11 based Media Access for Sink Nodes in Wireless Sensor Networks as an extension to Multi-channel Distributed Coordinated Function over Single Radio in Wireless Sensor Networks to study the problem of designing an efficient and distributed algorithm that overcomes the severe degradation at the sink node when using single radio to switch to multiple channels.
   a. Multichannel Multi-Radio (MCMR) [13-14] problem has been modelled as a unidirected graph where vertices represent radios comprising the wireless network and edges between vertices representing node links.
   b. A binary vector defines where only one channel can be assigned to each logical link between the lists of elements.
   c. The number of sink nodes increases to collect data from receiving nodes. The sink nodes will equip with a single radio and will be required to do channel switching in the same manner as in 2.
   d. Multiple radio interface increases in the sink node to receive data from each non-overlapping channel.

1.4 Research Methodology

The initial phase of the research is focused on literature review; relevant research articles, books, research papers which included conference proceedings and journal papers, IEEE standards, progress and proposals of IEEE task groups, and different white papers on Wireless Sensor Networks, heterogeneous wireless networks, MAC protocols, Transport protocols and Channel assignments and Cross layered approaches were studied. During this stage, basic definitions, types and classifications of MAC and transport protocols were examined and issues related to sensor networks and its recent extinctions, resource allocations in Ad-Hoc networks and multichannel multi-radio assignment were identified.

Literature review was followed by comparison study of IEEE 802.15.4 [15,16] and IEEE 802.11 MAC sub layer [17] controls access to the radio channel by using a Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism. The main differences involve the time slotted behaviour, the backoff algorithm, and the clear channel assessment (CCA) procedure used to sense whether the channel is idle. Different parameters and scenarios for each case were carried out using different performance metrics: aggregate throughput, delivery ratio and access delay. Not only the performance of each was tested but it also helped in developing a different perspective, such as, looking at the issues of long range transmission, data rate and the effect when the same channels are used by both in the same frequency band. An overlap between them can adversely impact on the operation of IEEE 802.15.4.

In the final stage, development of simulation models of different radio interface selection mechanisms based on static or dynamic factors have been implemented in order to compare them with the solutions introduced in this research. Apart from implementing the proposed protocols, Multichannel multi-radio assignments were also implemented at the sink node(s) to improve the performance. The proposed models and various components were designed and tested in NS2. NS2 [18] is an open source simulator and new models can be easily implemented using either C++ or Tool Command Language (TCL). However, NS2 creates trace files and NAM screen shots to visualise node movement in wireless networks, to collect the simulation results from NS2 a number of Perl scripts were written for this purpose. On the other hand, the work done for cognitive radio cognitive network (CRCN) [19] GUI provides easy, interactive environment in using NS2.

1.5 Thesis Structure

This thesis comprises six chapters. Chapter two examined various MAC and transport protocols and the need for cross-layer MAC-Transport scheme for WSN, in order to obtain a vivid perspective for future trend in the WSN arena and to shape the research objective for multichannel MAC protocol.

Chapter three outlined a comparative study of IEEE 802.15.4 and IEEE 802.11 MAC sub layer controls access to the radio channel by using a Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism. The differences detected from the comparison, greatly determined the design for the MC-DCF protocol.

Chapter four focused on the design of a new approach, Multi-channel Distributed Coordinated Function (MC-DCF) which takes advantage of multi-channel assignment. The backoff algorithm of the IEEE 802.11 distributed coordination function (DCF) was modified to invoke channel switching, based on threshold criteria in order to improve the overall throughput for wireless sensor networks (WSNs) over 802.11 networks.

Chapter five addressed the severe degradation at the sink node when using single radio to switch to multiple channels. However due to limited non-overlapping channels, delay and congestion, the problems at the sink node needed to be improved for MC-DCF to work efficiently with future networks and to considered for cross layered design.

The chapter provided necessary steps to verify the feasibility of round robin technique in these networks at the sink node by using the technique to regulate multi-radio multichannel assignment. Simulation results indicated that dynamic channel assignment scheme using the multi-radio, multichannel at a single sink node can perform close to optimal on the average while multiple sink node assignment also performed well. The methods proposed in the chapter can be a valuable tool for network designers in planning network deployment and for optimising different performance objectives.

Finally, the thesis summary conclusions are presented in chapter six along with some seminal ideas for future proposals based on the research carried out in this work.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Wireless communication is the most vibrant area in the communication field of research today. It has been a topic of research since the 1960’s but with the paradigm shift experienced through the transition from wired to wireless networks, new research advances have been created in the wireless arena which has seen a massive growth both in terms of services provided and the type of technology that have become available. These have revolutionised the entire wireless networks and will play an important role in future generation wireless sensor network for multimedia applications such as video surveillance systems.

Wireless Sensor Networks (WSNs) [1-2,4,10] are an emerging technology that has become one of the fastest growing areas in the communication industry. They consist of sensor nodes that use low power consumption which are powered by small replaceable batteries that collect real-world data, process it, and transmit the data by radio frequencies to their destination. WSNs are usually static nodes that send data to a server or a sink node for processing.

WSN based applications usually have relaxed bandwidth requirement, the demand for using this medium is increasing with wide range of deployment for monitoring and surveillance systems as well as for military, Internet and scientific purposes. WSNs can be classified under a number of areas including security and military sensing, home automation, consumer electronics, agriculture and environmental purposes, industrial control and monitoring.

Security and Military sensing applications are usually used for magnetic door opening, smoke detection, to locate and identify targets for potential attack. Home automation and consumer electronics include universal remote control; a personal digital assistant type of device, wireless keyboards, toys, light control and remote keyless entry.

Industrial control and monitoring sensors may include heating, ventilating and air conditioning unit of buildings that can regulate the temperature, the monitoring and controlling of moving machinery and detection of the presence of poisonous or dangerous material.

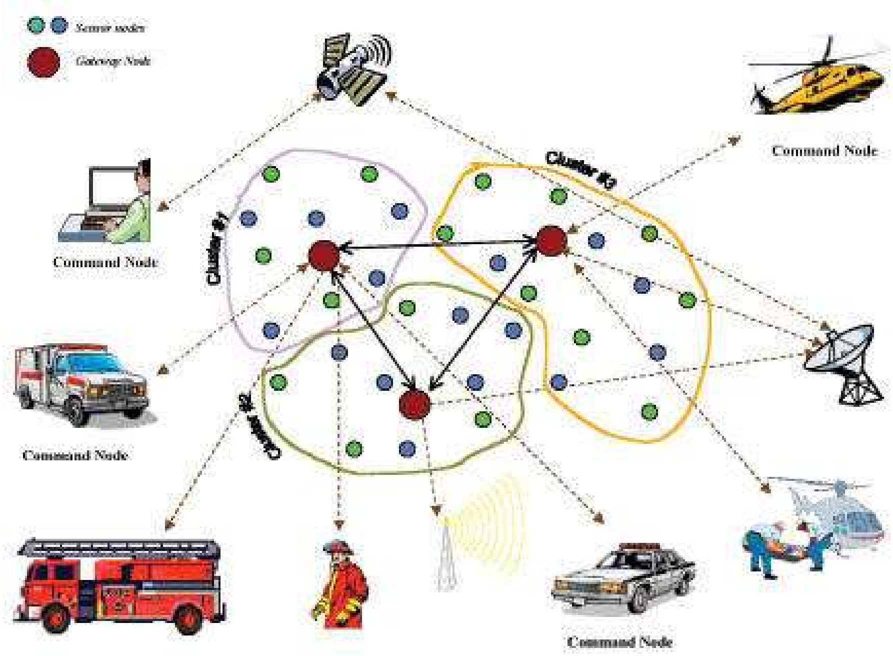

Figure 2-1: Wireless Sensor network architecture

Other applications such as environmental monitoring over large areas may require frequent battery replacement as such network nodes in this kind of WSN must employ other means of energy or obtain their energy from other sources such as energy scavenging [2] (photovoltaic cell, mechanical vibration). With the rapid development and fast growth of new technologies such as multimedia streaming over wireless medium arise the need for improved or new MAC and transport protocols in the WSN. However, these networks suffer from severe congestion, packet loss, unfair utilisation of bandwidth and unreliable data delivery to destination. Owing to the revolution of new technology, wireless sensor networks should be able to cope with multimedia traffic and delivery of data by a specific time [1].

In this chapter an overview of medium access control and transport layer protocols have been examined; as well as the need for cross-layer design among two layers, MAC and Transport for WSN. These will give a vivid perspective for future trend in the WSN arena and to aid the focus of the research objective for multichannel MAC protocol.

2.2 Medium Access Control (MAC) Overview

MAC protocol [1,4,10,11] is responsible for reliable, error free data transfer with minimum retransmissions; in order to meet performance requirements such as controlling bandwidth, power awareness, contention resolution, minimise interference and collision avoidance.

Data collection in WSN tends to suffer from heavy congestion especially nodes nearer to the sink node – which gather, control and store data collected by other sensor nodes. MAC protocols, proposed in literature, to combat these problems can be categorised as contention free or contention based while in [10] has classified these protocols as scheduled and unscheduled or random protocols.

2.2.1 MAC Protocols

MAC protocols can be categorised as Contention-free and Contention-based, as shown in Figure 2-2.

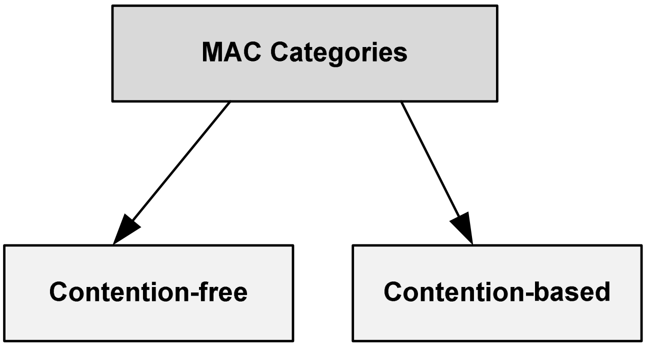

Figure 2-2: MAC protocols.

2.2.1.1 Contention Free Protocols

The contention free [1,4,10,11] protocols are more efficient than those of the contention based, they do not make the assumption that network traffic is intrinsically random, instead traffic is ordered in a bounded channel assignment. These schemes are generally based on TDMA, FDMA or CDMA that utilises the synchronisation technique and the channel access mechanism of the physical layer, where the structure of the network is spatially divided into slots or cells [4]. These protocols works well for multimedia traffic and are more applicable for static networks with centralise control. However, these schemes are more complex, require centralise control, use multiple channels simultaneously, specialised sensor hardware and there is a dependency on the physical layer. Therefore the focus is mainly on the contention based and transport layer schemes, where WSN need to cope with congestion, fairness and packet loss.

2.2.1.2 Contention Based Protocols

Most of the proposed contention based protocols use Carrier Sense Multiple Access (CSMA) [2,20] scheme, where for a station (STA) to transmit, it must sense the medium to determine if another station is transmitting. If the medium is busy, the STA will defer until the end of the current transmission. After deferral or just before attempting to transmit again, the STA shall select a random back-off interval and shall decrement the back-off interval counter while the medium is idle.

The transmitting and receiving STA exchange short control frames (RTS and CTS frames) after determining that the medium is idle and after any deferrals or back-offs, prior to data transmission.

The CSMA/CA protocol is designed to reduce collision between multiple stations accessing the medium. However CSAM/CA tends to suffer from hidden and exposed node problems.

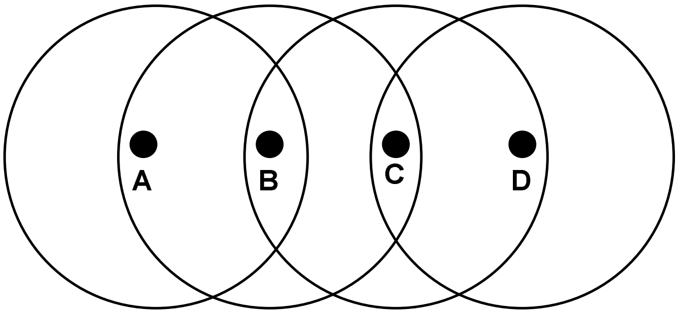

Figure 2-3: Hidden and Exposed node

2.2.1.2.1 Hidden Node

In Figure 2-3, nodes A and C are in the range of node B, but they are not in the range of each other. If node A is transmitting to node B, and Node C wishes to transit to node B, node C may sense the channel and find it idle and transmit causing collision at the receiving node, B with node A's transmission.

2.2.1.2.2 Exposed Node

In Figure 2-3 if node B is transmitting to node A, and node C wishes to transmit to D, node C may sense the channel, find it busy by node B and refrain from transmitting even though a transmission by node C to node D would not cause an interference at Node A.

To combat the problems encountered by CSMA a number of protocols have been developed to improve upon CSMA deficiencies such as:

- Multiple Access Collision Avoidance (MACA)
- Floor Acquisition Multiple Access (FAMA)
- Power Aware Multi Access with Signalling (PAMAS)
- 802.11 Distributed coordination function (DCF)

The MACA [10-11] protocols are an improvement of CSMA/CA that eliminates some of the inefficiencies. It does not use carrier sensing instead it uses the Request-To-Send/Clear-To-Send (RTS/CTS) control to avoid collisions. The main idea of MACA [10] is that any neighbouring node which overhears a RTS packet has to refrain from sending for some time. The RTS/CTS packets are much shorter than the data packets and as such collisions are much inexpensive and nodes sensing these messages can determine how long to delay before attempting to transmit. MACA has made an improvement over CSMA/CA in that the RTS/CTS packets are much shorter than the data packets. However, the hidden node problem is not completely solved and therefore collisions can occur when different nodes send RTS and CTS packets. In addition when a node receive a RTS that is destined for another node, but do not receive the CTS to begin data exchange, this can lead to exposed node inefficiencies. MACA also does not provide any acknowledgement of data transmission and if a transmission fails, retransmission has to be initiated by the transport layer [11].

The FAMA [11-12] is a MACA based scheme that allows every transmitting station to have control of the medium before sending data packets. It requires that collision avoidance be performed at the sender and at the receiver. FAMA uses non-persistent packet (NPP) sensing or non-persistent carrier sensing (NCS) RTS with response with CTS that plays the role of a busy signal and contains the address of the sending node. The packets repeat long enough so that hidden nodes can overhear it and refrain from sending. The objective of FAMA-NCS is for a station that has data to send to acquire control of the channel in the vicinity of the receiver before sending any data packet and to ensure that no data collides with any other packet at the receiver. The medium (the floor) is acquired using non-persistent carrier sensing with the RTS-CTS exchange. The length of CTS in FAMA-NCS is larger than the aggregate length of an RTS plus one maximum roundtrip time across the channel, the transmitter receives turnaround time, and any processing time. The length of the RTS is larger than the maximum channel propagation delay plus the transmit-to-receive turn-around time and any processing time. This is required to avoid one station hearing a complete RTS before another has started to receive it. The CTS is given dominance over the RTS based on its size. Once a station has begun transmission of a CTS, any other station within range of it that transmits an RTS simultaneously will hear at least a portion of the dominating CTS, which acts as a jamming signal and back off, thereby letting the next data packet to arrive free from collision.

FAMA-Non-persistent Packet Sensing (NPS) [12] does not use carrier sensing, for a packet with sensing to work with hidden terminal, the CTS must be transmitted multiple time. FAMA-NPS assumes that it is used in a fully connected network and CTS is transmitted only once. A station defers its transmission only after it has received and understood a complete RTS or CTS. FAMA-NPS does not enforce any waiting times after transmission periods, the RTS and CTS specify how long stations should defer. Following the deferment, there is a random waiting period before transmission begins.

The random waiting time enforces an idle period after a successful transmission and an unsuccessful period is also followed by an idle period, because any transmission attempt during (or adjacent to) the failed period would be included as part of the unsuccessful period. Therefore, FAMA-NPS busy period is limited to either a single successful transmission period or a failed transmission period. However the exposed nodes problem still exists with this technique [11].

PAMAS [11,21] was developed mainly for energy conservation, nodes would listen on the signalling channel to determine when to power off their transceivers. Similarly to MACA, PAMAS uses RTS/CTS packets and data packets which are sent over different channels utilising two transceivers in order to prevent collision and save power.

PAMAS devices power down under two conditions: the device has no data to transmit and a neighbour device begins transmitting to another device, or when the sender node has two neighbours involved in communication. The first case saves energy since the device cannot receive a data message without corruption, so the node may power down the transceivers. The second condition saves energy since the device cannot transmit or receive without a collision resulting at itself or its receiving neighbour. To determine the length of time to sleep, each data message includes the transmission duration so a device that overhears the start of the message can calculate the length of time to sleep.

PAMAS [21] also uses a busy tone signal on the RTS/CTS signalling channel such nodes that did not overhear the RTS and CTS would know that the data channel is busy.

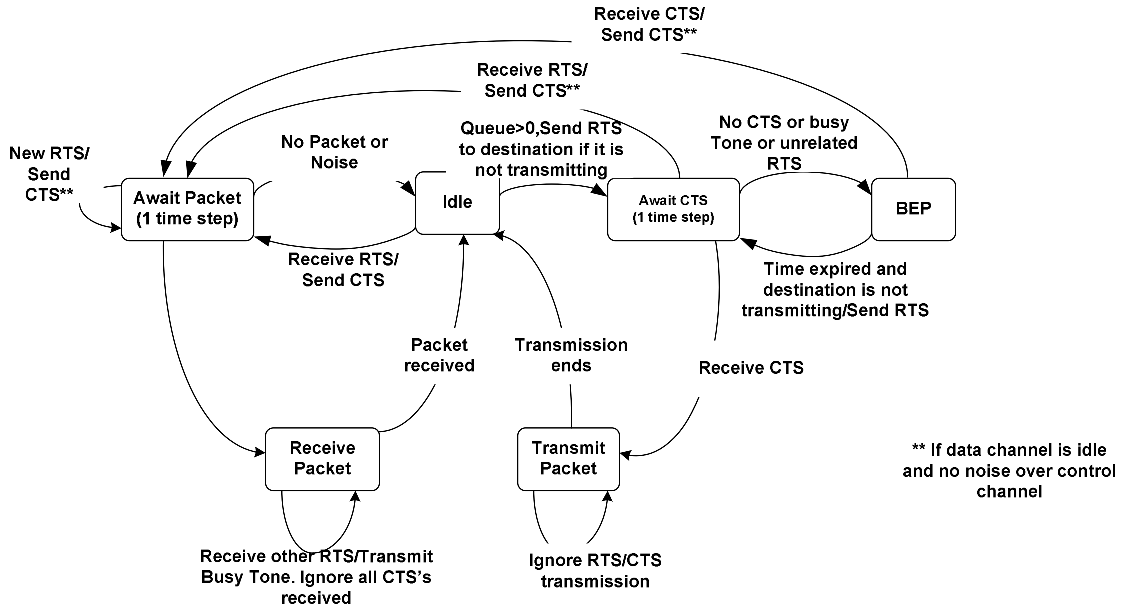

Figure 2-4: The PAMAS protocol [21].

Figure 2-4 outlines the behaviour of the PAMAS protocol. A node may be in any one of six states as outline in the figure:

- Idle
- AwaitCTS,
- BEB (Binary Exponential Backoff),
- Await Packet
- ReceivePacket
- Transmit Packet.

When a node is not transmitting or receiving a packet, or does not have any packets to transmit, or does have packets to transmit but cannot transmit, because a neighbour is receiving a transmission it is in the Idle state. When it gets a packet to transmit, it transmits an RTS and enters the AwaitCTS state. If the awaited CTS does not arrive, the node goes into binary exponential backoff. If CTS does arrive, it begins transmitting the packet and enters the Transmit Packet state. The intended receiver, upon transmitting the CTS, enters the Await Packet state. If the packet does not begin arriving within one roundtrip time (plus processing time), it returns to the Idle state. If the packet does begin arriving, it transmits a busy tone over the signalling channel and enters the Receive

Packet state. When a node is in the idle state receives a RTS, it responds with CTS, if no neighbour is in the Transmit Packet state or in the AwaitCTS state. It is easy for a node to determine if any neighbour is in the Transmit Packet state, by sensing the data channel. However, it is not always possible for a node to know if a neighbour is in the AwaitCTS state because the transmission of the RTS by that neighbour may have collided with another transmission over the control channel. If a node that is in the idle state and has a packet to transmit, it will transmit an RTS and enters the AwaitCTS state. If, however, a neighbour is receiving a packet that neighbour responds with a busy tone (twice as long as a RTS/CTS) that will collide with the reception of the CTS. This will force the node to enter the BEB state and not transmit a packet. If no neighbour transmits a busy tone and the CTS arrives correctly, transmission begins and the node enters the Transmit Packet state. Any node that transmitted an RTS but did not receive a CTS message, will enter the BEB state and waits to retransmit a RTS. If, however, some other neighbour transmits a RTS to this node, it leaves the BEB state, transmits CTS, if no neighbour is transmitting a packet or is in the AwaitCTS state and enters the Await Packet state (waits for a packet to arrive). When the packet begins arriving, it enters the Receive Packet state. If it does not hear the packet in the expected time (round trip time to the transmitter plus some small processing delay at the receiver), it goes back to the Idle state [21].

When a node begins receiving a packet, it enters the Receive Packet state and immediately transmits a busy tone (whose length is greater than twice the length of CTS). If the node hears a RTS transmission (directed to some other node) or noise over the control channel at any time during the period that it is receiving a packet, it transmits a busy tone. This ensures that the neighbour transmitting the RTS will not receive the expected CTS. Thus, the neighbour transmission which would have interfered with the node receiving a packet is blocked.

This scheme would be beneficial for large data stream such as multimedia data, however for small size data, utilising two transceivers would not be energy efficient.

IEEE 802.11 DCF [10,20] is based on CSMA with collision avoidance (CSMA/CA), it is mostly used for wireless LANs. It is a combination of CSMA and MACA schemes. This protocol uses RTS-CTS-DATA -ACK sequence for data transmission. This scheme uses a virtual carrier sense mechanism known as Network Allocation Vector (NAV) that predict the future traffic on the medium based on duration information that is announced in RTS/CTS frame. The RTS/CTS frames contain a duration field that defines the period of time that the medium is to be reserved to transmit the actual data from the returning ACK frame. Each device maintains the NAV, that indicates the channel activity whether it has a non-zero value. Each device update the NAV based on the length present in the control message they receive. Each device also periodically decrement its NAV so the current transmission ends when the NAV reaches zero. Using the NAV allows a device to quickly check for possible channel activity without having to activate the device transceiver. DCF also uses a back-off procedure that sets a back-off timer to a random time, all back-off slots occur following a DCF inter-frame space (DIFS) period during which the medium is determined to be idle for the duration of the DIFS period. All STA using DCF is allowed to transmit if its carrier sense (CS) mechanism determines that the medium is idle and its backoff time has expired. When a node successfully receives a data message it sends a short inter-frame space (SIFS). The SIF is the time from the end to the last symbol of the previous frame to the beginning of the first symbol of the preamble of the subsequent frame as seen at the wireless interface[10].

Figure 2-5 illustrates the DIFS backoff procedure used to invoke a station to transfer when finds the medium busy by the CS mechanism as well as to invoke when a transmitting STA infers a failed transmission.

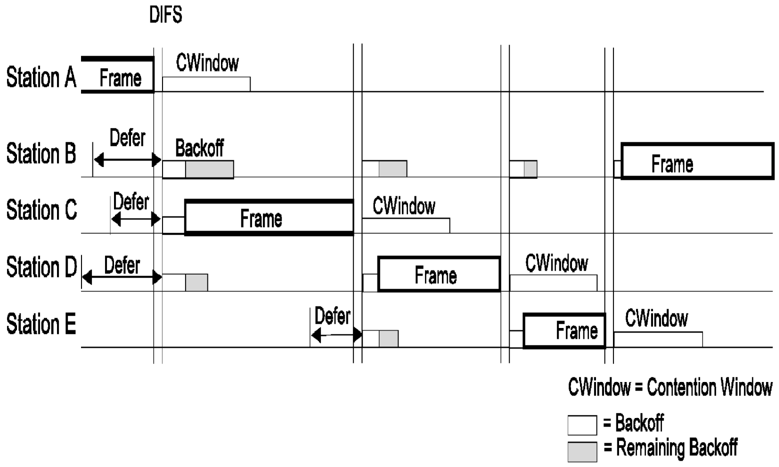

Figure 2-5: Back-off procedure [20].

This scheme will work well in WSN that have short transmission range. Collision can still occur based on the transmission range of the destination node that the packet is sent to.

The Contention-based protocols discussed in this paper demonstrate their improvement over the CSMA scheme that senses the medium before transmitting, to determine if the medium is free. Each attempt to resolve problems based on the hidden or exposed node and to save energy as in the case of PAMAS.

The MACA [10] technique improvement relates to RTS/CTS packets that are substantially shorter than data packets, however RTS/CTS enable nearby nodes to reduce collisions at the receiver but not at the sender. Collision can also occur between different RTS and even though each sending node waits for a random chosen interval time to attempt sending again, if constant collisions keep occurring the system will degrade significantly as well as increase in overhead. It should be noted that while the MACA technique partially overcomes the hidden node problem; if there is a transmission failure it does not send ACK. The sender therefore will have no clue that the packet was not transmitted successfully unless notification is received by the transport layer. The MACA technique may not work effectively in WSNs based on the deficiencies highlighted - collision occurrence, lack of ACK, and the requirement for node to incessantly sense the medium.

FAMA [12], an improvement of MACA [10] was designed to solve the short fall of MACA, by addressing the hidden node problem, in which the sender uses non-persistent carrier sensing to transmit a RTS. This lasts much longer than an RTS to force all hidden nodes to hear or sense that the medium is busy. This technique works well in addressing the hidden node problem, but the exposed nodes still exist even though RTS lasts longer than the maximum propagation delay and CTS last longer than the time it takes to transmit an RTS. Having RTS utilising the maximum propagation delay time and RTS taking a longer time on the medium, nodes wishing to transmit may experience a long wait time, causing packets to drop based on time-out issues, which is a drawback of this technique as well as collision of nodes owing to the fact that most features used utilises CSMA, where nodes wait a random time before transmitting.

PAMAS [21] main purpose was to save energy by having all RTS and CTS transmitting over a separate channel from the data packet. PAMAS actually uses a mix of MACA along with the idea of separating signal channel. In a sensing network packet transmitting will be overheard by all nodes in range and thus every node hearing the transmission will consume power regardless that they are not transmitting. However PAMAS implements control where nodes are turned off if they are not transmitting or required to transmit. In utilises more than one transceivers on the contrary utilises energy, even if the turnaround time is minimal. This was not considered in the PAMAS scheme, utilising two transceivers is not energy efficient for small packets; however this scheme would be advantageous for multimedia data.

The 802.11 DCF [20] was designed mainly for wireless networks, this scheme known to work well in WSNs that has a power saving mechanism which are used to synchronise nodes. However it uses a random back off mechanism that cannot provide deterministic upper bounds on channel access delay and as such cannot support real-time traffic. The contention and back off strategy is unfair to the already existing nodes that are backing off due to collisions, especially under heavy traffic conditions [10].

2.3 Transport layer overview

A transport layer is used to mitigate congestion, reduce packet loss, provide fairness in bandwidth allocation and guarantee reliable end-to end delivery. TCP and UDP [22] are two traditional transport protocols used in providing transportation within the Internet and cannot directly implement for WSN. TCP, a connection-oriented protocol, assumes that all packet losses are due to network congestion, as well both congestion and reliability are coupled with receipt of an acknowledgement (ACK) where as wireless networks packet losses are mainly due to high bit error rate.

UDP does not provide reliable delivery, no flow control and congestion control mechanism [22].

WSNs transport protocols should be designed to support and cope with multiple applications, variable reliability, packet-loss recovery and congestion control owing to the fact that WSNs do not only facilitate existing small sensor network with limited processing and computing resources, but take a paradigm shift in supporting multimedia traffic and applications. A number of studies [23-27] have proposed various techniques that can handle the congestion control and reliable transport.

2.3.1 Transport Protocols

A number of protocols have been proposed which are based on one or more of the following transport protocols [22] mechanism:

- Congestion Control [23,24, 25]
- Reliable Transport [26,27]
- Energy conservation [28,29]

2.3.1.1 Congestion Control Mechanism

Accurate and efficient congestion detection plays an important role in congestion control for sensor networks. A number of proposed congestion detection protocols have been designed such as:

- Congestion Detection and Avoidance (CODA)
- FUSION
- Priority-based Congestion Control Protocol (PCCP)

Congestion Detection and Avoidance (CODA) [23] is a congestion protocol that based on queue length at intermediate nodes and channel status on the basis of channel sampling and monitoring the current buffer occupancy. The authors propose the CODA energy efficient congestion control scheme that comprises three mechanisms namely:

- Congestion detection – this technique uses a combination of the present and past channel loading conditions and the current buffer occupancy to infer accurate detection at each receiver with low cost. CODA uses a sampling scheme that activates the local channel monitoring at the appropriate time to minimise cost while forming an accurate estimation. Nodes inform their upstream neighbours via a backpressure mechanism once congestion is detected.

- Open-loop, hop-by-hop backpressure – this technique broadcasts backpressure messages as long as it detects congestion. Back pressure signals are propagated upstream toward the source. When there is an impulse data event in dense networks the backpressure will propagate directly to the source. When an upstream node receives a backpressure message it decides whether or not to further send the message upstream, based on its own local network conditions.
- Closed-loop, multi-source regulation – this technique operates over a slower time scale and is capable of asserting congestion control over multiple sources from a single sink in the event of persistent congestion. When the source event rate is less than some fraction of the maximum theoretical throughput, the source regulates it. When the rate exceeds the maximum throughput a congestion control is triggered. At this point the source requires a constant, slow time-scale feedback from the sink to maintain its rate. If there is a failure from source in receiving acknowledgment in maintaining rates each nodes are forced to maintain their own rates.

In designing the CODA scheme two metrics were defined to analyse the performance of the system: namely the Average Energy Tax – which calculates the ratio between the total number of packets dropped and the total number of packets received at the sink node; and the Average Fidelity Penalty – which measures the difference between the average numbers of data packets received at the sink using CODA against other scheme. CODA provides congestion control as well as conserves energy; however, it does not provide reliability in scenarios with sparse source and high data rate.

FUSION [24] is similar to CODA and suffers from the similar deficiencies. This protocol uses a combination of three techniques to control congestion:

- Hop-by-hop flow control – nodes signal local congestion to each other via backpressure, reducing packet loss rates and preventing the wasteful transmission of packets that are only destined to be dropped at the downstream.

- Source rate limiting – this alleviate the serious unfairness towards sources that have to traverse a larger number hops. The rate control used is similar to the token bucket mechanism. This mechanism assumes that the data rate of each sensor nodes is the same.
- Prioritised MAC layer – this gives a backlogged node priority over non-backlogged nodes for access to the shared medium, hence avoiding buffer drops.

Although this scheme uses a combination of three techniques to control congestion, a performance comparison need to be evaluated and a rate limitation algorithm need to be design to correctly handles node failures.

PCCP [25] uses packet inter-arrival time and packet service to measure congestion. Congestion level is captured at the node or at the link through a parameter referred to as congestion degree which is the ratio of service over inter-arrival time. It employs weighted fairness to allow nodes to receive priority-dependent throughput. PCCP results in low buffer occupancy and as a result, it can avoid or reduce packet loss and therefore improve energy-efficiency as well as achieves high link utilisation and low packet delay. PCCP is made up of three main:

- Intelligent congestion detection (ICD), which detects congestion based on packet inter-arrival time and packet service time. The joint participation of inter-arrival and service times reflects the current congestion levels that provide relevant congestion information.
- Implicit congestion notification (ICN), this allows congestion information to be piggybacked in the header of data packets. Taking advantage of the broadcast nature of wireless channel, child nodes can capture such information when packets are forwarded by their parent nodes towards the sink.
- Priority-based Rate Adjustment (PRA), this rate adjustment is implemented in each sensor node in order to guarantee fairness and throughput, where each sensor node is given a priority index.

PCCP also uses implicit congestion notification to avoid transmission of additional control messages and therefore help improve energy-efficiency. This scheme suffers from the same drawback as CODA and FUSION.

2.3.1.2 Reliable Transport mechanism

Reliable Multi-Segment Transport (RMST) [26] and Reliable Bursty Convergecast (RBC) [27] are reliable transport protocols that provide reliability through a hop by hop loss recovery.

RMST is designed to run in conjunction with directed diffusion. In diffusion, a sink subscribes to an interest that names a particular type and source of data. The naming of data is accomplished via attribute-value pairs. It uses a filter that could be attached to any diffusion node on an as needed basis without recompilation of the diffusion core or gradient filter. Figure 2-6 demonstrates the relationship of RMST to a basic diffusion node.

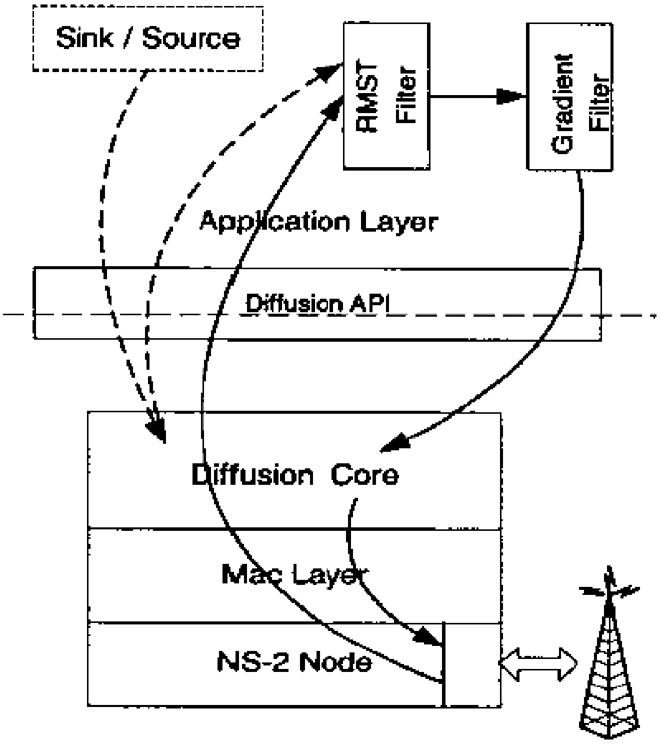

Figure 2-6: Relation of RMST to a Basic Diffusion Node [26].

RMST provides segmentation and reassembly of data packets and also guarantees delivery of all packets from each source to sink. Receivers are responsible for detecting whether or not a fragment needs to be resent. In the non-caching mode, only sinks monitor the integrity of an RMST entity in terms of fragment received and in a caching mode, an RMST node collects fragments which are capable of initiating recovery for missing fragments to the next node along the path toward the source. Reliability for all packets is inherently wasteful in many to one data transmission environment and it does not exploit the redundancy of traffic. Therefore RMST mechanism is not suitable of WSNs.

RBC design a window-less block acknowledgment scheme which guarantees continuous packet forwarding irrespective of the underlying link unreliability as well as the resulting packet- and ack-loss. It was shown to increase channel utilisation, reduce the probability of loss in acknowledgment for a received packet. To improve retransmission incurred channel contention different contention control was introduced which rank nodes by their queuing conditions as well as the number of times that the queued packets have been transmitted. In addition a timer-based retransmission control was designed to rectify the following:

- Continuous changing ACK delay by using an adaptive retransmission timer which adjust itself as network state changes.
- Reduce delay in timer-based retransmission and expedite retransmission of lost packets. RBC uses block-NACK, retransmission timer reset and channel utilisation protection in this regards.

In RBC a receiver switches to transmit mode immediately after receiving a packet and sends back the acknowledgement without going through the procedure of channel access control. It also takes advantage of the fact that every node except the base station, forward the packet it receives and the forward packet can act as the ACK to the sender of the previous hop. RBC therefore resolved the problems of hop by hop recovery mechanism. The scheme appears to be effective for burst traffic consisting of simple sensor data, but would require more bandwidth for multimedia traffic that may have more intense traffic burst and is jitter prone [22].

2.3.1.3 Congestion/Reliable/energy efficient mechanism

Sensor Transmission Control Protocol (STCP) [28] and Event to Sink Reliability Transport (ESRT) [29] are transport protocols that attempt to resolve more than one of the transport protocol mechanisms.

STCP implements both congestion control and reliability in a single protocol, it offers different control policies to both guarantee application requirements and improve energy efficiency. Before STCP transmit packets, sensors node establishes an association with the base station by a session initiation packet. The session initiation packet informs the base station of the number of flows coming from the node, the type of data flow, transmission rate and required reliability. For continuous flow the base station calculates the running average for the reliability; reliability is measured as a fraction of successfully received packets. If there are multiple nodes transmitting, a single initiation packet is send with each packet detail. STCP uses ACK/NACK mechanism. Sensor nodes retransmit packets only on receiving a NACK. The transmitted packets are buffered but a timer is maintained to prevent buffer overflow, once the threshold is reached the buffer is cleared.
For event driven flows, the base station cannot estimate arrival times of data thus ACK are used by source to know if a packet has reached the base station. The source node buffers each transmitted packets until an ACK is received, then the corresponding packet is deleted from the buffer.
STCP only send NACK when reliability goes below the required level, even if base station does not receive a packet within the expected time interval.

ESRT is a novel transport solution that seeks to achieve reliable event detection with minimum energy expenditure and congestion resolution. To achieve the desired event detection accuracy with minimum energy expenditure, ESRT uses a control mechanism that serves dual purposes of reliable detection and energy conservation. To also achieve reliability, the reporting frequency rate is aggressively increased to attain the required reliability as soon as possible. Only the sink and not the sensor nodes can determine the reliability and act accordingly. The authors think that end-to-end transmissions and

ACK/NACK overheads are a waste of limited sensor resources, hence the congestion detection mechanism is based on local buffer level monitoring in the sensor nodes. ESRT also address multiple event detection and uses an event ID field to determine if there is a single event or multiple events. This is done by checking the event ID when data packets are received at the sink; if the event IDs are the same it is assume to be a single event otherwise it is a multiple event.

ESRT implicitly assumed that the Event IDs can be obtained or distributed by using any existing high level network information collection mechanisms such as the existing in-network data aggregation method or location-aware routing for data aggregation or using the cluster-based event identification method. One simple conceivable Event ID assignment methodology is the dynamically random Event ID assignment strategy that is initiated at the time when the event is first detected. In such case, the sensor node that is the first in detecting the event chooses a random Event ID with a length of 16 bits. Since it first detects the event, generates the data packet conveying the event information and captures the wireless communication channel; it sends its data packet with the randomly selected Event ID. Any neighbouring node hearing the local broadcast uses the Event ID to stamp its packet headers. The randomly selected Event ID is dynamically propagated within the event coverage area.

Note that this dynamic event ID distribution terminates at the boundary of the event coverage area. Thus, the forwarding sensor nodes do not need to perform any modification on the Event ID field of the data packets being routed. On the other hand, when the event is first sensed by a sensor node which randomly assigns an Event ID and broadcasts its packets with it, the other sensor nodes may also sense the event and attempt to assign an ID to the same event. However, since the medium is not idle due to the local broadcast of the sensor node which was the first in sensing the event, they defer their broadcast at the MAC level. Hence, the other sensor nodes hear this first broadcast, and use this ID in the Event ID field of their packet headers. Therefore, it is also highly unlikely to generate two different Event IDs for the same event. Consequently, this dynamic random Event ID assignment strategy does not lead to ID conflict problem and can be used for this objective.

However, it should be noted that the ESRT operation for multiple event occurrence scenarios do not depend on a specific event ID assignment strategy, and hence other possible approaches for distributed ID assignment can be easily incorporated into the ESRT protocol operation.

The handling of large packets were not addressed and as such not guaranteed network scalability. Also data segmentation and accurate reassembly have not been addressed. It does not support end-to-end delivery and the sink node controls congestion.

Protocols	**Mechanism**		
	Congestion control	**Reliable**	**Energy conservation**
CODA	Yes	No	Yes
FUSION	Yes	No	No
PCCP	Yes	No	No
RMST	No	Yes	No
RBC	No	Yes	No
STCP	Yes	Yes	No
ESRT	Yes	Yes	*Yes (minimum)*

Table 2-1: Summary of Transport Protocols Mechanism

Table 2-1 summarily highlights the various transport protocol measured against three critical transport protocol mechanisms. In this chapter three mechanism discussed (congestion control, reliability and energy efficient) that are used to obtain an efficient and effective transportation of packets within the medium for WSNs. Congestion is the key problem, it not only waste energy due to large number of retransmissions and drop packets, but has a direct impact on reliability and energy efficiency. Congestion is very much a realistic problem in WSNs as nodes use radio channel to transmit their data toward the sink node, which is not a guided medium and as such suffers enormously from noise, interference and other external forces.

CODA [23] which attempts to solve the congestion problem allows a sink to regulate multiple sources associate with a single event just in case of persistent congestion. The open-loop back pressure cannot deal with persistence congestion and will drop data packets upon receiving them. More so, congestion interference in CODA is based on queue length at intermediate nodes.

CODA only regulates the source relates to a data event that contributed to congestion or impeded by hotspots between sources and sink. It does not use a single high powered control message but hop-by-hop signalling between the sink and sources. Also the cost of closed-loop flow control is typically high comparing to simple loop control because of the required feedback signalling.

CODA looks promising for future WSNs, since it can be integrated to support data dissemination schemes and can be responsive to a number of different congestion control scenarios. However, CODA needs to be tested on large scale WSNs to determine its future.

The mechanism used by FUSION is similar to CODA. It uses hob by hop flow control to prevent nodes from transmitting if their packets are destined to be dropped due to insufficient space in output queues at downstream nodes. Nodes are only allowed to send when its token count is above zero and the rates limits approach only allow nodes to send at the same rate of each of its descendants.

In FUSION it is difficult to adequately make provision for varied link capacity of large scale deployment as the nature of its technique makes transit node particularly prone to buffer drops and the correlated event workload need congestion control to handle the sudden burst of traffic that spatially correlated events generated.

For future FUSION would require a more robust rate limiting algorithm that can handles node failures and an alternative congestion control scheme to handle heavy traffic.

PCCP functionality and drawbacks are similar to that of CODA and FUSION. They all used implicit notification to reduce congestion, rate adjustment to apply channel fairness and hop by hop upstream flow control. However PCCP employed a priority index where nodes with higher priority index get more bandwidth and node with sufficient traffic gets more bandwidth than those that generate less traffic. Such technique shows that PCCP provides good fairness within the medium, although the index declines when traffic increases.

RMST was implemented for reliable transport, using a filter without recompilation of the diffusion core or gradient. It buffers packet at the intermediate node, in order to have a packet loss retransmit much faster. However there is an overhead of using limited buffer space at a given sensor node for caching packets destined for other nodes. This can cause excessive NACK traffic by constant flushing of the buffer or dropping of packets. This problem can be address as future work, if RMST will be considered for multimedia applications.

RBC technique similarly to RMST was designed to ensure reliability by the transport layer. RBC does cope well with retransmission and the design mechanism to alleviate delay incurred by retransmission as well as reduces the probability of ACK-loss. It also addresses the challenges of bursty convergecast on timer-based transmission. RBC design a window-less block ACK scheme, where packets are continuously being forwarded irrespective of the underlying link and unacknowledged packets are stored in a virtual queue, in order for newly arrived packet can be sent immediately. However, packets being forwarded irrespective of the link do not make the system energy efficient and also unacknowledged packets are stored in FIFO (first in first out) order, therefore preference is not placed on priority packets.

STCP and ESRT were both implemented to resolve congestion and reliability within the transport layer. ESRT take in some consideration of energy efficiency within its design. Most of the functionalities for these two techniques are implemented at the base station and as such before packets can be transmitted, the nodes have to establish an association with the base station.

Having the base station performing all the critical functions, nodes have to rely upon the base station to inform them of any anomalies such as congestion before each sending node can refrain from sending packets. This is not an optimal solution as congestion within a WSN tends to be closer to the base station and as such there is no guarantee that nodes further apart, especially when congestion is intense will be able to receive the message sent by the base station regarding congestion.

2.4 Cross-layer design

Traditional layered approach was designed for wired network, the Open System Interconnection (OSI) model [30], where all layers need not communicate with each other, as the architecture layout is built on top of the one below. Neither was there severe problems with sharing the medium as each layer offers services to the respective higher layer and provides an abstract interface for its service.

In the wireless environments users communicate over scarce and changeable transmission medium which are prone to interference, weak signal strength and other channel conditions. With these challenges protocols can no more develop in isolations and as such the invention of cross-layer approach. The idea of cross-layer design is where layers (example MAC and Transport), as shown in Figure 2-7, can exchange information between them in an intelligent way during communication to improve the performances of the system.

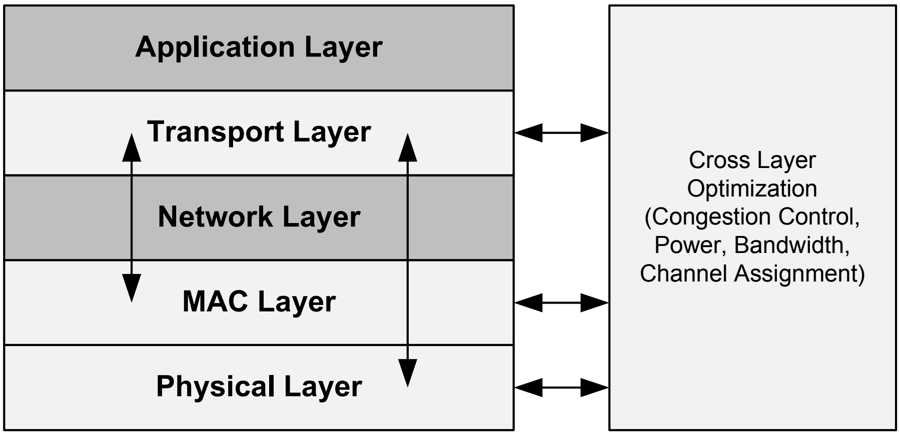

Figure 2-7: MAC and Transport Cross-Layer Optimisation.

In [31] discussed useful cross-layer information and differentiate the channel state as it relates to signal strength, interference level, and channel response estimate in time and frequency domain. The layering approach to network design does not fit in the wireless network as mentioned by [32], in which an in depth analysis of cross-layering approaches for wireless adhoc has been discussed. However a number of issues should be taken into consideration as it relates to cross-layer design in wireless network using the IEEE 802.11 medium which is based on shared media and node contentions. These include traffic flow(s) which will have impact on the available bandwidth of all its neighbouring nodes, nodes transmit and receive data on a single channel; the delivery of a single traffic flow involved and the contention of channel resource within the node(s). As a result, different nodes (i.e., the source, the destination, intermediate nodes, and neighbouring nodes along the end-to-end route) may consume different amount of bandwidth resource for the transmission of a specific traffic flow.

In IEEE 802.11, the available bandwidth cannot be estimated directly from the overall throughput being achieved, because of the following reasons:

- The maximum throughput is not constant for a given data rate, is affected by the average packet length and the number of active contending nodes.
- The data rates of links are not the same due to multi-rate supports.

Therefore the cross-layer interactions is a technique to boost the performance by effectively adapt to the dynamic environment.

A number of cross layer approach have studied among two or more layers to find a common communication among the layers and to effectively derive a workable solution. In [33-36] have used the layered approach to solve the cross-layered control problem, they use a feasible rate region that is similar to the wired network with simpler set of constraints. In general network settings, it is not possible to find such simple rate region, the rate region will also reduces the set of feasible rates that congestion control can utilise. There are also a number of cross-layered designs that have been developed by researchers to jointly optimisation congestion control and scheduling [37-43]. Different layers, transport for congestion control, network for routing and MAC for scheduling and power, has shown in [43] that through limited amount of information being passed back and forth optimal performance can be achieved through cross-layer solution. Cross layer design aims at coupling the functionality of network layers, with the goal of boosting system-wide performance which showed that the trend is more evident at the interface between the physical and MAC layers was studied in [44]. More studies in cross-layer design across various layers can be obtained at [45-49].

Many research studies focus on the effect of link layer on the congestion mechanism of TCP. A solution to mitigate the problem with the TCP congestion mechanism, where it can not differentiate between congestion and packet loss due to other reasons, has been proposed in [50] where they have devised to “Smooth” the channel by suitable coding and link layer automatic repeat request (ARQ) at a faster timescale than that of TCP control. Additional reference relating to the wireless link delay is perceived as a constant channel, but lower capacity can be obtained at [51].

In [52] they consider a stationary, multi-hop wireless network using IEEE 802.11 distributed coordinated function (DCF). A single wireless channel is shared among all nodes in the network. Only receivers within the transmission range of the sender can receive the packets. In IEEE 802.11 DCF, each packet transmission is preceded by a control handshake of RTS/CTS messages. Upon overhearing the handshake, the nodes in the neighbourhood of either the sender or the receiver will defer their transmissions and yield the channel for subsequent DATA-ACK transmissions. Because they use stationary network, they did not consider packet loss due to routing breakage. They assume that multi-hop contention, i.e., due to hidden/exposed terminal problem, is the main source for packet losses. Note that packets can also get dropped due to out-of-band channel errors. In IEEE 802.11 networks, the retransmission mechanism hides most uncorrelated channel noises for non broadcast traffic.

There are many studied TCP flavours such as New Reno [53], and SACK [54], which differ in how they react to packet loss. There implementations differ by manipulating the window size of the TCP by calculating the throughput, setting threshold and checking packet drops.

Having examined cross-layer design in WSN networks, it drives the sense of awareness that in wireless network each layers are not isolated from each other but communication between them should be taken into consideration when designing or improving upon a protocol at any of the layers. The intention of this thesis is to design a novel MAC protocol for congestion control using multichannel assignment. As mentioned before, the most popular contention based MAC is the CSMA/CA where a number of improved techniques have derived such as 802.11 DCF. The transport layer, which provides the end to end communication service, mainly uses the user datagram protocol (UDP) and the transmission control protocol (TCP), that the improve techniques covered are based on to support reliable flow and congestion as well as error recovery.

The challenges to be overcome as it relates to WSN are:

- Sensor nodes are more constrained in computational, energy and storage resources because of its limited energy which are usually batteries and are difficult to replace when consumed.
- Interference among the transmission, since more nodes are deployed in a sensor network, up to hundred or thousand nodes, than in other wireless networks.
- Redundant information since in most case neighbouring nodes often sense the same events from their environment thus forwarding the same data to the base station.
- Topology changes due to node failure even though most sensor nodes are usually stationary.

The transport layer using TCP for wireless transmission will create additional challenges as TCP makes assumption that packet losses are due to congestion. In wireless networks a number of issues may cause packet losses such as:

- Bit Error Rate (BER), which is usually high base on the changes within the environment.
- Bandwidth limitation
- Round Trip Time (RTT), the overall throughput and increase in delay will be affect because of longer latency within the wireless medium.

2.5 Multichannel Multi-radio assignments

Multiple non-overlapping channels present in the IEEE 802.11 ISM free frequency band have been exploited by mapping them to multiple-radios to increase the overall capacity and connectivity of the wireless mesh network’s backbone. A centralised, graph based approach has been proposed in [55], [56] and [57] where links and nodes are considered as edges and vertices of a graph respectively and formulating radio/channel assignment by assigning edges to vertices. The limitation of these methods is that it is very difficult to capture network load information with a graph model. Network flow based centralised approaches can be found in [58],[59] and [60], where multi radio multi-channel (MRMC) is modelled based on network flows and therefore overcomes the limitations associated with graph based approaches. These approaches are not realistic as constant traffic sources are assumed all the time while network traffic can be bursty in nature. A distributed gateway centred multi-radio multi-channel approach has been developed by [13] and [14] where mesh gateways are considered as sink and source of data.

Although the MRMC enormously increases network throughput, connectivity, robustness and resilience; it requires extra resources e.g. energy because addition of extra radios consumes more power. Keeping in view these constraints, applying MRMC techniques directly to WSN's needs further investigation for optimisation. None of the research work done in this area has considered the power constraint as WSN's nodes have limited energy supplies. The use of multiple channels with a single radio can also be an interesting future study where the power limitation is kept in mind. Furthermore, the effect of channel assignment on the transport layer has been ignored by the researchers. Since the channel condition at the MAC layer has a considerable effect on the TCP congestion mechanism, it needs to be further investigated with a cross layer optimisation.

2.6 Conclusion and Future MAC-Transport

This chapter has presented an overview of the contention-based MAC protocols, transport layer protocols, cross-layered design and multichannel multi-radio assignments. A number of existing protocols were analysed, each attempting to resolve one or more problems faced by the current layers; hidden and exposed nodes, congestion, fair utilisation or reliable transportation within the medium while providing energy conservation. The MAC protocols mentioned in this chapter mainly addressed the hidden or exposed node problem in the CSMA scheme but not both simultaneously, except for PAMAS which focused mainly on energy efficiency. The 802.11 DCF that was developed mainly for wireless networks scheme will work well for short transmission range, the back-off procedure used does not work well in noisy environment, therefore the need for longer range transmission need to be explored in WSNs, as well as the consideration of the effect for channel errors.

The transport protocols for WSNs have implemented a number of techniques for energy efficiency, reliability and congestion. However these techniques mainly considered a single or multiple solutions but not a complete solution for the entire existing problem except ERST and STCP, they both attempted to resolve both congestion and reliability problem. ERST also resolved energy consumption to a lesser extent. Overall, both MAC and transport worked in isolation in resolving the problems faced by both layers and as such cross-layer design was discussed as a means to optimise both layer to have them function as an entity to combat the problems, and to obtain an energy efficient WSNs.

For future work in this area, the implementation in real sensor network to realise the full potential and integrity of most of the studied techniques are recommended in a real sensor environment. A cross layer design to optimise and confer both MAC and transport is being recommended to maximise efficiency, allow both layers to communicate simultaneously, reduce packet overhead, to provide reliable transmission and to support multimedia traffic. To have cross-layer communications takes place effectively, the need to design a MAC or transport protocol to effectively utilise the single medium transmission for the contention-based protocol is the next step to achieve such efficiency.

This thesis focused on designing a multichannel assignment MAC protocol for contention-based wireless sensor networks in order to efficiently utilise the medium by having nodes options to switch channels during congestion. This research will aid future work to address most of the major limitations in WSNs across the MAC and transport protocol, with the use of the multichannel assignment. Multichannel assignment will create additional overhead in terms of switching delays, synchronisation among the nodes, extra control packets and hence more energy. However the research considered WSN for streaming high data rate and not the traditional WSN that periodically send data to its sink node. The researcher explored multiple non overlapping channels with minimum overhead for increased capacity and minimum power usage

Chapter 3

Comparison of IEEE 802.11 and IEEE 802.15.4 for Future Green Multichannel Multi-radio Wireless Sensor Networks

3.1 Overview

Multi-channel MAC protocols have recently obtained considerable attention in wireless networking research because of their promise to increase capacity of wireless networks significantly by exploiting multiple frequency bands. This chapter compares IEEE 802.11 and IEEE 802.15.4 networks and investigates the performance between both using simulations conducted in NS2. This investigation aims to determine the feasibility of having IEEE 802.11 utilised as a future medium for wireless sensor networks operating in a multichannel environment at high data rate with streaming data that would be a challenge for IEEE 802.15.4.

In IEEE 802.15.4, each operation can only begin at the boundary of time slots. Only when the backoff counter reaches zero does the node sense the channel. The backoff counter of a node decreases regardless of whether the channel is idle or busy and the contention window size is reset to its minimum value at the beginning of each retransmission attempt. In IEEE 802.11, the notion of a slot exists only insofar as backoff counting is concerned, nodes are constantly sensing while in backoff, thereby incurring an additional consumption of energy. The backoff counting pauses whenever the channel becomes busy and the contention window size is reset to its minimum value at the beginning of each retransmission attempt.

The demonstration through simulations showed that IEEE 802.11 perform better with high data rate, streaming constant bit rate, and at longer range comparing to 802.15.4 which operates better with small data size at much shorter range.

The outcome from this chapter will be valuable for future work in designing a multichannel MAC protocol for contention-based 802.11 WSN.

3.2 Introduction

Wireless technologies continue to be a popular interest in the communication arena and are increasingly replacing the wired technology in a number of areas such as monitoring and control applications. They have also become an integral part of the Internet. The IEEE 802.11[15] and the IEEE 802.15.4 [16] standard play a vital role for contention based networks and divide the wireless spectrum into different spectral bands called ‘‘channels”. This allows simultaneous communications and limits interference between nodes. Also allowing the coexistence of multiple wireless networks on different channels, frequency division to increases capacity of the wireless networks in infrastructure mode by operating on different channels.

IEEE 802.11 is concerned with features such as Ethernet matching speed, long range (100m), complexity to handle seamless roaming, message forwarding, and data throughput of 2-54Mbps, while IEEE 802.15.4 on a space around a person or object that typically extends up to 10m in all directions. The IEEE 802.15 working group is formed to create WPAN standard. This group has currently defined three classes of WPANs that are differentiated by data rates, battery drain and quality of service (QoS).

The study of wireless sensor networks (WSNs) [1-9] has become a hot topic in networking due to the convergence of data and telecommunication over IP based networks that paved the way for communication technologies innovation and security provision that will see many systems such as closed-circuit TV (CCTV) rely on the premises of WSN surveillance systems for tracking and create alerts from sensors rather than standalone video circuits. Current development indications, herald a future of WSNs operating at high data rate for streaming data over multichannel multi-radio assignment over IEEE 802.11 networks. This chapter does a comparison of IEEE 802.15.4 and IEEE 802.11 to determine such feasibility for WSN in 2.4 GHz frequency band as opposed to IEEE 802.15.4.

The feasibility for IEEE 802.15.4 to cope in the 2.4 GHz frequency band when the IEEE 802.11n becomes popular will be problematic, as at high traffic load 802.11n will be able to use a total bandwidth of 40MHz leaving no channel for IEEE 802.15.4 and also will not be free from channel interference of IEEE 802.11n. The future of WSN - which involve sending all data monitored to a sink - will be on channel assignment.

This thesis will focus on the popular 2.4 GHz range of operation and the MAC sublayer to formulate the outcome for a future green multichannel multi-radio WSN. The chapter is organised as follows: subsection 3.3 briefly details the IEEE 802.15.4 MAC protocol to convey an understanding of CSMA/CA and PAN coordinator. Subsection 3.4 briefly details the IEEE 802.11 MAC protocol highlighting elements of CSMA/CA and DCF. Subsection 3.5, deals with related work and in subsections 3.6 and 3.7, the focus area and the simulation results are discussed. Finally, subsection 3.8 concludes the chapter.

3.3 IEEE 802.15.4

Wireless Personal Area Networks (WPANs) [16] are used to convey data communication devices with low data rate, low power, low complexity and short range Radio Frequency (RF) transmissions. Unlike Wireless Local Area Networks (WLANs), connections effected via WPANs involve little or no infrastructure. This feature allows small, power-efficient, inexpensive solutions to be implemented for a wide range of devices. The data rate is 250kbps at 2.4GHz, 40kbps at 915MHz and 20kbps at 868MHz. IEEE and ZigBee Alliance [17] have been working closely to specify the entire protocol stack. IEEE Std 802.15.4 defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements typically operating in the Personal Operating Space (POS) of 10 m. It is foreseen that, depending on the application, a longer range at a lower data rate may be an acceptable trade-off. A central controller known as the personal area network (PAN) coordinator is used to builds the network in its personal operating space. The MAC layer has two mode of operation: beacon enable and beaconless. The beacon enabled mode allows splitting of time into multiple clusters where nodes have exclusive access to the transmission channel during its active duration. In beaconless operation there is no division of time and a node competes for channel access with other nodes in its radio range using unslotted CSMA/CA algorithm. This section will focus on the beaconless operation of the IEEE 802.15.4 MAC layer.

3.3.1 Medium Access Control (MAC) Sublayer

The IEEE 802.15.4 [16] MAC sub layer controls access to the radio channel by using a Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism. This sub layer is responsible for transmitting beacon frames, synchronisation and providing a reliable transmission mechanism. The MAC sublayer provides two services: the MAC data service and the MAC management service interfacing to the MAC sublayer management entity (MLME) service access point (SAP) (MLMESAP). The MAC data service enables the transmission and reception of MAC protocol data units (MPDU) across the PHY data service. Fig. 3-1 depicts the components and interfaces of the MAC sublayer.

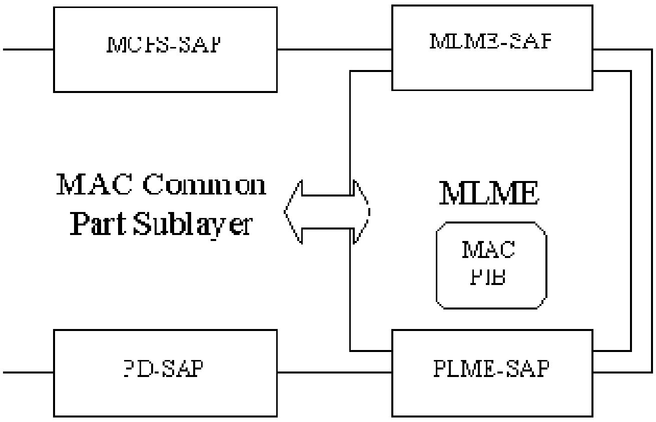

Figure 3-1: The MAC Sublayer Components [16].

3.3.1.1 CSMA-CA Algorithm

In the slotted CSMA/CA channel access mechanism each device will maintain three variables for each transmission attempt: Number of Backoff (NB), Contention Window (CW) and Backoff Exponent (BE). NB is the number of times the CSMA-CA algorithm is required to backoff while attempting the current transmission; this value shall be initialised to zero before each new transmission attempt.

CW is the contention window length, defining the number of backoff periods that need to be cleared of channel activity before the transmission can commence. This value shall be initialised to one before each transmission attempt and reset to one each time the channel is assessed to be busy. Otherwise this value shall be initialised to two before each transmission attempt and reset to two each time the channel is assessed to be busy.

The CW variable is only used for slotted CSMA-CA. In a slotted CSMA-CA system with the Battery Life Extension (BLE) subfield set to zero, the MAC sublayer shall ensure that, after the random backoff, the remaining CSMA-CA operations can be undertaken and the entire transaction can be transmitted before the end of the Contention Access Period (CAP). If the number of backoff periods is greater than the remaining number of backoff periods in the CAP, the MAC sublayer will pause the backoff countdown at the end of the CAP and resume it at the start of the CAP in the next superframe. If the number of backoff periods is less than or equal to the remaining number of backoff periods in the CAP, the MAC sublayer will apply its backoff delay and then evaluate whether it can proceed. If the MAC sublayer can proceed, it will request that the PHY perform the CCA in the current superframe. If the MAC sublayer cannot proceed, it will wait until the start of the CAP in the next superframe and apply a further random backoff delay before evaluating whether it can proceed again.

In a slotted CSMA-CA system with the BLE subfield set to one, the MAC sublayer shall ensure that, after the random backoff, the remaining CSMA-CA operations can be undertaken and the entire transaction can be transmitted before the end of the CAP. The backoff countdown shall only occur during the first macBattLifeExtPeriods full backoff periods after the end of the interframe space (IFS) period following the beacon. If the MAC sublayer can proceed, it shall request that the PHY perform the CCA in the current superframe. If the MAC sublayer cannot proceed, it shall wait until the start of the CAP in the next superframe and apply a further random backoff delay [step (2)] before evaluating whether it can proceed again.

If superframe structure is used in the PAN, then slotted CSMA-CA shall be used. If beacons are not being used in the PAN or a beacon cannot be located in a beacon-enabled network, unslotted CSMA-CA algorithm is used. In both cases, the algorithm is implemented using units of time called backoff periods, which is equal to aUnitBackoffPeriod symbols. In slotted CSMA-CA channel access mechanism, the backoff period boundaries of every device in the PAN are aligned with the superframe slot boundaries of the PAN coordinator. In slotted CSMA-CA, each time a device wishes to transmit data frames during the CAP, it shall locate the boundary of the next backoff period. The mechanism to be followed before accessing the channel is depicted in fig. 3-2 of the CSMA-CA flow chart.

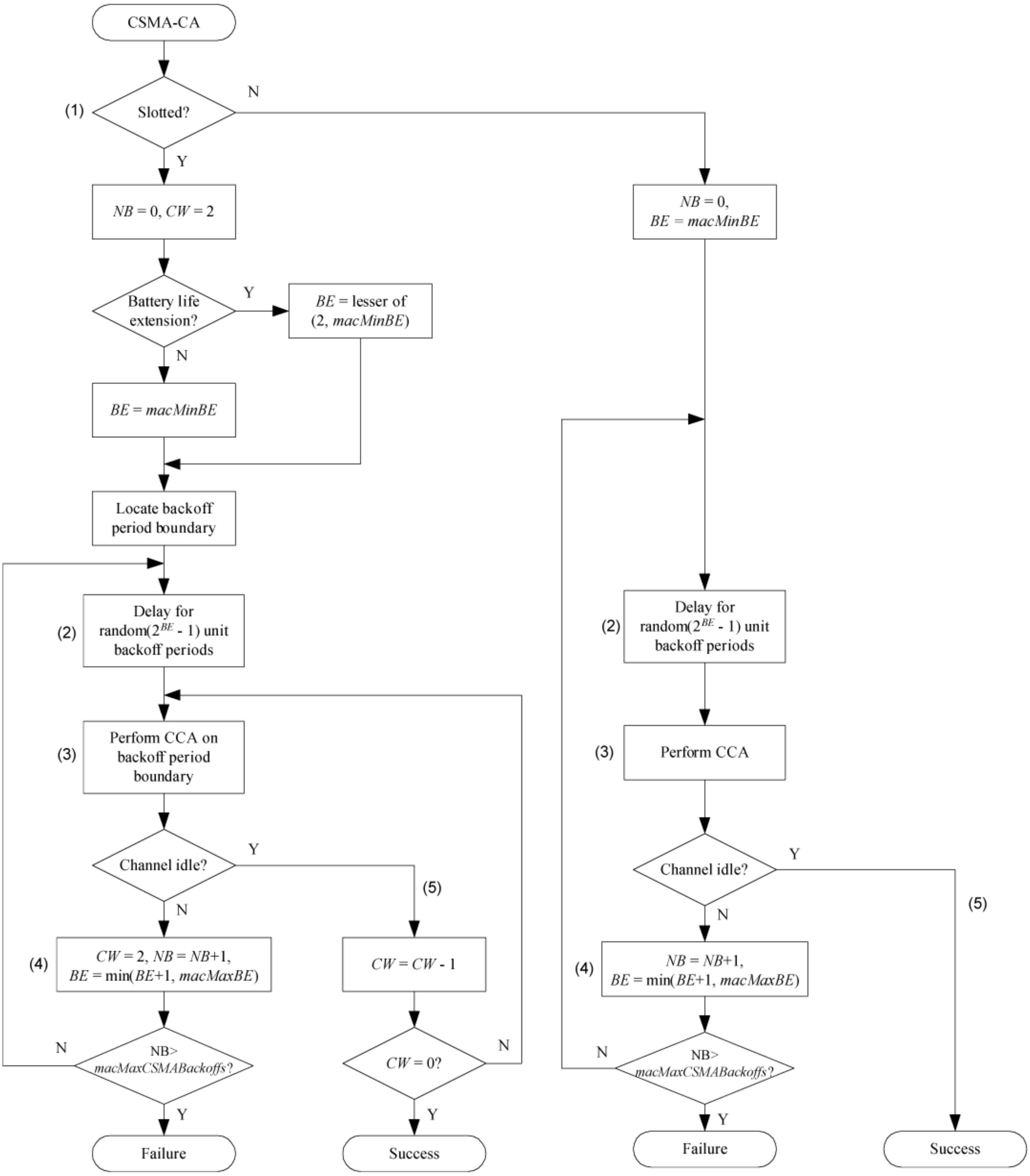

Figure 3-2: CSMA-CA Flowchart [16].

3.3.2 Channels

There are 16 channels between 2.4 and 2.4835GHz as shown in Fig. 3. The standard also allows dynamic channel selection, a scan function that steps through a list of supported channels in search of beacon, receiver energy detection, link quality indication, channel switching. The physical layer provides the capability to perform the Clear Channel Access (CCA) according to at least one of the following three methods:

- CCA Mode 1: CCA shall report a busy medium upon detecting any energy threshold.
- CCA Mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of a signal compliant with this standard with the same modulation and spreading characteristics of the physical layer that is currently in use by the device. This signal may be above or below the energy detection (ED) threshold.
- CCA Mode 3: Carrier sense with energy above threshold. CCA will report a busy medium using a logical combination of:
    - Detection of a signal with the modulation and spreading characteristics of this standard and
    - Energy above the ED threshold, where the logical operator may be AND or OR.
    -

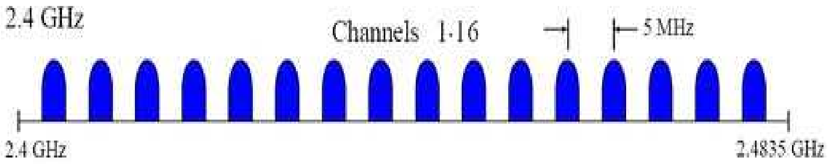

Figure 3-3: Channels for IEEE 802.15.4 [17].

3.4 IEEE 802.11

3.4.1 MAC Sublayer

The MAC sublayer [15] of the IEEE 802.11, defines the Distributed Coordination Function (DCF), the Point Coordination Function (PCF), the Hybrid Coordination Function (HCF). The focus will be on the DCF that allows automatic medium sharing.

3.4.1.1 Basic Access

The basic access mechanism called DCF is a carrier senses multiple access collision avoidance (CSMA/CA) mechanism. The CSMA protocol allows a station wishing to transmit to sense the medium, if the medium is busy it defer its transmission but if the medium is free then the station is allowed to transmit. CSMA is very effective when the medium does not have high traffic, since all medium transmit with minimum delay. Stations transmitting at the same time result in collision as the protocol initially are designed for single channel transmission. CA allows the medium that is busy and defers to wait and allow the medium to be free for a specific time called distributed interframe space (DIFS) then the station is allowed to transmit. Fig. 3.4 illustrates the basic access with immediate access when the medium is free.

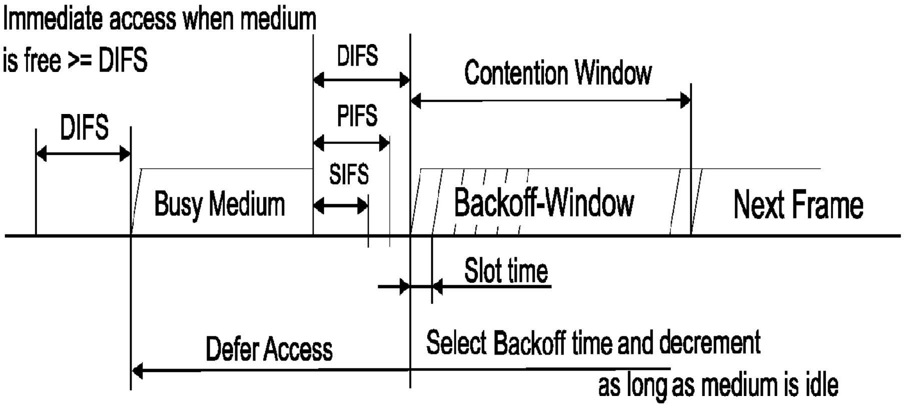

Figure 3-4: Basic Access Method [15].

3.4.1.2 DCF

DCF [15] is the basic and mandatory MAC mechanism of legacy IEEE 802.11 WLANs that allows for automatic medium sharing between compatible physical layers through the use of CSMA/CA and a random backoff time following a busy medium condition. In addition, all individually addressed traffic uses immediate positive acknowledgment (ACK frame) where retransmission is scheduled by the sender if no ACK is received.

The CSMA/CA protocol is designed to reduce the collision probability between multiple stations accessing the medium, at the point where collisions would most likely occur. Multiple collision occur more frequently after a busy period when there are multiple stations waiting on the medium to transmit their data. This situation necessitates a random backoff procedure to resolve medium contention conflicts through carrier sense (CS) functions. CS can be performed both through physical and virtual mechanisms. The virtual CS mechanism is achieved by distributing reservation information announcing the impending use of the medium. It reduces the probability of two stations colliding that cannot hear each other.

3.4.1.3 CS Mechanism

Both the physical and virtual CS functions are used to determine whether the medium is busy or idle. When either function indicates a busy medium, the medium will be considered busy otherwise, it shall be considered idle. The virtual CS mechanism is provided by the MAC referred to as the network allocation vector (NAV) which predicts the future traffic on the medium. The CS mechanism combines the NAV state and the station’s transmitter status with physical CS to determine the busy/idle state of the medium. The NAV also act as a counter, which counts down to zero at a uniform rate. When the counter is zero, the virtual CS indicates that the medium is idle and when nonzero indicates busy.

3.4.1.4 Random Backoff Time

In this procedure, a station with a packet to transmit waits until the medium becomes idle, when it senses that the medium is busy. When the medium is left idle for the duration of Distributed Interframe Space (DIFS) period, the station sets its Backoff timer to *random()***aSlotTime*. *aSlotTime* is set at a time which is equal to the time needed at any station to detect the transmission of packet from any other station. *Random()* = Pseudo-random integer drawn from a uniform distribution over the interval [0, CW], where CW is an integer within the range of values of the physical layer characteristics of the minimum and maximum window (aCWmin and aCWmax), aCWmin ≤ CW ≤ aCWmax. In 802.11 the default value of *aSlotTime* is 20 µs for 802.11b and 9 µs for 802.11a/g, if no medium activity is indicated for the duration of a particular backoff slot then the Backoff slot is decreased by *aSlotTime*. If the medium is sensed as busy during a backoff slot, the backoff timer is suspended until the medium is idled for the duration of DIFS period, then the backoff timer will resume again. When the backoff timer reaches zero, transmission will start and after the transmission gives an acknowledgement indicating whether or not the transmission was successful. If the transmission was successful, the station will set its backoff timer again before transmitting the next packet. However, the Control Window (CW) will take the next value in the series every time there is an unsuccessful attempt to transmit. This allows either station retry counter to increment, until the CW reaches the value of the maximum window size (aCWmax). Once it reaches aCWmax, the CW shall remain at the value of aCWmax until the CW is reset; Fig. 3-5 illustrates the exponential increase of CW. The CW will reset to aCWmin after every successful attempt in transmitting data or after a station long retry count.

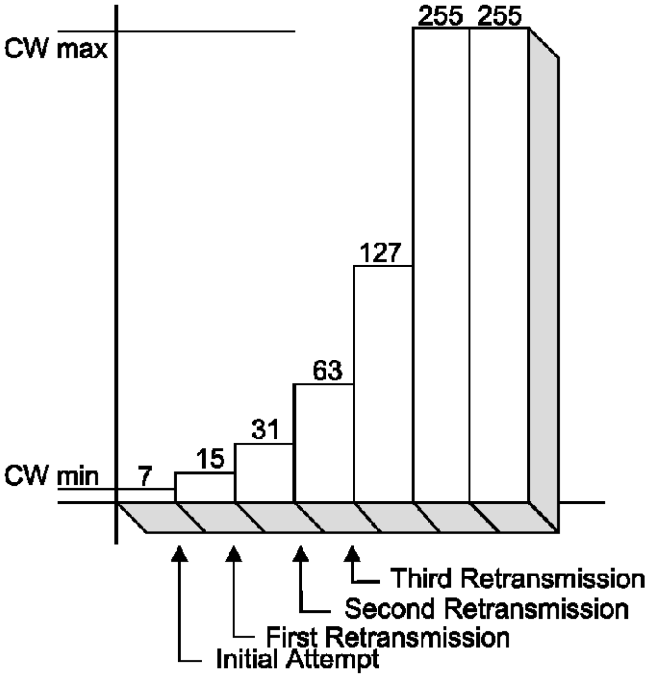

Figure 3-5: Exponential increase of CW [15].

The backoff procedure will be invoked when a station is ready to transfer a frame and finding the medium busy as by the indication of the physical or virtual CS mechanism. The backoff procedure will also be invoked when a transmitting station infers a failed transmission. The station will set its backoff timer to a random backoff following a DIFS period during which the medium is determined to be idle. The station performing the backoff procedure will use the CS mechanism to determine any activities during the backoff slot. If there is no activity indicated the backoff procedure will decrement it backoff time by aSlotTime. Figure 3-6 illustrates a backoff procedure with multiple stations deferring and go into random backoff.

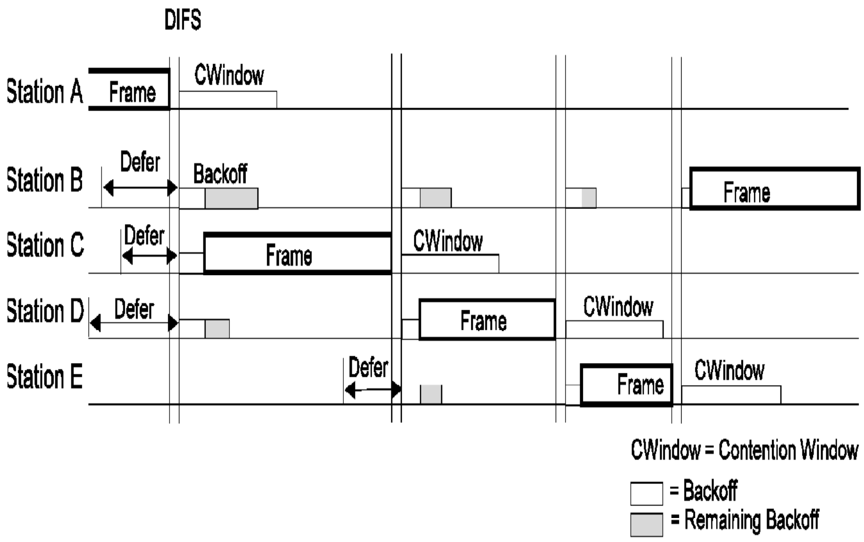

Figure 3-6: DCF Back-off Procedure [15].

3.4.2 Channels

In IEEE 802.11, there are 14 possible channels in the 2.4 GHz frequency range. The channel width is 22 MHz and each channel is spaced 5 MHz apart. This creates an overlap between channels. IT professional will often use channels 1, 6, and 11 non-overlapping to avoid using the overlapping channels. Fig. 3-7 illustrates the channel centre frequency which is defined in sequential 1.0 MHz steps beginning with the first channel. Occupied channel bandwidth will meet all applicable local geographic regulations for 1 MHz channel spacing. The rate at which the PMD entity will hop is governed by the MAC. The hop rate is an attribute with a maximum dwell time subject to local geographic regulations [15].

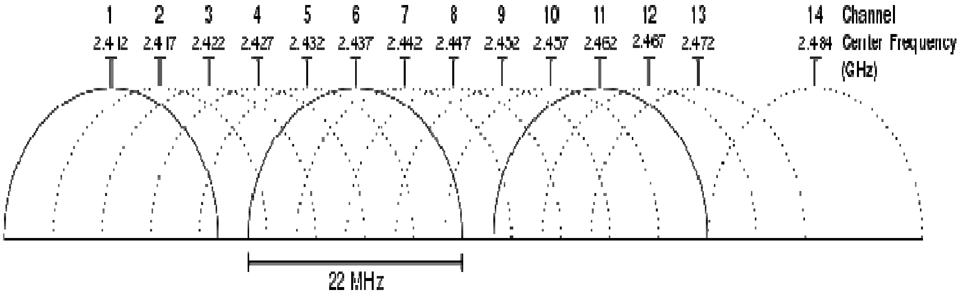

Figure 3-7: Channel Centre Frequency for IEEE 802.11 in the 2.4 GHz Range

3.5 Related Work

A number of researchers [61-72] have used a combination of both the IEEE 802.15.4 and the IEEE 802.11 networks within the WSN for comparison and evaluation in different scenarios or 802.11 is use as Access Point (AP) and at cluster heads to relay 802.15.4 sensor network data to sink and other network servers and applications. In [61] they introduce distributed algorithms to optimise the 802.15.4 performance under varying 802.11 interference pattern. Nakatsuka et al [66] adjust the 802.11 b/g protocol to prevent inter-channel interference between 802.15.4 in order to have both protocols operating in the same frequency channel, they conclude that inter-channel interference between 802.14.5 and 802.11 b/g can be mitigated by sharing time controlling traffic of 802.11 b/g but they have not considered the effect of 802.11n when it becomes popular with the multiple input, multiple output (MIMO) effect and significant increase in the maximum raw data rate from 54 Mbps to 600 Mbps with the use of four spatial streams at a channel width of 40 MHz. Bertocco et al [68] presented in their work a new simulator allowing cross-layer analysis of interference arising among 802.15.4 and 802.11 and predicts possible interference effect, this is still a work in progress for the researchers.

3.6 Formulation

Both IEEE 802.15.4 and IEEE 802.11 use the CSMA/CA mechanism for contention based network. The slotted CSMA/CA mechanism adopted with the PAN mode of IEEE 802.15.4 is different from the well-known IEEE 802.11 CSMA/CA scheme. The main differences involve the time slotted behaviour, the backoff algorithm, and the clear channel assessment (CCA) procedure used to sense whether the channel is idle. The differences are outline as follows:

- In IEEE 802.15.4, each operation (channel access, backoff count, CCA) can only begin at the boundary of time slots, which recall is termed backoff periods. In

IEEE 802.11, the notion of a slot exists only insofar as backoff counting is concerned.

- In IEEE 802.15.4, only when the backoff counter reaches zero does the node sense the channel (CCA).
- In IEEE 802.11, nodes are constantly sensing while in backoff, thereby incurring an additional consumption of energy.
- In IEEE 802.15.4, the backoff counter of a node decreases regardless of whether the channel is idle or busy. In contrast, in IEEE 802.11 the backoff counting pauses whenever the channel becomes busy.
- In IEEE 802.15.4, unlike in IEEE 802.11, the contention window size is reset to its minimum value at the beginning of each retransmission attempt.

When IEEE 802.15.4 and IEEE 802.11 use the same channels, their CSMA/CA functions enable them to share the same time slot. When the same channels are used by both it cause 802.15.4 to suffer long delays while having 802.11 with a higher frequency range provides priority access of the channel in most cases. An overlap between them can adversely impact on the operation of IEEE 802.15.4, since it is a low power protocol which uses a small channel width compared to the transmitted power levels and channel width used by IEEE 802.11. The frequency bands in which these interference issues are more critical for wireless network include the 2.4 GHz Industrial, Scientifical and Medical (ISM) band. See Fig. 3-8 showing 802.11 and 802.15.4 channels in the 2.4 GHz ISM band.

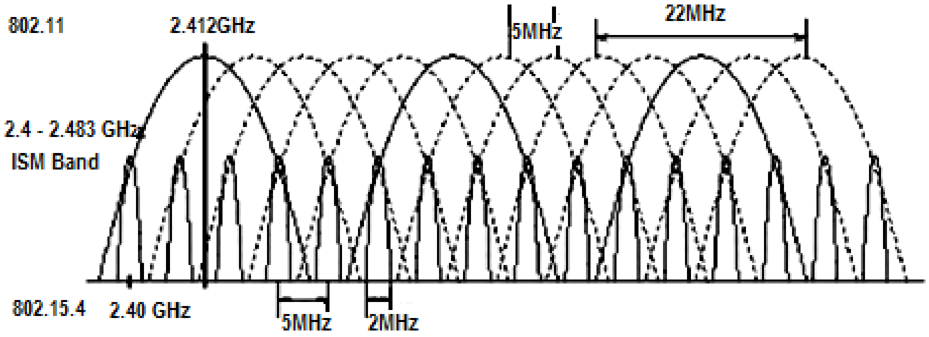

Figure 3-8: Channels Comparison of 802.11 and 802.15.4 [65].

In non-beacon enabled mode and under moderate data rate, the new IEEE 802.15.4 standard, compared with IEEE 802.11, is more efficient in terms of overhead and resource consumption. It also enjoys a low hop delay on average. However, 802.11n can have a data rate as high as 248 Mbps in the same frequency band as the other standards. The major large in increase in data rate and range is achieved by using technique called Multiple-Input Multiple-Output (MIMO). MIMO uses more than one sender and receiver antennas and combines this with special coding techniques in order to squeeze even more data through the same frequencies. For example in Polepalli et al [71] their test bed results showed that an overlap with IEEE 802.11n control channel causes severe deterioration in both loss rate and packet latency for IEEE 802.15.4 traffic and that the overlap is much more serious with the extension channel of 802.11n. IEEE 802.11 is better suited for high rate sensor and voice applications, while 802.15.4 is better suited for low rate sensors and devices used for control applications that do not require high data rate but must have long battery life, low user interventions and mobile topology. The new short range, low power, low rate wireless networking protocol, 802.15.4, complements the high data rate technologies such as WLAN and open the door for many new applications when using a combination of both because the predicted environment of these devices demands maximisation of battery life. The protocols tend to favour the methods which lead to it, implementing periodic checks for pending messages, the frequency of which depends on application needs. However when the environment intends to focus purely on high data rate with streaming data such as multimedia systems and sensor surveillance system that rely on their image and data over wireless networks, the consideration of 802.11 need to be the focus as such systems will not be able to cope with periodic transmission.

3.7 Simulation Results and Discussions

The simulation model used is based on NS2 [18] using the existing MACs protocol stack and the work done for cognitive radio cognitive network (CRCN) [73] GUI, SNR lab/Michigan Technological University and the Hyacinth model [19] for multi-channel, single-radio. This model already provided many radio models including 802.11 and 802.15.4, this NS2 also incorporates different topology and traffic generator which enable the creation of different simulation scenarios. Different simulation scenarios will be studied according to three different performance metrics: aggregate throughput, delivery ratio and access delay. The sensor nodes are randomly placed in a 1000x1000m^2 area. The number of nodes is 50 and simulation run for 300s. Data will be sending to a sink node. The distributed coordination function of IEEE 802.11 and IEEE 802.15.4 is used as the MAC layer. The researcher does not assume large networks that are densely deployed; but considered a sensor network with continuous streaming data that could be deployed for organisation, parks and vehicular traffic not for remote monitoring. In this instance nodes will always be static and powered and as such the depletion of battery life is not considered. The simulation of CBR traffic is to be sent every 2 seconds to prevent buffer overflow and to replicate streaming data and investigated the effect of both 802.11 and 802.15.4 to analyse the effect with different data rates at different ranges.

Figure 3-9 represents an access delay comparison between the 802.11 and the 802.15.4 networks. The access delay is the backoff time used in both networks. Nodes only transmit to neighboring nodes within range. In this scenario nodes were placed at an interval of 10m and the data rate set at 100kbps, access delay was measured in units of seconds. This comparison aimed to determine the efficiency of either network in relation to access delay based on distance between nodes and varying data rates.

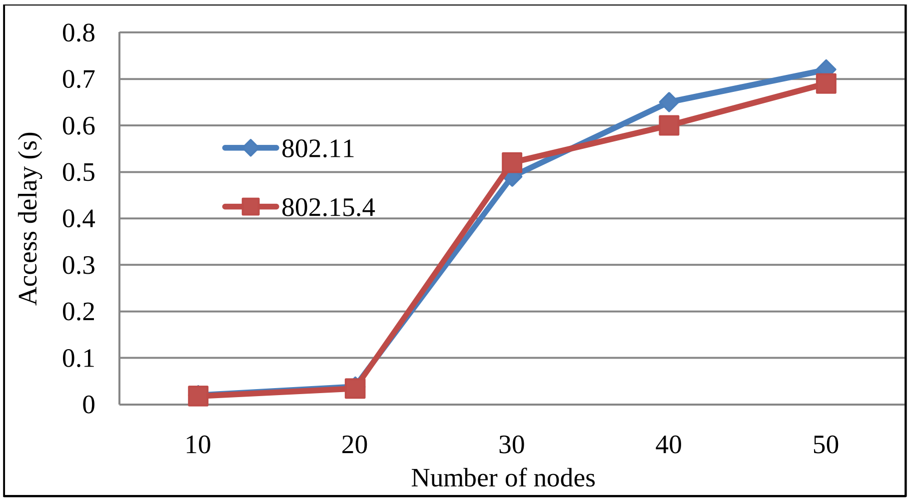

Figure 3-9: Delay comparison for 802.11 and 802.15.4 at 10m range and data of 100kbps.

Both networks performed virtually similar when transmitting data in this scenario up to 20 nodes. However, after 20 nodes both protocols start experiencing high delay in transmitting data packets. The comparatively higher delay experienced after 30 nodes at low data rate resulted from streaming data which created buffer overflow and constant backing off as all nodes are contending for the medium and the succession of the data is not periodic. Even though 802.11 was designed for high data rate [15] the simulation result indicated that it can perform at lower data rates and short ranges. Both networks utilises the CSMA/CA scheme when sending data. The protocol overheads that associate with this scheme such as the contention process, interframe spacing, physical layer level headers (Preamble + PLCP) and acknowledgment frames, impact negatively on small data size, consequently rendering 802.11unfeasible to operate at low data rate.

Figure 3-10 compares the Access Delay performance of both networks in a scenario where the interval between nodes is increased from 10m to 50m range and data rate increased from 100kbps to 2Mbps. When the distance between nodes and the data rates is increased a significant difference in access delay between networks resulted. The result showed that 802.11 out-performed 802.15.4 by over 65% and that the 802.11 had a significantly lower delay in packet transmission, but gradually access delay increased after 30 nodes. This is normal as all nodes are contending for the same medium.

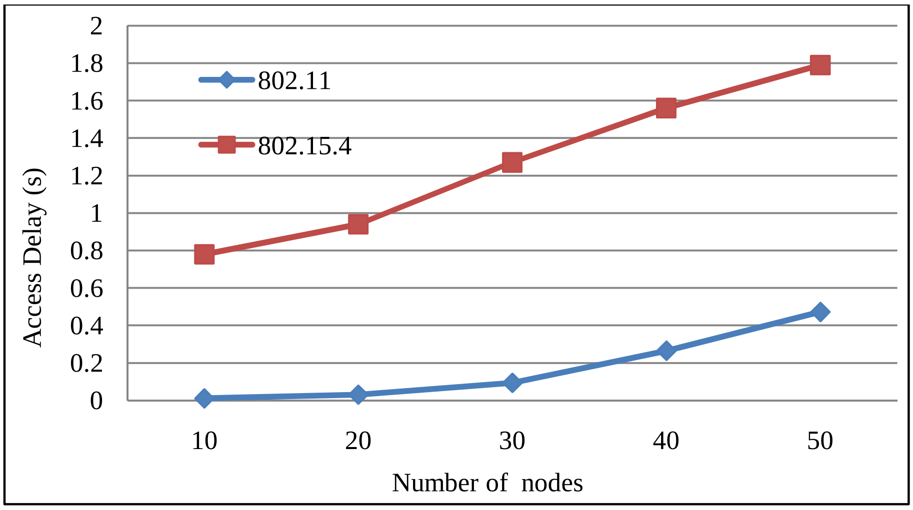

Figure 3-10: Delay comparison for 802.11 and 802.15.4 at 50m range and data of 2Mbps.

The comparatively poor performance of 802.15.4 occurred because of the high data rate, streaming data and the distance to transmit data; these effect have caused buffer overflow, data loss, constant backing off of the medium which does not allow the capability of 802.15.4 to operate effectively under such severe constraint. The result is consistent with 802.15.4 network which perform more effectively at short ranges between nodes and with small data packet size [62], therefore it is inconsistent for 802.15.4 network to operate efficiently with streaming data – which require high data rate.

Figure 3-11 represents a Packet Delivery ratio comparison between 802.11 and the 802.15.4 networks, based on distance between nodes and varying data rates. The delivery ratio is the ratio of total number of packets received by the nodes to the total number of packets transmitted multiplied by the total number of receivers. In this scenario the nodes were placed at an interval range of 10m, and data rate set at 100kbps. The performance of both networks followed the same basic pattern, that is, packet delivery ratio decreased progressively as the number of nodes increased. 802.11 perform slightly better after 20 nodes than 802.15.4.

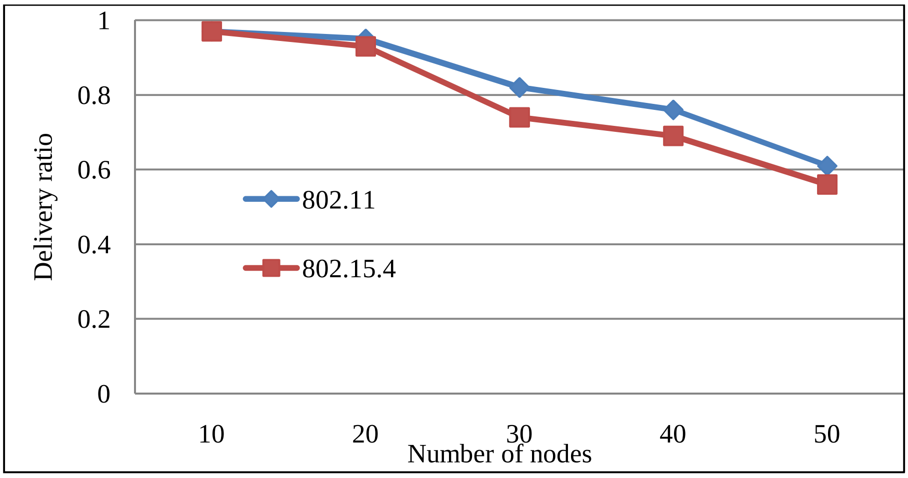

Figure 3-11: Delivery ratio comparison for 802.11 and 802.15.4 at 10m range and data of 100kbps.

Figure 3-12 represents the Packet Delivery ratio comparison between both networks when the interval between nodes is increased from 10m to 50m range and data rates increased from 100kbps to 2Mbps. Similar to the access delay scenario, when the distance between nodes and the data rates are increased the 802.11 network significantly outperformed the 802.15.4 network. This result indicates that 802.15.4 cannot perform well with streaming data even if operating at low data rate and would not be feasible for sensor network with multimedia or surveillance system that rely on image and data over the wireless medium.

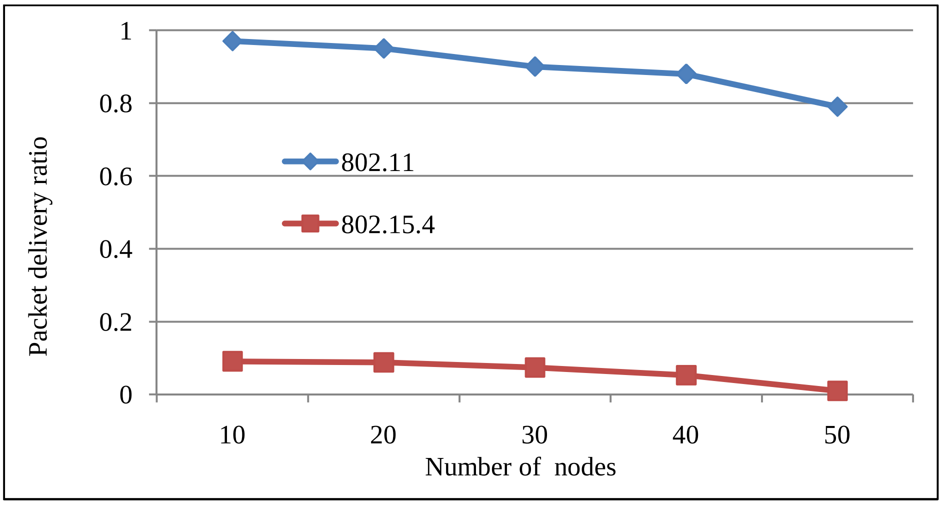

Figure 3-12: Delivery ratio comparison for 802.11 and 802.15.4 at 50m range and data of 2Mbps

Figure 3-13 represents the Aggregate MAC throughput comparison between the 802.11 and the 802.15.4 networks. The Aggregate MAC throughput is denoted by the total amount of data delivered to the sink per unit time by the MAC protocol, and is measured in kbps. In this scenario the distance between nodes is 10m and the data rate set at 100kbps. The result indicated that has the number of nodes increased aggregate throughput declined over both networks. This decline was greater in the 802.15.4 network as compared to the 802.11 network.

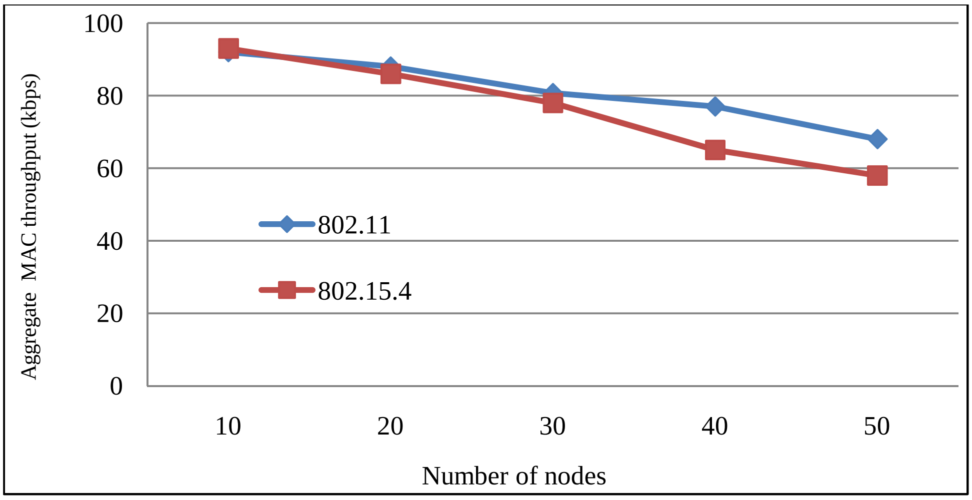

Figure 3-13: Throughput comparison for 802.11 and 802.15.4 at 10m range and data of 100kbps

Figure 3-14 represents the Aggregate MAC throughput comparison between both networks when both distance between nodes and the data rate are increased. The interval between nodes was increased from 10m to 50m and the data rate from 100kbps to 2Mbps.

As was evident from the Access Delay and Delivery Ratio tests; a significance difference in performance resulted in both networks when distance between nodes and data rate were increased.

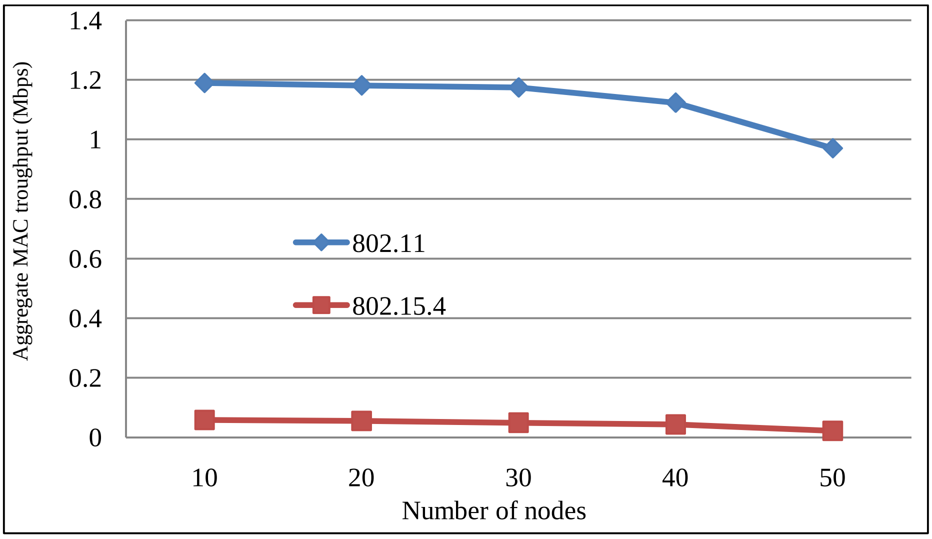

Figure 3-14: Throughput comparison for 802.11 and 802.15.4 at 50m range and data of 2Mbps

The 802.11 networks exhibited comparatively higher aggregate throughput when compared to the 802.15.4 indicating its superior performance in a high data rate environment. On the other hand the significantly poor performance of the 802.15.4 network in a high data rate and wide node range environment make it unsuitable for streaming data in a WSN.

3.8 Conclusion

In this Chapter the MAC sublayers for IEEE 802.15.4 and IEEE 802.11 MAC protocol were studied to aid the understanding of 802.11 and 802.15.4 CSMA/CA scheme. The performance of both have been investigated and evaluated through simulation results conducted in NS2 to make a rational decision which protocol is feasible for future WSN operating with multimedia or surveillance system in a multichannel multi-radio environment. The result obtained from simulation outcome through streaming data with 100kbps and 2Mbps at 10 and 50m range respectively, shows that 802.15.4 is at a disadvantage performing at long range with high data rate streaming and or at low data rate with streaming data. The aggregate throughput, delivery ratio and access delay performance metrics were used, where 802.15.4 performed very poorly at high data rate and having 802.11 perform slightly better after 20 nodes at low streaming data rate. It was concluded that 802.15.4 is not feasible for sensor multimedia or surveillance system with streaming data for future multichannel multi-radio systems.

Having investigating the performance between IEEE 802.11 and IEEE 802.15.4 it became feasible to design the 802.11 contention-based protocols for multichannel assignment. The proposed design is a multichannel distributed coordinate function over single radio for WSNs. The designed protocol was tested with simulation scenarios from NS2. The overall goal for such design proposal was to utilise multichannel transmission for future 802.11 wireless sensor surveillance systems to process video data for automated real-time alerts and also to consider a more cost effective solution for WSN.

Chapter 4

Multi-channel Distributed Coordinated Function over Single Radio in Wireless Sensor Networks

4.1 Overview

Multi-channel assignments are becoming the solution of choice to improve performance in single radio for wireless networks. Multi-channel allows wireless networks to assign different channels to different nodes in real-time transmission. In this chapter, a new approach, Multi-channel Distributed Coordinated Function (MC-DCF) which takes advantage of multi-channel assignment is examined. The backoff algorithm of the IEEE 802.11 DCF was modified to invoke channel switching, based on threshold criteria in order to improve the overall throughput for wireless sensor networks (WSNs) over 802.11 networks.

Simulation experiments were conducted in order to investigate the characteristics of multi-channel communication in wireless sensor networks using an NS2 platform. Nodes only use a single radio and perform channel switching only after specified threshold is reached. Single radio can only work on one channel at any given time. All nodes initiate constant bit rate streams towards the receiving nodes. In this work, the impact of non-overlapping channels in the 2.4 frequency band was studied based on: Constant Bit Rate (CBR) streams, node density, source nodes sending data directly to sink and signal strength by varying distances between the sensor nodes and operating frequencies of the radios with different data rates.

Results showed that multi-channel enhancement using the proposed algorithm provides significant improvement in terms of throughput, packet delivery ratio and delay. This technique can be considered for WSNs future use in 802.11 networks.

4.2 Introduction

Wireless Sensor Networks (WSNs) [1-4] are used over a wide range and in varying fields such as military application, environmental monitoring, medical care, smart buildings and other industries. WSNs sensors are generally deployed randomly in the field of interest, delivering myriad types of events from simple periodic reports to unpredictable bursts of messages triggered by external events that are being sensed. These sensor nodes will work collaboratively to sense a given environment, perform in-network computations and communicate with a base station when a targeted event occurs. A large number of WSN based applications are emerging when compared with conventional wireless networks. WSNs also have several defined characteristics including limited transmission bandwidth, limited computation capability of individual nodes and limited energy supply. The current WSNs paradigm also has some interesting features including self-organisation, dynamic network topology and multi-hop routing. These are important features for many real world applications nowadays.

The 802.15.4 standard defines a protocol for Low Rate Wireless Personal Area Networks (LR-WPAN). This allows for low cost of components, reduced coverage area, low transmission power, low bit rate and energy consumption [64]. The 802.15.4 PHY layer can operate at 868MHz, 915MHz and 2.4GHz bands. The network bandwidth is very limited and the MAC layer packet is very small with a typical size of 30 – 50 bytes compared to 512 bytes in the 802.11 networks. The 802.15.4 networks typically operate at 2.4GHz Industrial, Scientific and Medical (ISM) band, which is used by popular 802.11 networks as well.

A number of researchers [66-72] have used a combination of both the 802.15.4 and the 802.11 networks within WSNs for comparison and evaluation purposes considering different scenarios, or 802.11 is used as an access point (AP) and at cluster heads to relay 802.15.4 sensor network data to sinks and other network servers and applications. When 802.15.4 and 802.11 are using the same channels, their CSMA/CA functions enable them to share time slots. However, using the same channels will cause 802.15.4 to suffer long delays while having 802.11 with a higher frequency range provides priority access of the channel in most cases. An overlap between them may adversely impact on the operation of 802.15.4, since it is a low power protocol which uses a small channel width compared to the transmitted power levels and channel width used by 802.11. The frequency band in which such interference issues are nowadays more critical for wireless networks.

The 802.11 standard [15] defines a communication protocol for wireless local area networks (WLANs), providing a total of 14 frequency channels, each of which is characterised by 22 MHz bandwidth. The fundamental media access method of the 802.11 is a DCF known as Carrier Sense Multiple Access with collision avoidance (CSMA/CA). It is a contention-based protocol that concentrates on the collisions of transmitted data and was developed mainly for wireless networks. Applying a multi-channel assignment to this scheme would help to reduce contention for a single medium, collision and congestion.

Multi-channel as it relates to wireless networks is used to assign different nodes to different channels in real-time transmission. This gives rise to having communications on different frequency bands. When sensor nodes are densely deployed, single channel MAC protocols may be inadequate due to a higher demand for the limited bandwidth. There have been a number of proposed MAC protocols lately, in order to improve network performance in WSNs using multi-channel assignments [58, 60, 74-85].

The research focused on the design of multi-channel communication based on the 802.11 DCF over a single radio for WSNs in order to improve its communication performance namely throughput, end-to-end delay and channel access delay. Multi-channel protocols utilise bandwidth better and thus may perform favorably in cases of applications demanding high data rates. The 802.11 standards provide up to 12 non-overlapped channels, respectively, in 2.4 GHz and 5 GHz spectrums. Nodes within the transmission range of each other can operate on different non-overlapped channels so as to avoid interference. The following factors are considered when focusing on using 802.11 for WSNs:

- Like 802.15.4, the 802.11 DCF operations are also based on the CSMA/CA algorithm. It can be used for a wireless sensor surveillance system that is low-cost, reliable, easy to manage, easy to deploy and can process video data for automated real-time alerts. Despite much attention in recent years, researchers have yet to achieve the goal of long term, independent operations of sensor network deployments under this constraint.

- 802.15.4 is applied to low data rate and short distance communication sensor networks where topology of a sensor network changes very frequently. Having 802.15.4 and 802.11 operating within the same frequency band may become problematic when 802.11n networks are in use. 802.11n has several new features such as the use of multiple input and output streams (MIMO) and channel bonding that would allow the data rates up to 450 Mbps to be achieved. In particular, channel bonding refers to the use of a 20MHz wide extension channel in addition to the control channel used by 802.11 networks. At high traffic loads, an 802.11n network would use a total bandwidth of 40MHz when operating in 2.4GHz band. Two or more 802.11n networks operating in the same location with an 802.15.4 network would leave no 802.15.4 channel free from 802.11n interference.

The rest of this chapter presents related work, the proposed system model and how nodes are assigned to channels, simulation results, and the performance analysis. Finally the conclusion is presented.

4.3 Related Work

Multi-channel assignment for WSNs has been studied by a number of researchers. The hybrid approach studied in [74] are similar wherein each node has a fixed interface on a common channel which is used for package control and exchange while the other interfaces are switched among the remaining channels for data transmission.

Other hybrid multi-channel protocols in [58] consist of two parts wherein one part handles MAC issues such as queuing, switching and broadcast and the second part is a distributed assignment algorithm. These models maintain a table which records the channels being used by its neighbors. In this technique, nodes constantly check the table in order to determine the number of nodes assigned to a channel. In [75], they also proposed a hybrid approach for each semi-fixed channel assignment, a heuristic algorithm used based on transferring from a coloring based problem.

In [58, 60, 75-76] static and dynamic strategies were used to assign channels. In [74], a load-aware channel assignment was proposed. In [74,77-80], multi-channel MAC protocols were proposed; these protocols either require multiple radio transceivers at each node or certain kind of messages for channel negotiation. However, using multiple transceivers require the use of energy which is a constraint in WSNs. In this case channel negotiation packets are not seen as a small overhead. Both TMMAC [81] and MMSN [82] are multi-channel MAC protocols designed for WSNs. They are protocols that were designed to assign different channels to nodes in a two hop neighborhood so as to avoid potential interferences.

Simulation results show that they improve performance compared to single channel protocols. The downside is that a node has a different channel from its downstream and upstream nodes. In the multi-hop flow, nodes have to switch channels in order to receive and forward packets. This causes frequent channel switching and potential packet losses. In order to prevent packet loss these protocols use some negotiation or scheduling schemes to coordinate channel switching and transmission among nodes with different channels. The challenges they face are that they need many orthogonal channels for channel assignment in dense networks; they also require precise time synchronisation at nodes with frequent channel switching delays and scheduling overheads especially for high data traffic. In [80], empirical experiments with Micaz motes were done to show that node-based protocols may not be suitable for WSNs in practice.

In [83], a channel scheduling mechanism is used to manage and decide when a node should switch channel to support the current communication requirements. They also adopt the graph base approach.

Ozlem et al. [84] proposed a multi-channel scheme based on LMAC which allows the node to utilise new frequency channels on-demand, if the network reaches a density limit. This method is composed of two phases, one where the nodes try to select timeslots according to the single channel in LMAC rule and the second involves nodes which are unable to grab a timeslot in the first phase invite the neighbor nodes which are free to listen to them on an agreed channel or time slot.

Nasipuri's scheme [85] was one of the first multi-channel CSMA protocols that used channel reservation. If there are *N* channels, the protocol assumes that each node can monitor all *N* channels simultaneously with *N* transceivers. This multi-channel scheme was just a simple extension from the single channel 802.11 MAC, which requires each node to have *N* transceivers with one for each channel; this was not feasible for a practical system.

4.4 Proposal for MC-DCF

This approach will use multi-channel assignments in 802.11 DCF over a single radio for WSNs known as MC-DCF. Node interface will be able to switch between channels. The approach will have all nodes aware of the channels in use but each node interface can only tune into one channel at a given time. At initialisation, a random assigner that employs uniform distribution will be applied to distribute node interfaces to channels. This ensures that each channel will have about the same number of neighboring nodes assigned to it at start up. A number of approaches that have been used are highlighted in the related work. This will increase the number of nodes that are granted access to the wireless medium.

In this approach nodes will switch channel when the contention window of DCF has reach an assign threshold. The sink node will perform interface switching in order to receive data from channels coming from source nodes. If there is a collision, the MAC method will invoke the backoff procedure implemented within the MAC protocol. Nodes will only monitor activities on the current channel they are assigned to and when switched to another channel it will listen to the signal within range and update itself. If all the channels are busy they will revert to backoff state.

4.4.1 Existing Challenges

There were existing challenges in WSN that needed to be considered when operating in the 802.11 network, which were considered in our simulation set-up. These issues which included interferences among neighboring nodes were addressed using non-overlapping channels. Bandwidth limitation, hidden terminal nodes and single channel architecture were addressed with the use of multichannel. The considerable decrease in the performance of 802.11 DCF in multi-hop network due to collision, and Contention for the medium was addressed by utilising channel switching technique. The topology of sensor network which changes very frequently, as well as the limitation in energy consumption was addressed by the use of static nodes.

4.4.2 IEEE 802.11 DCF Backoff Procedure

The original random backoff timer is invoked when finding a medium busy by the carrier sense (CS) mechanism of the DCF. This will be modified to invoke channel switching based on a set threshold criteria. The implementation will be done in NS2 for multi-channel, single-radio by using the existing MACs protocol stack and the work done by for cognitive radio cognitive network (CRCN) GUI, SNR lab/Michigan Technological University and the Hyacinth model. In the designs, multiple channel objects have been created through the TCL library. Nodes will be switching to different channel objects during the simulation process. During network initialisation all nodes will be made known of the channels by a channel notifier. The channel sensor invokes the random assigner after the channel notifier updates node of all channels on the network and will uniformly distribute radios of nodes to a channel in a load balancing format. When a node intends to transmit and senses that the medium busy, it will back-off and re-try. If the contention window threshold is reached the sensor will invoke and initiate channel switching. Nodes will switch to other channels in order to check if they are busy. If another channel is free, a node will update itself off its neighboring node on the same channel and will transmit based on the MC-DCF procedure in Figure 4-1.

MC-DCF Procedure

<table>
<tr><td>Channel is free
Immediate Access</td><td>DIFS</td><td colspan="2">Data</td></tr>
<tr><td>Busy Channel</td><td>Back-off timer</td><td colspan="2">Contention window</td></tr>
<tr><td>Differ Access</td><td colspan="2">Threshold</td><td>Channel switching</td></tr>
</table>

Figure 4- 1: MC-DCF procedure.

4.4.3 Multi-Channel

In the design approach, dynamic assignments have been utilised. As regards the dynamic assignment, each node is assigned a channel for data transmission, once sending data the node will not be able to switch channel. It will be able to switch channel if searching for an available channel to transmit and update its information about neighboring nodes on the same channel. Each node will know the number of channel available for switching at initialisation. Having a dynamic assignment utilising a single interface can provide significant performance benefits over a static approach - as it can potentially utilise instantaneous traffic or interference information and reduce wastage of the precious already limited bandwidth. This is due to the fact that WSN cannot provide reliable and timely communication with high data rate requirements over single channel because of interference, radio collision and limited bandwidth, since they are mainly for nodes placed in a remote area that periodically send data to the host.

Why multi-channel over 802.11 DCF which uses high data rate? As previously mentioned in this work WSN is an emerging technology that has become one of the fastest growing areas in the communication industry. The demand for using this medium is increasing with a wide range of deployment for monitoring, surveillance systems and other multimedia systems such as streaming or real time data. With this in mind, 802.11 standard has been utilised which uses a range of data rate.

4.4.4 Channel Switching

Nodes are not bound to a particular channel and have the option of switching between channels. Channel switching among sending nodes will only occur after a set threshold has been reached during the backoff period. The radio will not switch during transmission, as this can cause data packet to get lost or corrupted. Therefore, during transmission the radio will remain on the channel until completion of transmission. However, at the receiving/sink node channel switching will be more intense as the sink node will be receiving data from more than one source nodes. The switching delay incurred will depend on the packet size being received at each interface. Consider for example a data packet of 1kb being accepted. On the premise that the maximum data capacity for the medium is 54Mbps, the time taken for transmission of $54x10^6$ bits - representing the link capacity - is equal to 1 second. Time required to transmit one bit ($54*10^6$) = packet size (1kb or 8000 bits) divided by data rate.

Hence:

Time taken by 1 bit $\frac{8000\ b}{54*10^6\ bps}$

The radio will take 160µs to switch to the next channel.

The impact of channel switching will be studied from simulation scenarios between the sources that are sending data directly to the sink.

4.4.5 System Modeling

In order to develop sensor algorithms for assigning all channels to node interfaces, channel checking and switching, this proposal has utilised the 802.11 DCF contention based protocol where decisions are made base on the window size and backoff algorithm on multiple non-overlapping channels over single radio. The problem in a contention based network is that all nodes contend for the same medium. Multi-channel will have nodes contending for greater than one channel instead of a single channel. The backoff mechanism of DCF cannot provide deterministic upper bound channel access delay for sensor networks. The contention and backoff strategy is unfair to the already existing nodes that are backing off. Implementing channel sensor and switching within the backoff mechanism will eliminate the unfair strategy on the backing off for all nodes and a node will only keep updated with its neighboring nodes with range on the same channel. This approach is a novel one that has not been done by any other research to the knowledge of this author. The overall goal for this design is to have multi-channel sensor network with 802.11 so that nodes can switch channels and prevent severe delay, packet losses, increased throughput and having nodes options of channel to transmit, with no central scheduler to assign channels. As constant traffic sources cannot be assumed at all times and traffic can be bursty in nature.

4.4.6 Design Approach

NS-2 is used as the simulation platform. At initialisation, all nodes are made aware of the number of channels available through a channel notifier. When a node requires transferring data, the Carrier Sense (CS) mechanism is invoked in order to determine if the channel is busy or idle. If the CS is zero, this indicates that the channel is idle; otherwise the channel is busy and will be determined as transmitting data. During the backoff period of the original DCF, the contention window (CW) parameter will take an initial value of the control window (CWmin). The CW will take the next value in series every time an unsuccessful attempt to transmit causes the retry counter to increment. When the CW reaches maximum (CWmax), it will remain until the window is reset. In the proposal model the retry counter will reach its threshold after the third attempt and switch channel based on the design parameters. Nodes will enter wait state if all channels are busy.

In Figure 4-2 during initialisation of the network, the channel notifier uses combined functions from the management system in order to obtain information regarding the number of interfaces at the upper layer by invoking a logical communication with the Distribution System Medium (DSM) [15] at the MAC sub layer. The channel notifier will assume that all nodes are in the same basic service set (BSS) and broadcast all the available channels within the BSS. The random assigner and channel switching is under control of the channel sensor that references the channel notifier. The sensor invokes the random assigner after the channel notifier updates nodes of all channels on the network.

The assigner keeps a count of interfaces from which a uniform distribution algorithm mandates the proportionality for each channel i.e. how many interfaces to a channel. The random assigner randomly assigns interfaces to channels during the initialisation process. Each node keeps updated information of its neighbors on the same channel within range by sensing the medium periodically and learning about the medium through the virtual carrier sense mechanism [15]. The CS also determines the busy/idle state of the medium as outlined in [15].

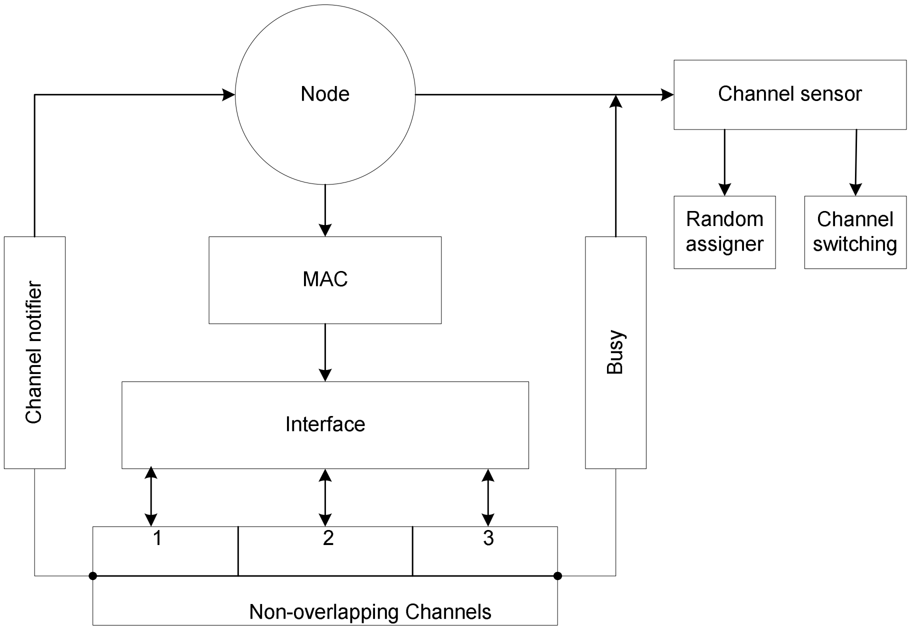

Figure 4-2: MC-DCF Design Model

The MC-DCF model proposed for WSN in Figure 4-2 is a multi-channel model using a contention based technique in a carrier sensed co-coordinated function process. This multi-channel backoff model brings added qualities of the diverse MAC resolution mechanisms of WSN. It is made up of three different MC-DCF techniques: channel notifier, channel sensor and the non-overlapping channels. These techniques allow nodes to be aware of the available channels, switch to another channel and to enter wait state when no channel is available.

During channel assignment where C is the number of non-overlapping channels available and N_i is the number of nodes interfaces to be assigned to channels within the IBSS (B).

$C = (C_1, C_2, C_3, \ldots C_n)$, where n is the channel number $N = (1, 2, 3, \ldots i)$ where i is the total number of node interfaces. The calculated uniform distribution equation is:

$$\frac{\sum_{i=1}^{C} N_i}{\mathrm{C}} \qquad (4.1)$$

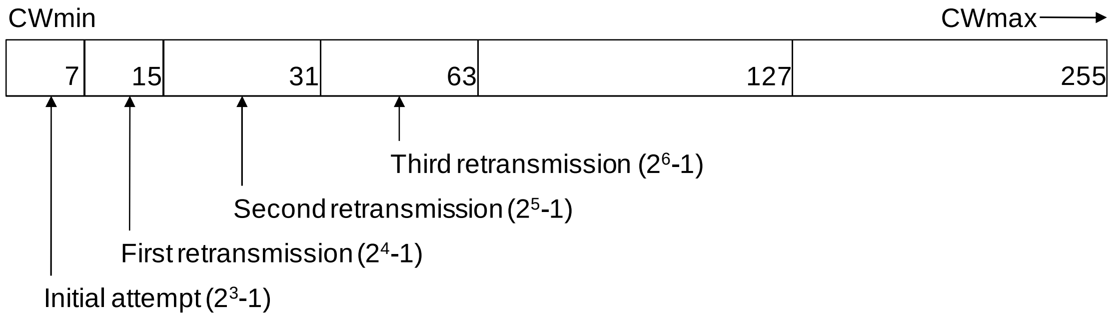

Figure 4-3: Contention window with defined threshold 2^6-1.

When a station (STA) wishing to transmit and sense busy, the CW shall take the next value in series every time an unsuccessful attempt to transmit causes the STA retry counter to increment. The channel sensor shall maintain a retry counter and after the define threshold is reached; it will invoke the channel switching parameter. Figure 4-3 shows the contention window with the define threshold 2^6-1.

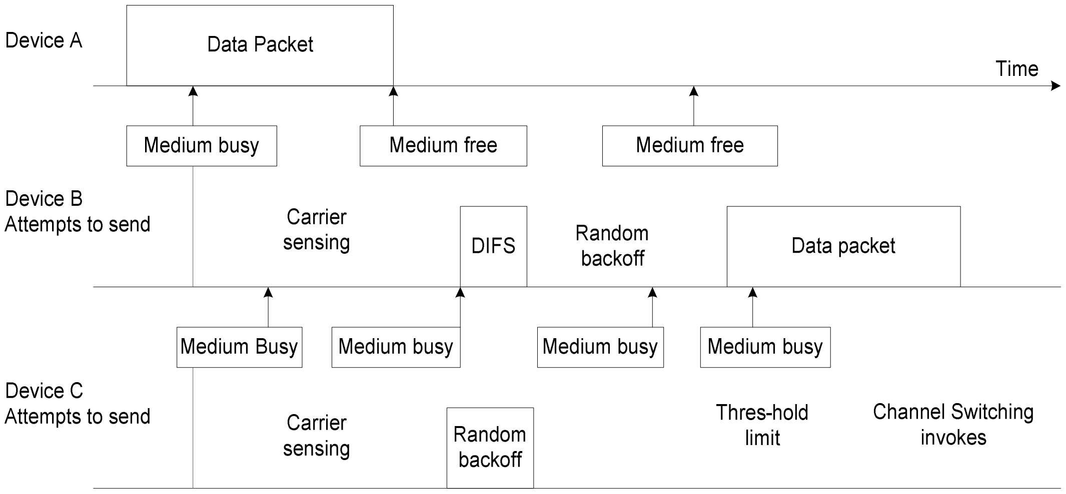

Figure 4-4: Contention period and channel switching.

In Figure 4-4, if node A is transmitting a data packet and node B senses that the medium is busy and waits, after the initial attempt of waiting to transmit it senses the medium on the channel being used, attempts on the first retry and detects that the medium is free of other transmissions. The node waits for a predetermined DIFS (distributed inter-frame spacing) period [15]; once it senses no other transmission before the end of the DIFS period, it computes a random backoff time between values of CWmin and CWmax then commences its transmission. Node C senses the medium to be busy and makes three repeated attempts, after the initial attempt to transmit a packet; the computed backoff period is doubled with each attempt until the specified threshold is reached. When the threshold is reached the channel sensor invokes the channel switching. The node interface will tune to another channel, senses if the medium is busy. If busy, it will switch otherwise it will proceed with transmission. If all channels are busy the node will revert to random backoff time and set its backoff timer using the equation in [15].

Contention based techniques are best resolved by preventive methods but are most difficult to predict due to all nodes contending for a single channel. These clearly indicate that multi-channel with switching control systems as shown in Figure 4-5 will provide the needed best overall practice access control in accessing the medium while reducing collision, delay and the hidden node problem in the WSN. The idea is to achieve a multi-access, simultaneous transmission and maintain a good quality of communication which can be obtained as long as the distance between the sensor node and the sink node are short enough and the adequate strength of the signals are received.

The challenges in the MAC channel access control, highlighted previously in this chapter, and the DCF backoff algorithm coupled with the channels within the 2.4 GHz frequency band can be mitigated by the combination and integration of the MC-DCF Models as shown in Figures 4-2 and 4-5 and further linking them to other application in 802.11 WLAN and ad hoc network systems.

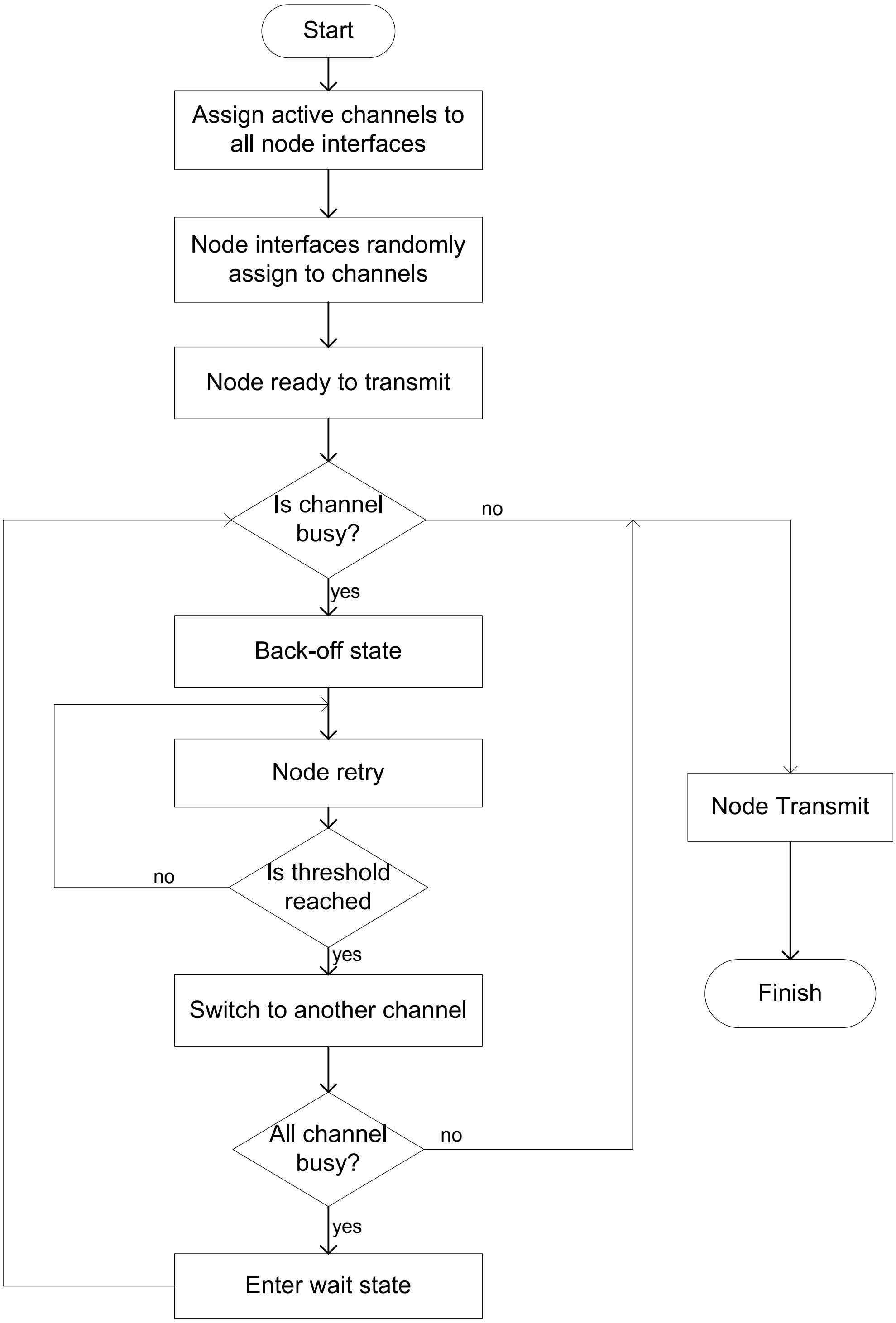

Figure 4-5: Flow chart for channel assignments.

4.5 Results and Discussion

4.5.1. Simulation Procedure

MC-DCF being the proposed protocol for Multi-channel Distributed Coordinated Function will be studied using the NS-2 simulation platform. As mentioned before, at initialisation all nodes will be made aware of the number of channels available. When a node wants to transfer data the Carrier Sense (CS) mechanism is invoked in order to determine if the channel is busy or idle. During the backoff period the contention window (CW) parameter will reach its threshold after the third attempt and switch channel. A node will enter a wait state if all channels are busy.

In this chapter, the performance of the MC-DCF protocol by extensive simulations with NS2 is analysed. The aim is to investigate multi-channel performance within a single-hop (the link quality), i.e. the packet reception rate. Different simulation scenarios were studied according to three different performance metrics: aggregate throughput, delivery ratio and access delay.

The sensor nodes were randomly placed in a 1000x1000m^2 area, the radio range is set to 50m, and the radio bandwidth at 2Mbps. The number of nodes is 100 and the simulation time for each scenario is 500 seconds (s). The number of channels ranges from 3 to 10 since the spectral mask only defines power output restrictions up to ±11 MHz from the centre frequency to be attenuated by 30 dB. It is often assumed that the energy of the channel extends no further than these limits.

The 802.11 channels are effectively 22 MHz wide, the consequence is that stations can only use every fourth or fifth channel without overlap, typically 1, 6 and 11 in the Americas, and in theory, 1, 5, 9 and 13 in Europe although 1, 6, and 11 are typical there too. However if transmitters are closer together, overlap between the channels may cause unacceptable degradation of signal quality and throughput. The MAC protocols are 802.11 DCF and MC-DCF.

The aggregate throughput is calculated as the total amount of data delivered to the sink per unit time by the MAC protocol and is computed as:

$$\text{Aggregate throughput} = \sum_{i=1}^{n} \left(R_{\mathrm{i}} \times \frac{\mathrm{B}}{\mathrm{t}} \right), \qquad (4.2)$$

where n is the number of receiver R, throughput is B/t, B is the bytes received by a receiver i in some duration of time and i = {1, 2, 3,...,n}.

The delivery ratio is the ratio of total number of packets received by the nodes to the total number of packets transmitted times the number of receivers and is computed as:

$$\frac{\sum_{i=1}^{n} R_{\mathrm{i}}}{\sum_{i=1}^{n} S_{\mathrm{i}}}, \qquad (4.3)$$

where S_{i} means total data size of CBR packet node i sent, R_{i} means total data size of CBR packet node i received.

The access delay is the backoff time used in DCF [15], the access delay can also be calculated as the packet size x 8 (1 byte) divided by the link size plus the propagation delay that is

$$\frac{\text{packet size} \times 8}{\text{link size}} + \text{Propagation delay}. \qquad (4.4)$$

Nodes only transmit to neighboring nodes within range, transmitting over a wider range may consume more energy which is not desired by WSN and also to eliminate communication interference and hidden node problems [2].

4.5.2 Performance Analysis of the Proposed MC-DCF Protocol

In the simulation scenarios the network is considered for sensor surveillance system with continuous streaming data - large densely deployed networks were not assumed. Surveillance systems are mainly deployed for organisation, parks and vehicular traffic not for remote monitoring. In this instance nodes will always be static and powered and as such the depletion of battery life is not considered. CBR traffic will be simulated and sent every 2 second to prevent buffer overflow and to replicate streaming data. The default data rate for MC-DCF will be 2Mbps.

4.5.2.1 Performance Analysis: 802.11DCF, MC-DCF and MMSN Protocols

Figures 4-6, 4-7, and 4-8, analysed the performance of 802.11 DCF, MC-DCF and MMSN protocols based on number of channels, measured against the three mentioned metrics – channel access delay, aggregate MAC throughput and packet delivery ratio. Zhou et al [82] introduced the MMSN multi-frequency MAC protocol that was designed for WSN. It is a slotted CSMA protocol which at the beginning of each timeslot, nodes needs to contend for the medium before they transmit.

Figure 4-6 shows the comparative delay impact performance of each protocol as it relates to multichannel. In this scenario both MMSN and MC-DCF followed the same performance pattern. As the number of channels increased there is a downward trend in channel access delay, although MMSN showed comparatively lower delays. The 802.11 DCF protocol performed the most stable of all three protocol showing virtually little change in channel access delay across the multiple channels. The performance however occurs with a significantly higher level of channels access delay when compared to MMSN and MC-DCF. This performance of the 802.11 is consistent with its design for use over single channel. In essence it lacks the capability to perform efficiently in a multichannel environment, due to its inability to detect multichannel.

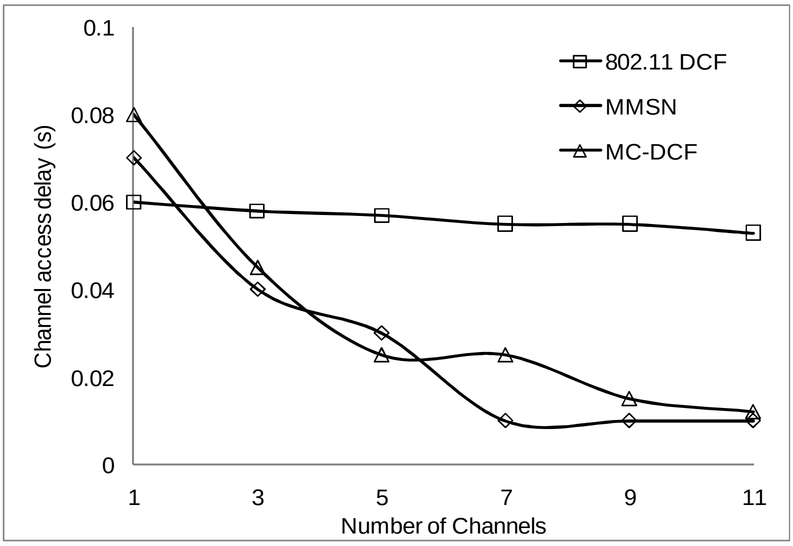

Figure 4-6: Impact of Multi-Channels on Channel Access Delay

Figure 4-7 shows the comparative aggregate MAC throughput performance of the three protocols over multiple channels. In this scenario both MMSN and MC-DCF performed similarly. As the number of channels increase so does aggregate MAC throughput of these two protocols. The 802.11 DCF protocol on the other hand showed significantly lower level of aggregate MAC throughput of all three protocols. This comparatively lower throughput remains virtually unchanged even as the number of channels increases.

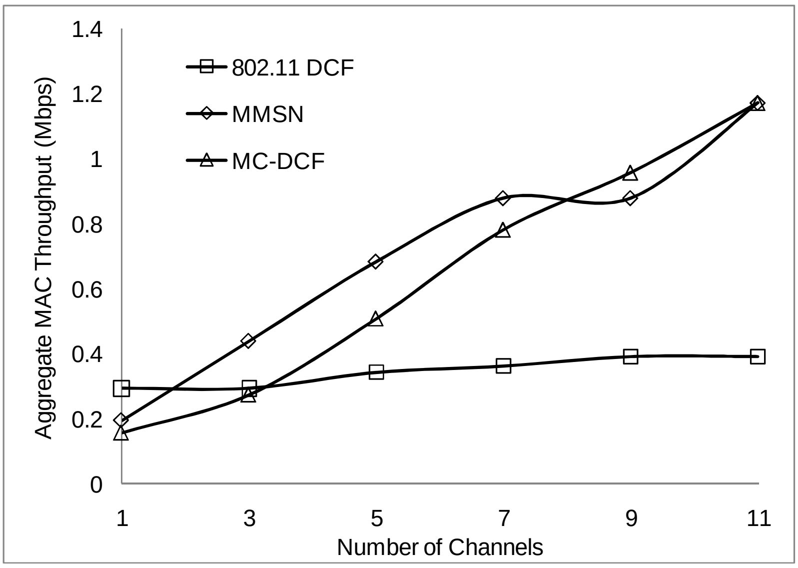

Figure 4-7: Impact of Mutli-Channels on Aggregate MAC Throughput

Figure 4-8 shows a packet delivery ratio comparison of the three protocols performing over multiple channels. In this scenario both the MMSN and the MC-DCF outperformed the 802.11 DCF protocol over multichannel, as it relates to packet delivery ratio. While the packet delivery ratio increased for the MMSN and MC-DCF as the number of channels increased, the performance of the 802.11 DCF remains virtually unchanged with a significantly lower packet delivery ratio. Overall the MC-DCF protocols had the highest packet delivery ratio of all three protocols over multiple channels.

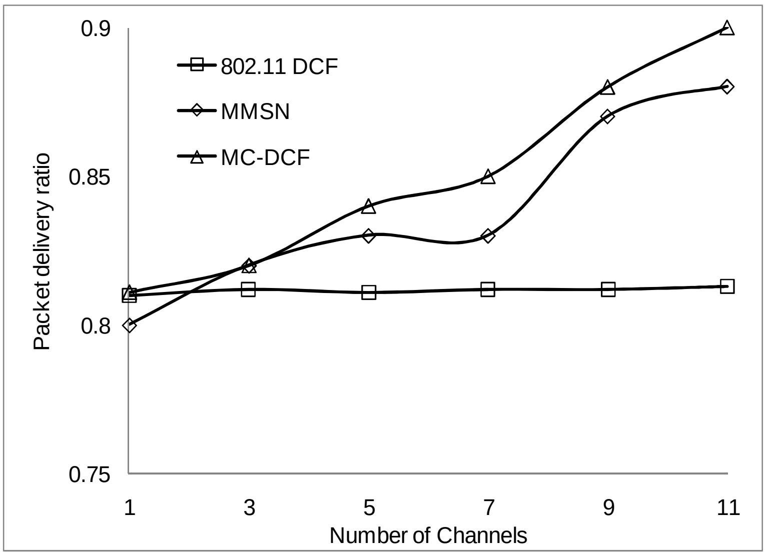

Figure 4-8: Impact of Multi-Channels on Packet Delivery Ratio

The MC-DCF protocol yielded the highest packet delivery ratio of the three protocols, however, MMSN performed slightly better than MC-DCF in relation to channel access delay and aggregate throughput. However, MC-DCF will outperform MMSN in the 802.11 network, should both protocols operate within the data rates ranging from 2Mbps up to 54Mbps of the 802.11 networks. MMSN uses a small packet size of 30-50 bytes, which contributed to the slightly better performance.

4.5.2.2 Performance Analysis: 802.11DCF and MC-DCF *(1-3 Channels)*

Figures 4-9, 4-10 and 4-11 analysed the performance of 802.11 DCF against MC-DCF using one, two and three channels. This comparative performance was measured within context of the three mention metrics using the CBR data streams.

Figure 4-9 shows a comparison between the 802.11 DCF protocol and the proposed MC-DCF protocol. In this analysis the channel access delay of CBR data stream on each protocol is measured. In this scenario MC-DCF over three channels recorded the lowest level of channel access delay even as the CBR stream increased. Conversely when transmitting over one channel the MC-DCF protocol recorded the highest level of channel access delay which is similar in performance to the 802.11 DCF protocol – which is designed to operate over a single channel.

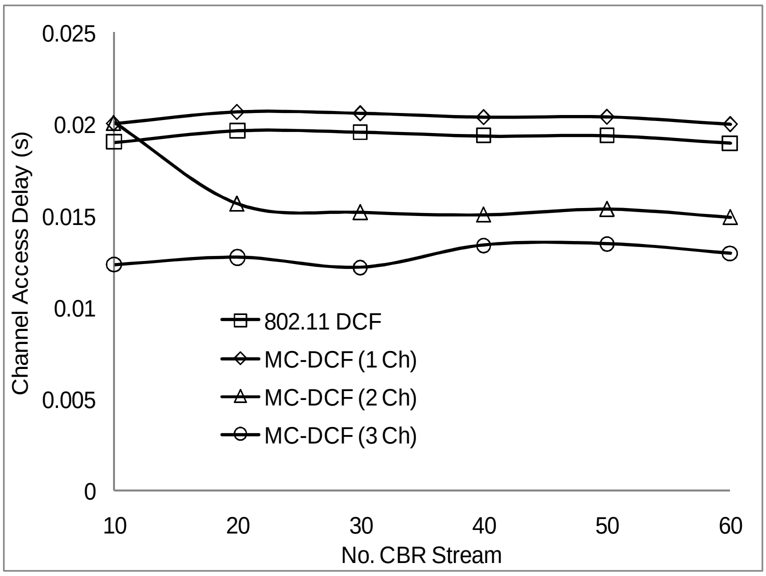

Figure 4-9: Impact of CBR Streams on Channel Access Delay

Increasing the CBR stream using a single channel demonstrate that 802.11 DCF and MC-DCF with one channel become saturated from backing off and buffer overflow. However, having multiple channels resulted in reduction of channel access delay.

Figure 4-10 shows that the delivery ratio when three channels are used have more packets delivered compared to one and two channels. Having one channel as can be seen in 802.11 DCF and MC-DCF (1 Ch) resulted in constant degradation as the CBR stream increases. This degradation resulted in constant backing off where nodes are contending for the same channel which gave rise to more packet loss.

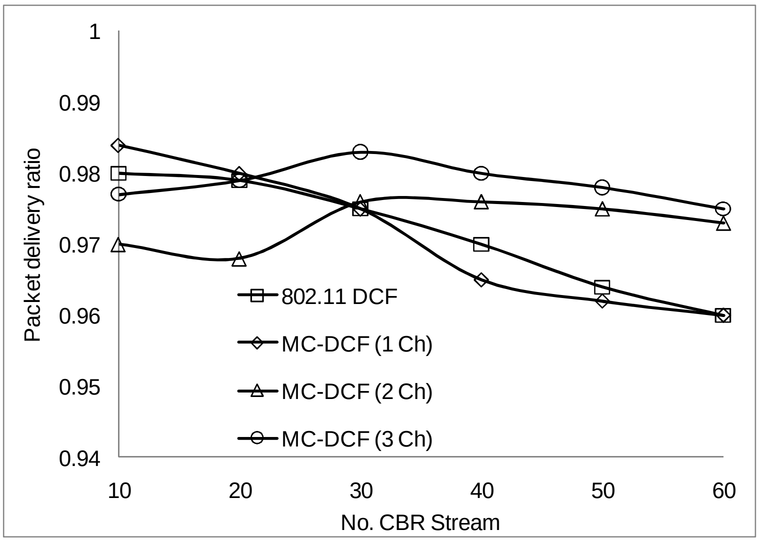

Figure 4-10: Impact of CBR Stream on Packet Delivery Ratio

In Figure 4-11, a similar trend is seen where MC-DCF with 3 channels has a better aggregate throughput, where more data are delivered to the receiving node. This showed that with the modification to the backoff algorithm nodes have options to switch channels. If this procedure remained while using a single channel, backing off becomes more frequent as the threshold is reached much quicker. MC-DCF with single channel performs worse with having more unsuccessful attempts with less data delivered to the receiving node. In using a single channel the original 802.11 DCF performed better than the MC-DCF single channel.

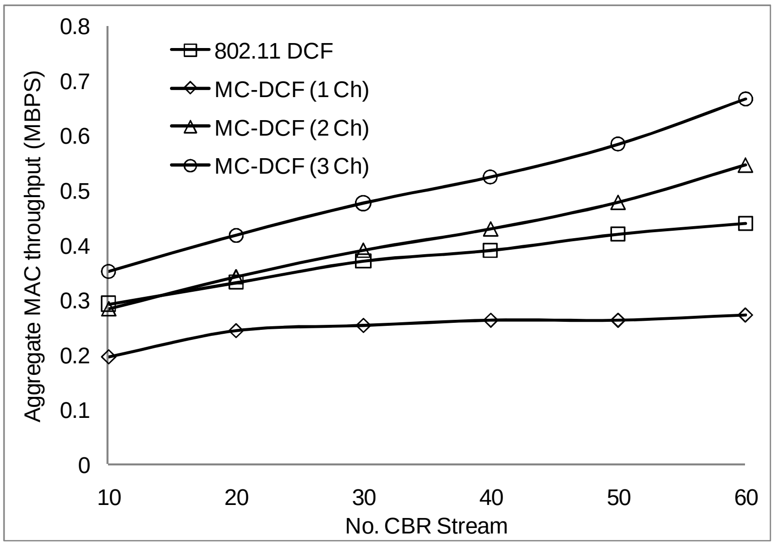

Figure 4-11: Impact of CBR Streams on Aggregate MAC Throughput

4.5.2.3 Performance Analysis: Impact of Node Density on 802.11DCF and MC-DCF (*1-3 Channels)*

Figures 4-12, 4-13 and 4-14 analysed the impact of node density on the performance of 802.11DCF, and MC-DCF using one, two, and three channels - by varying the number of nodes. This comparative performance was measured within context of the three mentioned metrics by varying the number of nodes sending CBR streams every 2 seconds. MC-DCF performed better when nodes have 3 channels to transmit on simultaneously.

Figure 4-12 shows 802.11 DCF and MC-DCF experienced the highest delays as more nodes transmit more packets and the network become denser. When two or more channels are transmitting there is a relative improvement in delay. The MC-DCF with three channels recorded the lowest level of channel access delays as the node density of the network increases.

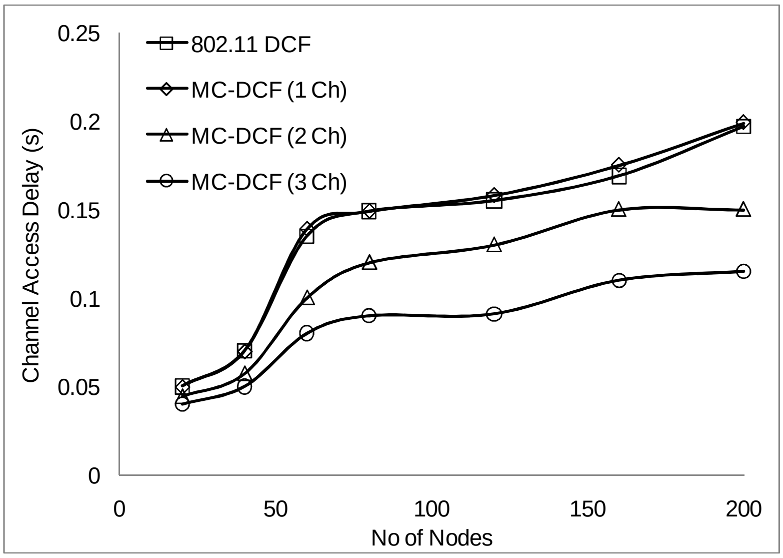

Figure 4-12: Impact of Node Density on Channel Access Delay

In Figures 4-13 and 4-14 the packet delivery ratio and the aggregate throughput respectively show a comparatively better performance when two or more channels are used. Although there is a comparatively better performance over two or more channels; as the number of nodes transmitting packets through the network increases, the performance of the network correspondingly degrades. This is not unusual as nodes will be switching channels, backing off and entering wait state which is the norm in a contention based network.

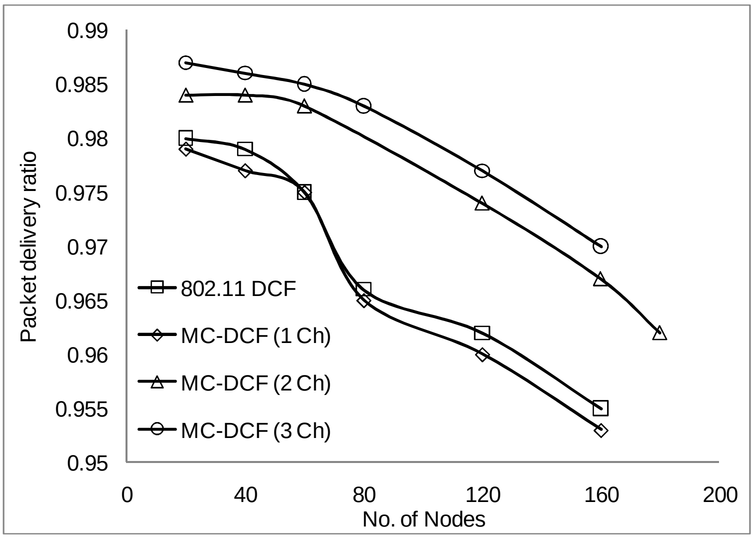

Figure 4-13: Impact of Node Density on Packet Delivery Ratio

In Figure 4-13, the MC-DCF with three channels yielded the highest level of packet delivery ratio. However, as the density of the network increased, packet delivery ratio progressively declined – as was evident of all protocols in this simulating scenario. The single channel protocols [802.11 DCF and MC-DCF (1Ch)] recorded the lowest and fastest declining packet delivery ratios of all protocols tested. An average of approximately 2.1% degradation of packet delivery ratio occurred compared with a total of 97% delivery ratio for 3 channels.

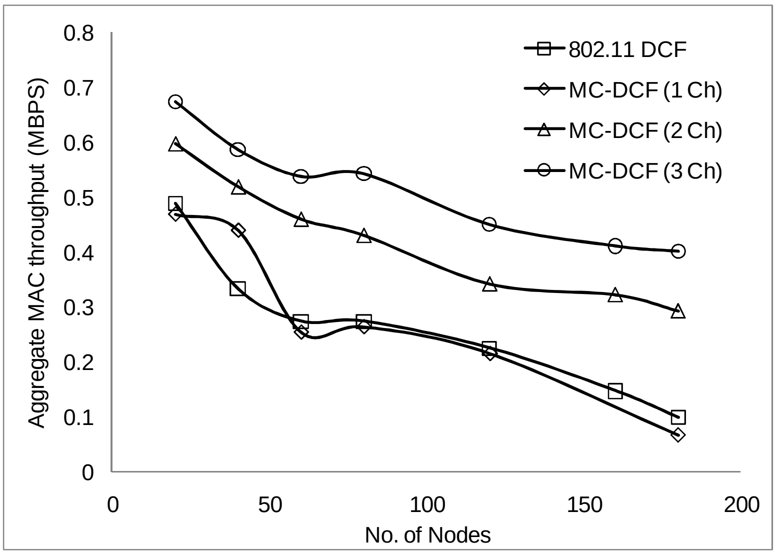

Figure 4-14: Impact of Node Density on Aggregate MAC Throughput

In Figure 4-14 MC-DCF with three channels recorded the highest level of aggregate MAC throughput, of all the tested protocols even as the node density of the network increased. Similar to the packet delivery ratio performance, mentioned above, the 802.11DCF and MC-DCF (Ch1), recorded declines in performance as the density of the network increases. In addition all protocols recorded declines in aggregate MAC throughput as the density of the network increases. The aggregate throughput as a function of the offered load for 3 channels showed a throughput decrease of 14%.

4.5.2.4 Performance Analysis: Sink Node with Single Radio

Figure 4-15 shows a sink node with a single radio switching between channels in order to receive data from more than one source nodes. Channel switching performance was observed at the sink by varying the number of source nodes the sink received data from. Access delay and packet delivery ratio was measured at the sink node.

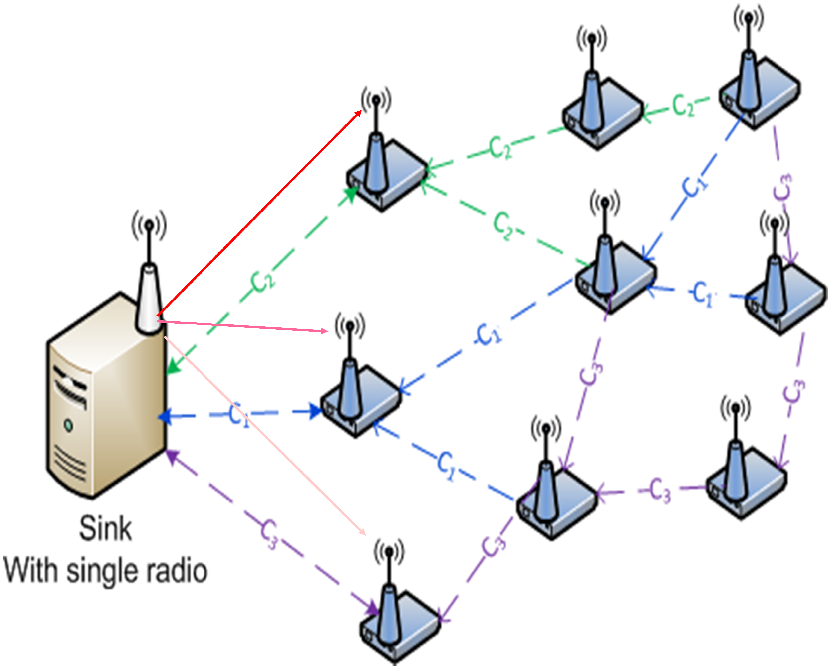

Figure 4-15: Sink node with single radio doing channel switching

Figures 4-16 and 4-17, examined the performance of the sink node receiving data directly from source nodes within its range that are sending data to be received. From observation, the more sources delivering to the sink the more delays encountered and the packet delivery ratio decreases in a corresponding manner. This is due to the sink node having to be constantly switching between channels in order to receive data, which incur severe switching delay in addition to the time taken to accept data before switching. The findings indicated that 802.11 DCF and MC-DCF with a single channel gave a better performance than the multi-channel protocols. This is due to the fact that the sink node is operating in a single channel mode with no extra overhead and switching delay occurring when receiving data.

The aggregate throughput degradation that has been observed in previous simulation within two or more channels can be accounted for mainly at the sink node where severe delay has been encountered. This results in drop packets. More work will be done in this area in order to improve delivery of packets from the source to the sink in a multi-channel environment.

In Figure 4-16 as the number of source nodes within range of the sink increases, the level of access delay at the sink correspondingly increases. This degradation of performance holds consistently for all protocols - single or multi channels. The single channel protocols (802.11 and MC-DCF(Ch1), however, outperformed the multi-channel protocols at the sink, due to the fact that the sink node is operating in a single channel mode with no extra overhead and switching delay occurring when receiving data.

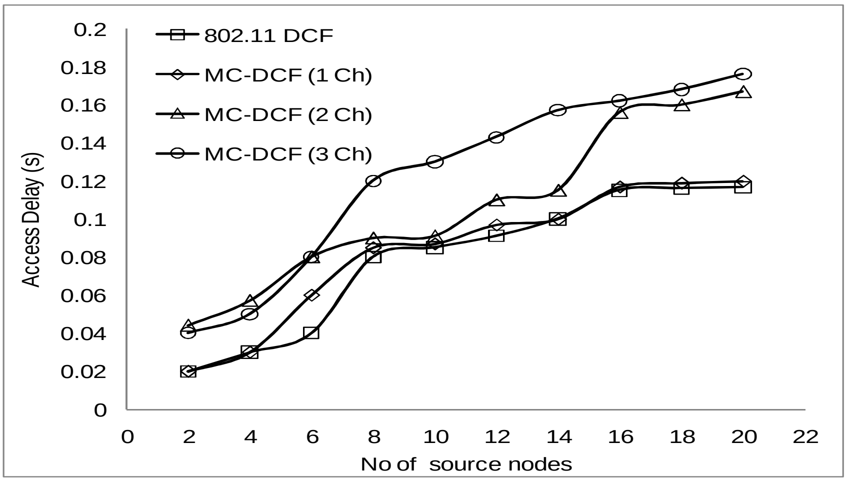

Figure 4-16: Impact of Source Node Density on Access Delay at the Sink

In Figure 4-17 all protocols recorded declining levels of packet delivery ratio at the sink as the number of source nodes within range of sink increased. The highest rate of decline was evident in the protocols with at two or more channels.

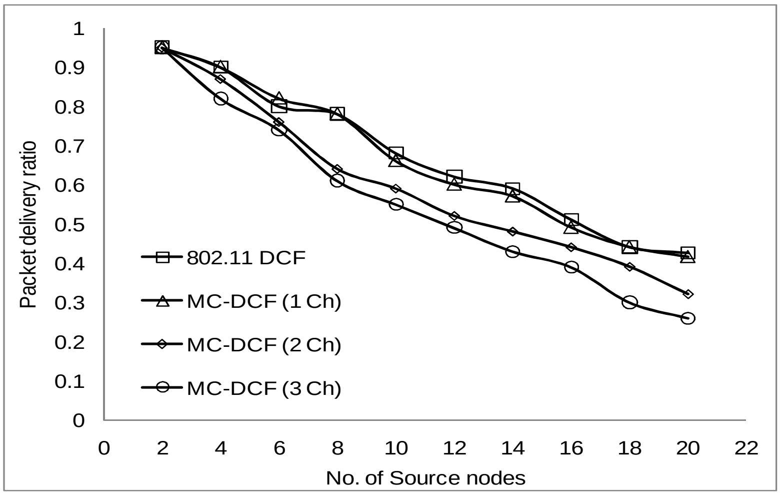

Figure 4-17: Impact of Source Node Density on Packet Delivery Ratio at the Sink

4.5.3. Performance Analysis of 802.11a/b/g Networks

Simulations were conducted to analyse the signal strength with different data rate over the 802.11a/b/g networks. The same metrics were used: access delay, delivery ratio and aggregate throughput to analyse the performances. The performance among the networks will aid in determining the range, data rate and preferable 802.11 networks to operate WSN. The above simulations indicated that WSN can operate in 802.11 networks for sensor surveillance system with continuous streaming data which is not densely deployed. Nodes will always be static and powered and as such the depletion of battery life is not considered.

In the simulation scenarios, for analysing the performance of 802.11a/b/g networks: sensor nodes were placed in a 1000x1000m2 area, the radio range and radio bandwidth with each scenario in order to determine suitable signal strength when operating in the 802.11 network for WSN. The number of nodes was 100 and the number of non-overlapping channels was 4 - using the UK 2.400-2.4835 GHz frequency band. The proposed MC-DCF MAC protocol was configured to operate with the 802.11a/b/g network for channel assignment and switching the multichannel to analyse the impact on 802.11a/b/g and the radio range.

4.5.3.1 Packet Delay Analysis: 802.11a/b/g Networks

The experiment results in Figures 4-18 and 4-19 shows the delay that occurred when transmitting 2Mbps over 50m and 100m ranges for 802.11a/b/g. In Figure 4-18 nodes are placed at 50m intervals with data transmitting at a rate of 2Mbps. In this simulation, delays declined over all three networks as the number of channels increased. The most significant decrease in delays occurred when three channels were transmitting. When the distance between nodes were increased from 50m to 100m range – depicted in Figure 4-19 - access delays increased dramatically for all three networks, as compared to performance at the 50m node ranges. The increase in delay that is experienced by all networks indicates that 100m range among nodes results in weak signal, which makes it difficult for transmission and as such degradation of the networks.

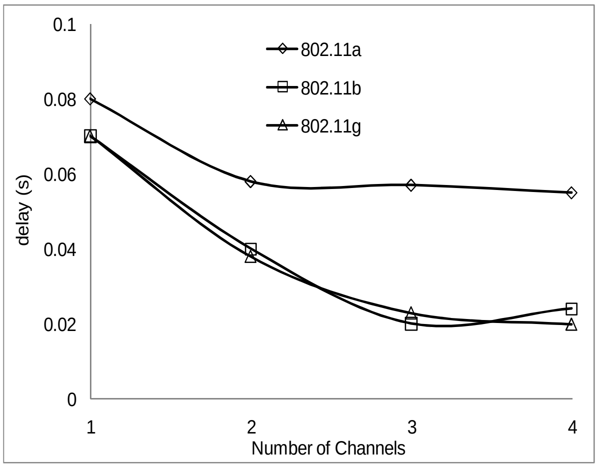

Figure 4-19: Delay at 50m range and data rate at 2Mbps

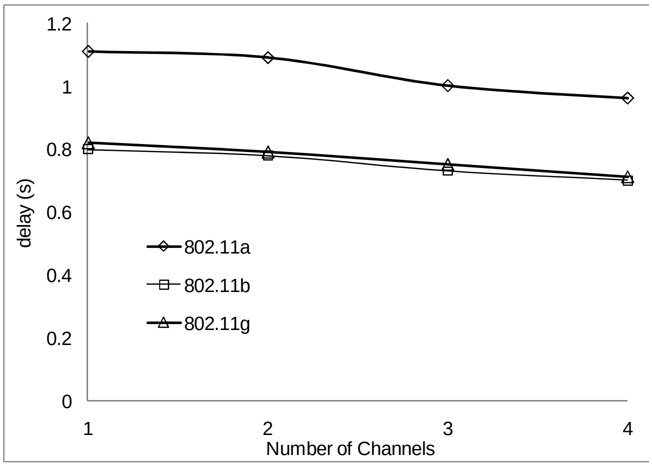

Figure 4-18: Delay at 100m range and data rate at 2Mbps

Figures 4-20 and 4-21 show the delay that occurs when simulating at 10Mbps over 50m and 100m node intervals. At the 50m range the lowest level of delays occurred, contrary to the pattern in performance experienced at the 100m range where degradation of the networks is much higher. However, 802.11a also shows an improvement in delay, this indicates that 802.11a operates better at 6Mbps and above but 802.11b/g gives a better performance which shows that if signal quality becomes an issue 802.11b/g can scale back to lower transfer data rate.

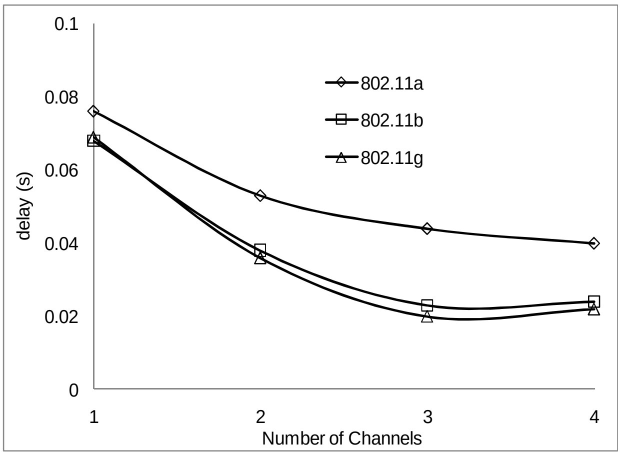

Figure 4-22: Delay at 50m range and data rate at 10Mbps.

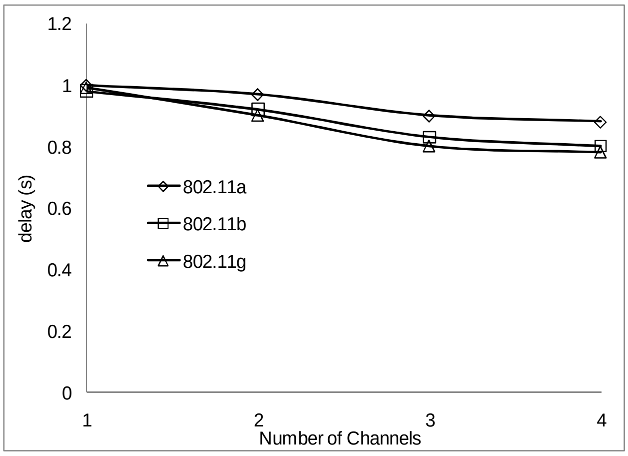

Figure 4-21: Delay at 100m range and data rate at 10Mbps.

Figure 4-20 shows that a higher level of delay occurred in 802.11a network compared to 802.11b/g. When the range is increased from 50m to 100m, increases in packet delay occurred among the tested networks - 802.11a/b/g - with 802.11a experiencing the highest delay. The high delay experienced by 802.11a resulted from it not being backward compatible to 802.11b; in addition to the fact that it was designed to operate at a minimum data rate of 6Mbps. Therefore operating with a data rate of 2Mbps causes possible frequent dropped connections and degradation of service.

Figures 4-22 and 4-23 show the delay that occurred at 54Mbps. Both 802.11a/g show a better performance than 802.11b, which seems not to show any improvement during the simulation over all the channels. This clearly showed that 802.11b cannot operate with data rate higher than 11Mbps. Also from the simulation results the data rate does not make a positive impact regarding operating at 100m range. At 100m range the networks experience high delay which degrades the system significantly.

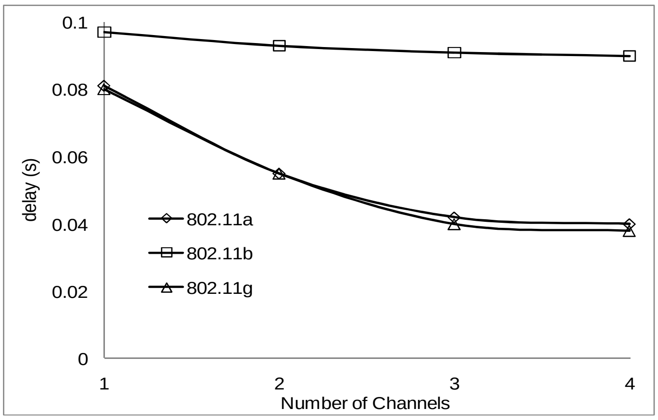

Figure 4-23: Delay at 50m range and data rate at 54Mbps

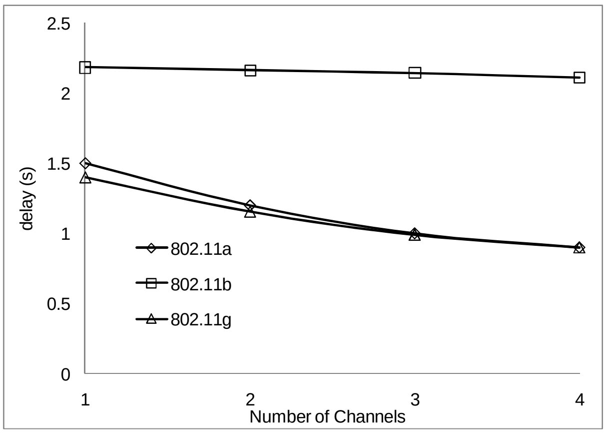

Figure 4-24: Delay at 100m range and data rate at 54Mbps

Throughout the group of simulations, the impact on delay over different range and channels show that a better performance is achieved at the 50m range to that at the 100m range in delays. Also when 2 or more non-overlap channels within the 2.4 frequency band are used, there are even better performances achieved, evident in Figures 4-18, 4-20 and 4-22.

4.5.3.2 Aggregate Throughput Analysis: 802.11a/b/g Networks

The performance results on the aggregate throughput are shown below. The results have been simulated over the 50m and the 100m range with different data rates, 2, 10 and 54Mbps for 802.11a/b/g on 4 non-overlapping channels. The results show a similar pattern where the 50m range results in better performance having more data delivered at the receiving nodes. Figures 4-24 and 4-25 show that 802.11a performed worse at a 2Mbps data rate.

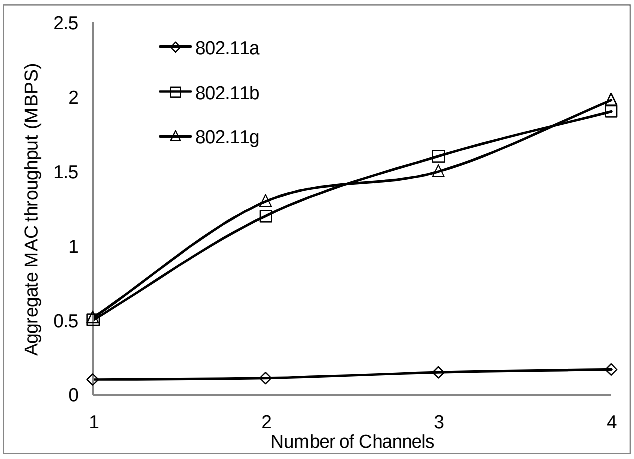

Figure 4-25: Aggregate throughput: 50m range and data rate of 2Mbps

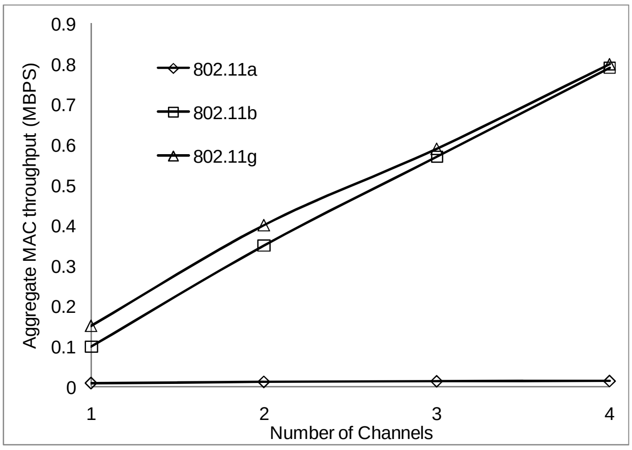

Figure 4-26: Aggregate throughput: 100m range and data rate of 2Mbps

Figure 4-26 shows that all network performance at 10Mbps have slight variations with a maximum throughput of 8.8Mbps when operating over 4 non-overlapping channels. The results showed that with streaming data every 2 seconds with more than 1 channel at data rate of 10Mbps with the option to switch channel can yield a high performance among all the networks. Figure 4-27 shows significant network degradation when operating at the 100m range with aggregate throughput within the range of 0.1 to 1.75Mbps.

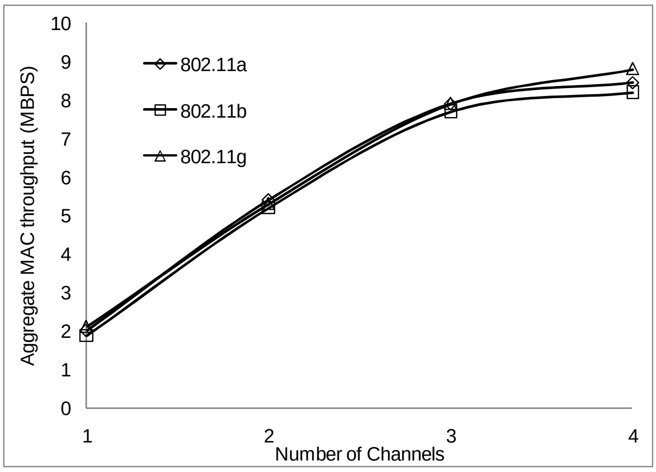

Figure 4-27: Aggregate throughput: 50m range and data rate of 10Mbps

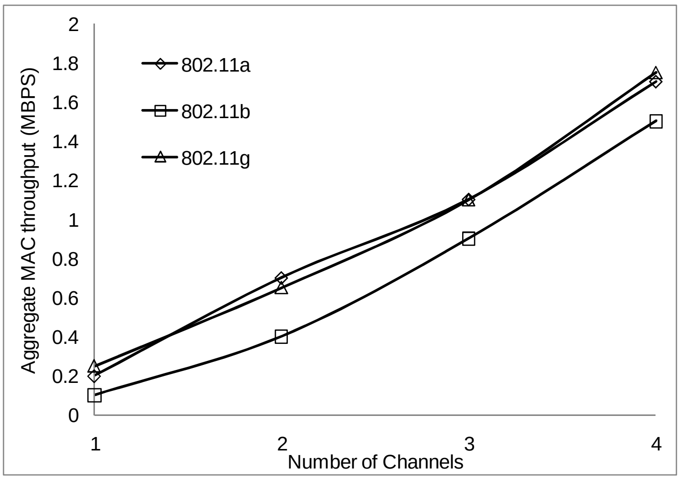

Figure 4-28: Aggregate throughput: 100m range and data rate of 10Mbps

Figures 4-28 and 4-29 with data rate of 54Mbps the 802.11a/g networks outperformed the 802.11b which showed no performance change when the range is increased from 50m to 100m; again this is due to the maximum data rate of 11Mbps for 802.11b.

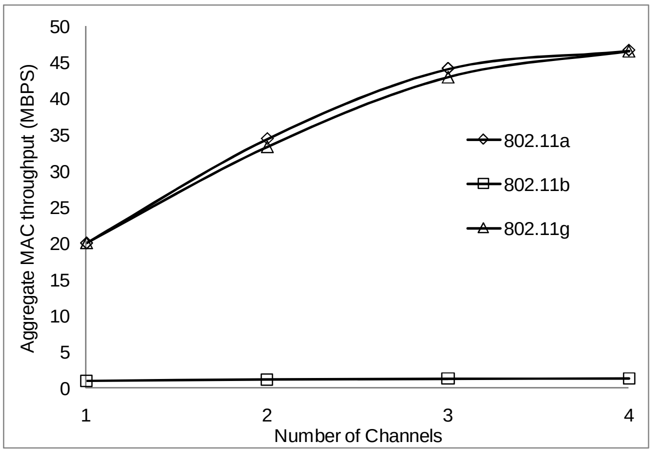

Figure 4-29: Aggregate throughput: 50m range and data rate of 54Mbps

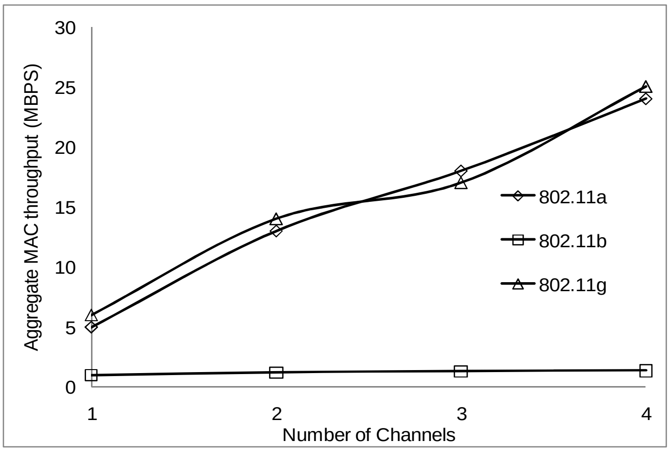

Figure 4-30: Aggregate throughput: 100m range and data rate of 54Mbps

4.5.3.3 Packet Delivery Analysis: 802.11a/b/g Networks

The packet delivery ratio results are shown below in Figures 4-30 to 4-35 as a function of the number of 4 overlapping channels. Performance was measured at 50m and 100m intervals while the data rate varied from 2Mbps to 54Mbps. In Figure 4-30, while there was an increase in packet delivery for the 802.11a/g networks as the number of channels increase, there was virtually zero percent (0%) delivery rates for 802.11a – which does not perform well under 6Mbps. This performance remained virtually similar over all three networks when the node range was increased from 50m to 100m, as depicted in Figure 4-31.

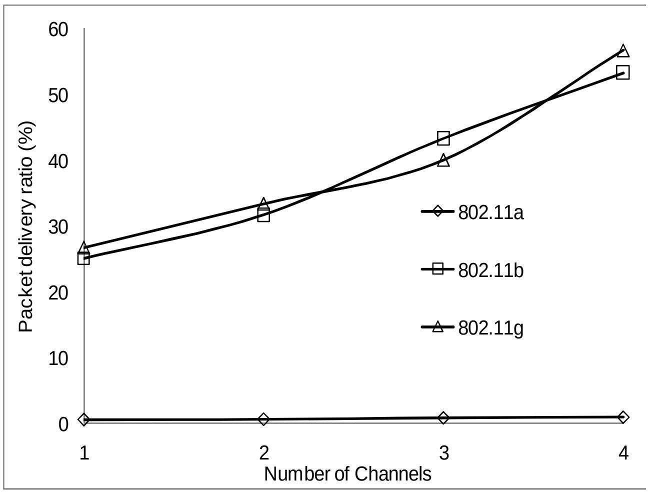

Figure 4-32: Delivery ratio at 50m range and data rate of 2Mbps

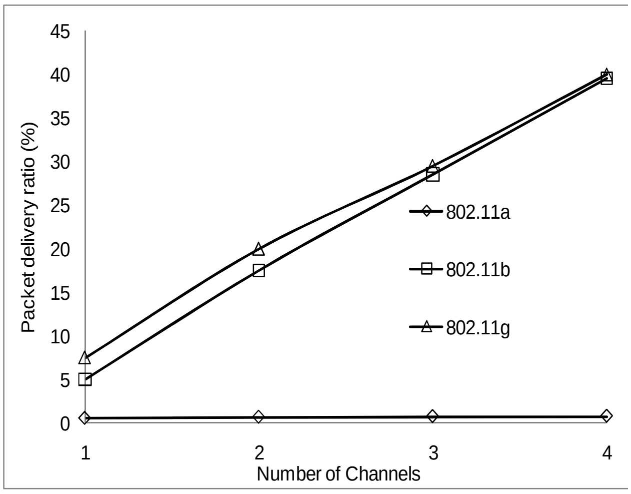

Figure 4-31: Delivery ratio at 100m range and data rate of 2Mbps.

Figures 4-32 and 4-33 all networks delivered almost similar number of packets ranging between 20-87% delivery rates, except for the 802.11a which showed virtually no packets being delivered. Significantly lower percentages of packet delivery ratio was evident as the node range increased from 50m to 100m, although there was an upward trend in packet delivery over the four channels in that scenario.

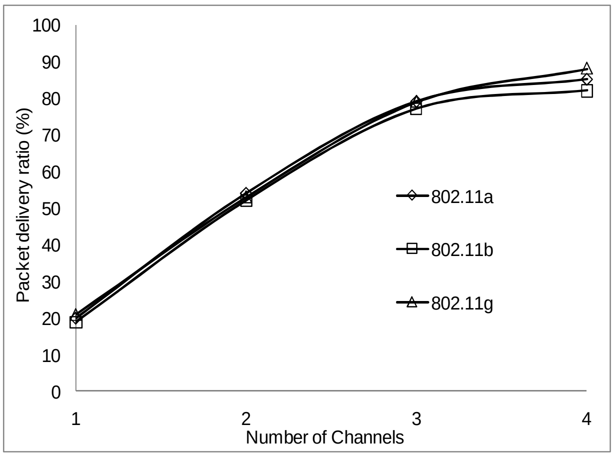

Figure 4-34: Delivery ratio at 50m range and data rate of 10Mbps

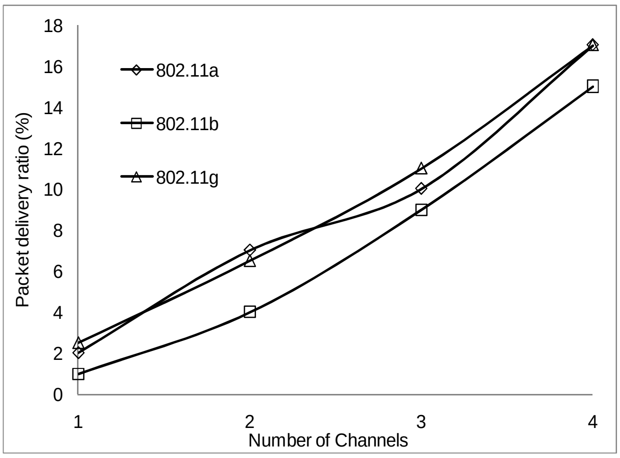

Figure 4-33: Delivery ratio at 100m range and data rate of 10Mbps

Figures 4-34 and 4-35 showed that the 802.11b delivery rate was significantly below 10% at 54Mbps. This is owing to the fact that 802.11b has a maximum raw data rate of 11 Mbps. All networks performed poorly under 50% delivery rate when operating at 100m range at 2, 10 and 54 Mbps data rate as can be seen in Fig. 4-31, 4-33 and 4-35.

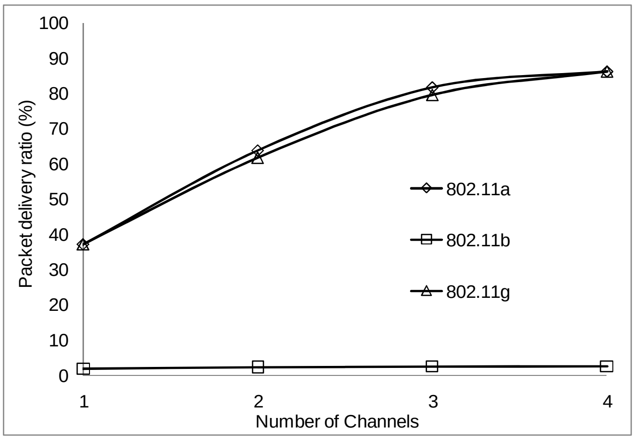

Figure 4-36: Delivery ratio at 50m range and data rate of 54Mbps

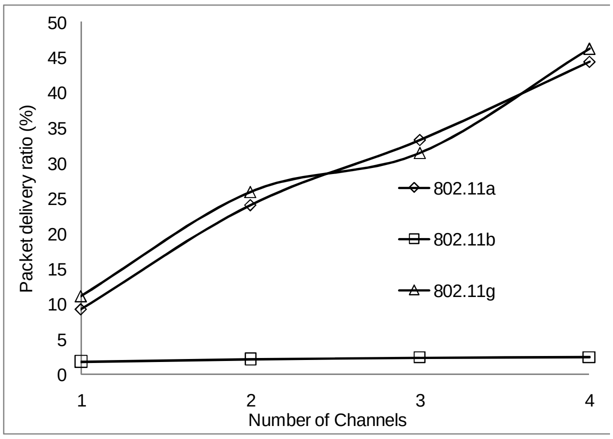

Figure 4-35: Delivery ratio at 100m range and data rate of 54Mbps

The results are similar to that of the aggregate throughput, in that, the more channels utilised for transmission, the more packets are delivered. The most packets are delivered at the range interval of 50m, and data rate of 10Mbps.

This clearly showed that contention based network perform poorly when the communication range exceeds 50m. Moreover, the additional overhead experienced during channel switching along with the distance range affect the performance. There are factors that can influence the data delivery performance in wireless network with no exception to WSNs including the environment, network topology, and traffic patterns- the precise impacts of these could be examined in a future work. In addition the 2.4GHz frequency band is already overcrowded with activities of other networks sharing the same unlicensed band. WSN gives a better performance at short range and with continuous streaming data long range transmission may experience many of the mentioned factors which result in poor performance and as such long range transmission not recommended for WSN.

4.6 Conclusions

In this chapter, the proposed MC-DCF that is a backoff algorithm for multi-channel access based on the 802.11 DCF protocols was examined. This algorithm allows node to have access to multiple non-overlapping channels by accessing channels dynamically through channel switching after a set threshold has been met. During the MC-DCF design, the need for multi-channel assignment in WSN was analysed and discussed, where the future sensor surveillance system with streaming data may find it difficult to operate in 802.15.4 network due to congestion of the most frequently used 2.4GHz frequency band. The results from the simulation results proved futile for future development in this area for 802.11 networks. It was observed that better performance is achieved when using MC-DCF in analysing the impact of WSN in the 802.11 network. MC-DCF was further tested in 802.11a/b/g networks at different distance and rates. It was observed that at the 50m range with 10Mbps all network performed well. Overall 802.11g performed well with all data rate and this is because it has the additional legacy for backward compatibility with 802.11b, up to 80% delivery rate was obtained.

Overall, MC-DCF exhibited prominent ability to utilise multi-channel transmission for the future with 802.11 for wireless sensor surveillance system that is low-cost, reliable, easy to manage, easy to deploy and can process video data for automated real-time alerts.

Researchers will be able to achieve the goal of long term, independent operation of sensor network deployments under this constraint.

4.7 Acknowledgements

The work was supported by NAP of Korea Research Council of Fundamental Science and Technology.

Chapter 5

Multi-channel Multi-radio using 802.11 based Media Access for Sink Nodes in Wireless Sensor Networks

5.1 Overview

The next generation surveillance and multimedia systems will become increasingly deployed as wireless sensor networks in order to monitor parks, public places and for business applications. The convergence of data and telecommunication over IP based networks has paved the way for wireless networks. Functions become more intertwined by the compelling force of innovation and technology. For example many closed-circuit TV premises surveillance systems now rely images and data over IP networks instead of standalone video circuits.

These systems will increase their reliability in the future on wireless networks and on IEEE 802.11 networks. However due to limited non-overlapping channels, delay and congestion there will be problems at the sink node. The necessary steps are provided to verify the feasibility of round robin technique in these networks at the sink node by using the technique to regulate multichannel multi-radio (MCMR) assignment. Demonstration through simulations that dynamic channel assignment scheme using the multi-radio, multichannel at sink nodes can perform close to optimal on the average while multiple sink node assignment also performs well. The methods proposed in this chanpter can be a valuable tool for network designers in planning network deployment and for optimising different performance objectives.

5.2 Introduction

Wireless sensor networks are renowned for having limited transmission ranges and organise themselves in an ad hoc fashion. When wireless sensor cannot reach the receiver directly it relies on other sensor nodes to relay data between them. They are assumed to have constrained energy sources because they rely on batteries which can or cannot be replaced. Wireless sensor networks consist of large number of sensors [1,3-6,86] each are equipped with the capability of sensing the physical environment, data processing and communicating wirelessly with other sensors. The number of nodes in a sensor network is significantly larger than other wireless networks; the difference can be of several orders of magnitude. Sensors are usually low-cost devices with severe constraints with respect to energy source, power, computation capabilities and memory. Sensors are usually densely deployed and the probability of failure is usually much higher. The sensors are usually stationary rather than constantly moving, however the topology can still change frequently due to node failure.

The previous chapter and works [87-88] studied multichannel communication based on the 802.11 DCF over a single radio for wireless sensor networks in order to improve its communication performance on throughput, end-to-end delay and channel access delay. The proposed backoff algorithm, MC-DCF allows node to have access to multiple non-overlapping channels by accessing channels dynamically through channel switching after a set threshold has been met. These works focus on high data rate streaming that would be considered for sensor surveillance system that would be deployed for organisation, parks, and vehicular traffic not for remote monitoring. For this reason static nodes that are always powered were considered and as such the depletion of battery life was not considered. In the previous chapter MC-DCF performance analysed the non-overlapping channels on the mentioned metric against other protocols, it studied the impact of the number of non-over-lapping channel in the 2.4 frequency band of the 802.11 network, analysed the density of the network, examined the effect of the sink node receiving data directly from sources within its range and finally the a performance analysis of 802.11a/b/g was done. It was observed that MC-DCF had encountered poor performance when receiving data at the sink node due to a single radio that had to be constantly switching channels and as such more work needed to be done in this area to improve the performance at the sink. Also it was observed that at 50m range with 10Mbps all network performed well. In this chapter the focus is on improving the severe degradation that resulted at the sink node and the relationship between communication links from a graph based approach; this approach has been formally modelled by researchers and the following will be considered to improve the MC-DCF model:

- Multiple sinks with single radio
- Single sink with multiple radios
- Single sink with multi-radios in a round robin fashion
- Multiple sink with multi-radios

These solutions improve contention, limited bandwidth and interference which are some of the barriers preventing successful delivery of large amount of data. The multichannel MAC protocol designed to provide high throughput and high delivery ratio during high rate traffic in the IEEE 802.11 network that normally use as Access Points (APs) or at cluster heads in sensor networks. WSN in our studies uses constant bit rate (CBR) for streaming data that mimics surveillance and multimedia sensor network data that is foresee to pose significant problem operating in smaller network such as IEEE 802.15.4 and when IEEE 802.11n becomes popular in the future. Exploring the best possible use is a challenging problem, but the future of WSN is foreseen to be used on hand held devices such as mobile phones to sense and interact around environment for safety of individual travelling in areas such as parks and or lonesome areas that trigger alerts to security personnel.

A number of works has been devoted to the problems of sensor networks but not for high data rate for 802.11 networks as in the previous chapter. This work looked at topology control [89-90], power management [44,91], energy aware and optimal routing [92-101]. Recent focus has shown concentration in multichannel assignment [58,75-82,84,100,102]. Multichannel communication is an efficient method to eliminate interference and contention on wireless medium by enabling parallel transmissions over different frequency channels. Most work on multichannel focus on:

- Static approach where each interface is fixed permanently or for a long period of time on a channel.
- Dynamic approach, which allows interfaces to switch channel from time to time to exploit the maximum channel diversity.

- Hybrid approach, where a fix interface on a channel is used for package control and exchange. The other interfaces are used to switch among remaining channels for data transmission. Other hybrid approaches consist of two parts; one part handles MAC issues and the second part is a distributed assignment algorithm.

The rest of this chapter is organised as related work, system model and problem formulation, simulation results and discussions, and, finally conclusion and future work.

5.3 Related Work

The multichannel multi-radio approach in IEEE 802.11 based wireless networks has been widely studied by a number of researchers and can be categorised as centralised and distributed approaches. The centralised approach has been further categorised as:

- Flow based
- Graph based
- Partition based

A centralised flow based approach presented in [58,74,103-104] proposes a centralised joint channel assignment and multi-path routing algorithm. The channel assignment algorithm first considers high load edges. The routing algorithm uses both shortest path routing and randomised multi-path routing which is a set of paths used between any pair of communicating nodes. The joint channel assignment and multi-path routing algorithm proceeds in an iterative fashion. However, their algorithm is based on heuristics and the worst performance bound on its performance is not known. In addition to their scheme no guarantees on fair allocation of bandwidth is provided. However, simulation study shows that by deploying just 2 NICs per node, it is possible to achieve a factor of up to 8 times improvements in the overall network goodput, when it is compared with the conventional single-NIC-per-node on wireless ad hoc networks. This is inherently limited to one single radio channel. In [74] they assumed that there is no system or hardware support to allow a radio interface to switch channels on a per-packet basis. They also assumed a radio interface is capable of switching channels rapidly and is supported by system software. Their evaluation demonstrates that our algorithm can effectively exploit the increased number of channels and radios, and performs much better than the theoretical worst case bounds. Kodialam et al [103] define a standard multi-commodity flow problem on a MC-MR network; they assume that the traffic demand for different source destination pairs is given in the form of a rate vector. In their algorithms, it is not clear if it is possible to jointly optimise routing, link channel assignment and scheduling in a distributed manner.

A centralised, graph based approach has been proposed in [56-57,105], where links and nodes are considered as edges and vertices of a graph respectively in formulating radio and channel assignment by assigning edges to vertices. The limitation of these methods is that it is very difficult to capture network load information with a graph model. Network flow based centralised approaches can be found in [58,74] and [103], where multi-radio multichannel is modeled based on network flows to overcome the limitations associated with graph based approaches. These approaches are not realistic as constant traffic sources are assumed all the time while network traffic can be bursty in nature. Mahesh et al [105] have considered the channel assignment, radio-channel mapping problem in multi-radio wireless mesh networks. They have argued that a traffic-independent channel assignment that provides a connected and low interference topology can serve as a basis for dynamic, efficient and flexible utilisation of available channels and radios. In [78] a simple approach to address this issue is common channel assignment (CCA) which assumes that radio interfaces at each node are assigned to the same set of channels. This leads to inefficient channel utilisation in the typical case where number of interfaces per node is fewer relative to the number of channels. Another graph based approach studied in [57] on an extensive evaluation via simulations shows that multi-radio scenarios, yields performance gains in excess of 40% compared to a static assignment of channels. In [106], authors have addressed co-existence of heterogeneous interfaces and introduced a radio based novel graph model which captures the heterogeneity of interfaces.

A partition approach [107] designs a new algorithm that takes advantage of the inherent multi-radio capability of Wireless Mesh Networks (WMNs). They partition a network in a manner that not only expands the capacity regions of sub-networks but also allows distributed algorithms to achieve the capacity regions. However, they will need to allow dynamic channel allocation that will require the channel allocation algorithms for online and distributed operation.

A distributed gateway for multi-radio multichannel approach has been developed by [13] and [14] where mesh gateways are considered as sink and source of data. These approaches consider the coexistence of more than one radio interfaces of the same homogenous standard on a mesh router and use more than one available orthogonal channel. In [106], authors have addressed co-existence of heterogeneous interfaces and introduced a radio based novel graph model which captures the heterogeneity of interfaces. They have also formulated scheduling, routing and channel assignment as an optimisation problem. Their results show improvement in network capacity while preserving node level fairness. In [108] the given network consists of a set of stationary wireless routers where some of them also act as gateways to the Internet. They assume that the paths between the routers and the gateways have been pre-determined, for example, the neighbor-to-interface binding mechanism in [13] which can be used to determine the paths and the logical topology of the network. In their work the implementation can either be centralised or distributed. For distributed implementation, each node is responsible for assigning the optimal channels to some links. One of the distinct advantages of this algorithm is that it has the ability to assign the non-overlapping channels and also the partially overlapping channels. This allows the IEEE 802.11 frequency band to be fully utilised.

5.4 Problem formulation

The problem of designing an efficient and distributed algorithm was studied to overcome the severe degradation at the sink node when using single radio to switch to multiple channels. The aim is to achieve better performance in terms of delay, throughput and packet delivery ratio. In the previous works [87-88] the single radio switches nodes to receive data from other sending nodes on different channels. The results obtained at the sink from the sending nodes have been observed that MC-DCF performs very poorly. Source nodes close to the sink suffer from severe delay in delivering packets to the sink. This was as a result of more than one channel delivering packet to sink node which operate on a single radio, where switching between channel has caused build up of congestion in that a bottleneck has been created. The problem will be addressed at the sink node in the following ways:

5.4.1 Multiple sink nodes

The number of sink nodes will increase to collect data from receiving nodes. The sink nodes will equip with a single radio and will be required to do channel switching in the same manner as in [87-88]. The advantage is that all data from senders will be received by more sink nodes located in strategic position. This will eliminate the burden encounter by a single sink node.

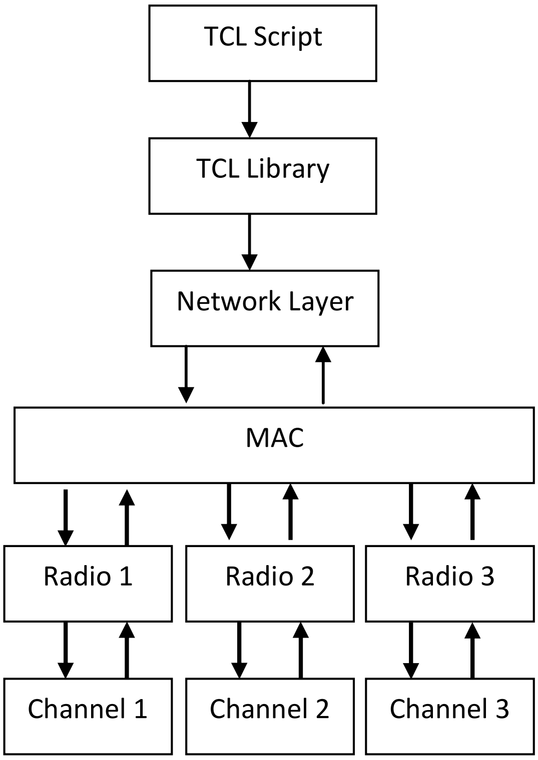

Figure 5-1: Design overview for Multi-channel Multi-radio

Multiple radio interfaces will be assigned in the sink node to receive data from each non-overlapping channel. Each radio is assigned to a channel from each sending nodes.

This will eliminate channel switching to all sending nodes by a single radio interface. Figure 5-1 shows modification at the MAC of the existing MACs protocol stack [73] this incorporate multiple radios, a new component is added to define the radio and radio number is set in the TCL script of the NS2. A new field is also created in the MAC into the packet header to index the channel object. This helps to achieve conflict free or reduce interference among neighbouring nodes. To reduce communication interference nodes within communication range sense the network and conduct channel switching as illustrate in [87-88] and in chapter 4.

It was taken into consideration that it is not practical to have same number of radio and same number of channels at all time. The practicality of it depends on the network size. A medium to large network may have more nodes sending data to the sink.

By taking advantage of physical characteristics of the radio environment, the same channel can be reused by two or more nodes provided that the nodes are spaced sufficiently. To avoid co-channel interference non-overlapping channels have been used. Since nodes are aware of all the channels at start-up and are able to switch channels based on a set criterion in [87-88], the nodes sending packets to the sink are set to operate on a particular channel. All nodes are place where they are in reach of the sink but separated by enough gaps between sending nodes. The reason for such arrangement is to ensure radio interface switching between nodes on same channel will avoid co-channel interference.

Formally, channel assignments problems have been modelled as:

- Graph based [109-110] where the vertices V correspond to nodes and edges correspond to pairs of stations whose transmission areas intersect.
- Ring based [110] is considered as a form of vector where the ring is a sequence of n vertices.
- Grid based [110] is considered a form of vector represent tessellations of a plane with regular polygon, where the grid has row (r) and column (c) indexed from top to bottom and from left to right. The grid based can be classified as:
    - Bi-dimensional
    - Cellular
    - honeycomb

- Tree based [110] a unidirected graph T= (V, E) is a free tree when it is connected and has exactly |V|-1 edges.

These assignment techniques all used various vectors colouring problems which are based on arithmetic progressions to solve the channel assignment problems.

5.4.2 Multi-Radio Switching

The WSN considered in [87-88] has been formed by static nodes and a sink node. The multichannel assignment will be presented into two ways. One way, each sink node is equipped with a single radio and can switch channels to receive data packets. The other way, sink node is equipped with multiple radio interfaces and has a distinct channel assign to each radio. However the transmitting nodes to sink remain on the same channel and not allowed to switch channel during transmission. In case of any changes or failure of any node or radio interface should occur, the sink node will update itself about the changes.

Multichannel Multi-Radio (MCMR) problem can be modelled as an undirected graph where vertices denoting radios comprise the wireless network and a set of unidirected edges between vertices representing node link. The rationale is to prevent nodes on same channel to attempt to send to the same radio interface. Nodes are numbered to prevent conflicts. Transmission take place interns base on number. Unidirected graph modelling [108] has been used to model channel assignment in wireless network.

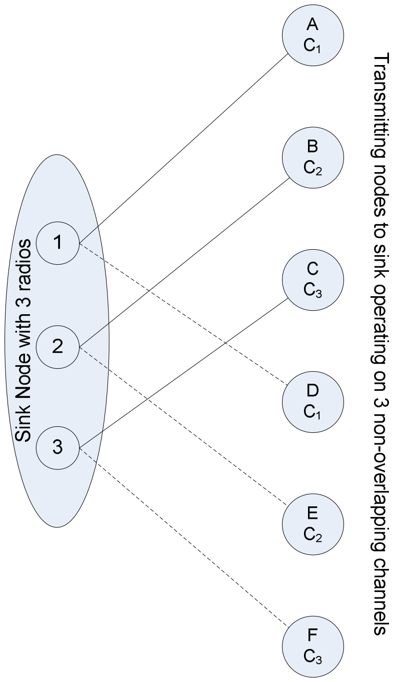

Figure 5-2: Sink Node with 3 Radios Receiving from 6 Transmitting Nodes on 3 non-overlapping channels (C_1, C_2, C_3)

Consider a graph G = (V, E) where V is the set of wireless radios at the sink and L is the set of communication links between radios and transmitting nodes. For example, there are three radio interfaces at the sink node as illustrated in fig. 5-2 $R_{1...i}$, each radio interface is correspond to one or more edge nodes $N_{i...x}$ but only one link can be active at any given time. The broken line represents the inactive link and only becomes active when the associate radio switches to the active channel of that node. Each transmitting node is assign to a channel and each radio only switch to a node on the same channel. A radio can receive data packet from more than one node on same channel. The radio link derives as: $R_i \leq N_{xn}$, where x and n is the node and channel number respectively. Consequently, only three links in fig. 5-2 can be active simultaneously, if D, E, F attempt to transmit when A, B, C is transmitting then a radio link conflict graph colouring problem has occurred. To avoid a conflict graph colouring problem from occurring each Edge (E) that connected to a Vertex (V) is assign a different colour. In the case where there are two E connected to each V, they are given colours True and False, this means that all the True can be transmitted at the same time and all the false become inactive. The colour false becomes active when the radio link switches to the inactive edge.

Algorithm 1: Relationship between two communication links using G = (V, E).

G represents a graph, while V represents Vertex and E Edge(s).

- For this algorithm V is a single Vertex while E can be 2 or greater ($E \geq 2$).
- The equation G = (V, E) can therefore be replaced by G = (V, E_I), where the subscript ‘I’ represents the variable for the number of Edges available.

The graph methodology is used to express the relationship between two communication links (represented by E in the equation) sending data to a single radio receiver (represented by V in the equation) non-simultaneously. Therefore at no time should both communication links be active to the common receiver/radio interface. The algorithm shown below represents a system using two communication links or edges. The objective is to ensure that only one communication link is active at any one time. The algorithm is laid out in a semi programming format.

```
Integer E1; /*E one of $E_I$*/
Integer E2; /*E two of $E_I$*/
Integer Communication_Link_Active_Status;
Integer Communication_Active_Link;
Integer Active;
```

```
Start Program;

POLLING_TX _ACTIVE_STATUS: /*Program location*/
Poll (Communication_Link_Active_Status);
Active = 1
If (Communication_Link_Active_Status == Active);
{
Goto (ACTIVE_TX_SELECT);
}
Else
{
Goto (POLLING_TX _ACTIVE_STATUS);
}

ACTIVE_TX_SELECT: /*Program location*/
While (Communication_Link_Active_Status == Active);
{
  Poll (Communication_Link_Active);
    If (Communication_Link_Active >0);
    {
      if (Communication_Link_Active == 1);
      {
        Print (“Edge 1 is the active link.”);
       }
        If (Communication_Link_Active == 2);
        {
          Print (“Edge 2 is the active link.”);
```

```
                    }
                    If (Communication_Link_Active > 2);
                    {
                        E_Greater_Than_Two = Communication_Link_Active;
                        Print ("Edge %i is the active link.\n ", E_Greater_Than_Two);
                    }
    }
    Else
    {
        Print ("Error! Not active communication link found.\n");
        Goto (END_PROGRAM);
    }
}
Goto (POLLING_TX _ACTIVE_STATUS);
END_PROGRAM: /*Program location*/
End Program;
```

<u>Keys:</u>
Goto = Jump to program location (Location Name)
Poll = Check the status flag (Status Flag Name)

The unidirectional links considered between the sink node and the transmitting nodes. Each source node is equipped with a single radio but has access to multiple channels. The sink node which represents the server is equipped with a set of receiving radio interfaces. The ability for success transmission between sender and receiver within the wireless range is denoted by a set of logical link (L) with C channels available. A binary vector define as $L_{l;\ l}$ the number of links to a channel C_n; n the number of channels as follows:

$$L_{(l-1)}C + n = \begin{cases} 1, & if\ l^{th}\ link\ uses\ the\ n^{th}\ channel \\ 0, & Otherwise \end{cases} \qquad (5.1)$$

For n = 1,..C, l = 1,..,L

Since only one channel can be assigned to each logical link l, between the lists of elements $L_{(l-1)}C + 1, L_{(l-1)}C + 2 \ldots, L_{lC,}$ only one of them is equal to 1 and the rest are equal to 0. Therefore, the following equality constraints:

$$L_{(l-1)}C + 1 + \cdots + L_{(l-1)}C + n = 1, \forall\ l = 1 \ldots, L \quad (5.2)$$

$$\Rightarrow\ AL = 1$$

The dimension of the matrix A depends on the link on the same channel which uses the same radio interface. The active link is always equal to 1 and 0 otherwise. Therefore for each row in matrix A one of the entry is equal to 1 and 0 otherwise.

The second constraint is imposed by the sink interfaces. The sink interfaces is the solution of interface to node binding problem. The constraint requires some links from a given node to use the same channel and radio. That is, if two links, y and z from a given node are assigned to use the same radio, then these two links need to be assigned to the same channel. This can be expressed as:

$$L_{(y-1)}C + n = L_{(z-1)}C + n, \;\; \forall\, n = 1 \ldots, C \qquad (5.3)$$

$$\Rightarrow \mathrm{BV} = 0$$

For each row in matrix B, two of the entries are equal to 1 and -1 respectively, and all other entries are equal to 0. The dimension of B depends on the number of link pairs that share a common radio interface. The vector definition in (1) and the equality constraints in (2) and (3), together form the following non-empty feasible set.

$$\varphi = \{L : l \in \{0,1\} \cap AL = 1 \cap BL = 0\} \quad (5.4)$$

Any of φ represent one feasible link assignment to a radio interface on same channel allocation.

Let's consider any two arbitrary links d and e, and their associate elements in vector V. Two C x 1 vectors have been defined as follows:

$$V_d = \left[L_{(d-1)}C + 1 \; L_{(d-1)}C + 2 \ldots L_d C\right]^T$$

$$V_e = \left[L_{(e-1)}C + 1 \; L_{(e-1)}C + 2 \ldots L_e C\right]^T \qquad (5.5)$$

$R_{i\,x\,i}$ define as the radio matrix at the sink. The element R_{AD} Є [0, 1] represents the radio interface portion between nodes A and D to switch on the same channel $C_{n.}$ R is a symmetric matrix and its diagonal elements all equal to 1. If node A and D are assigned to links d and e respectively, then

$$V_d^T R\, V_e = r_{AD} \qquad (5.6)$$

For example, using the three non-overlapping channels i.e. C = 3. R becomes a 3 x 3 unitary matrix. If two arbitrary links d and e are assigned the same channel, then $V_d^T R\ V_e = 1$. otherwise, the product will equal to zero.

5.5 Simulation Results and Discussions

The simulations will be using the design model of chapter 4 and the work in [87-88], where the original 802.11 DCF was modified to design an improved contention based MC-DCF protocol to perform channel switching in a multichannel single radio environment. This environment was improved upon at the sink node, where previously it was observed that channel switching among nodes by a single radio at the sink node causes severe degradation. This resulted in high packet delay and delivery ratio. The performance was analysed at the sink of the MC-DCF protocol by simulations with NS2 [18]. The 802.11 radio model of the NS2 used; this model has different topology and traffic generator.

Different simulation scenarios have been studied according to three different performance metrics: aggregate throughput, delivery ratio and access delay. The sensor nodes randomly placed in a 1000x1000m2 areas. The radio range is set to 50m, simulations run for 500s in each scenario and the radio bandwidth 10Mbps. These settings have been maintained from chapter 4 and the work in [87-88] where it was also observed that MC-DCF performed well within the mentioned range and rate in comparison to other ranges and rates. The number of nodes is 100. The numbers of channels used are three non-overlapping of the IEEE 802.11 that was used in our previous work [87-88] and which are used to compare result and measure the performance improvement. Since the spectral mask only defines power output restrictions up to ±11 MHz from the centre frequency to be attenuated by 30 dB. It is often assumed that the energy of the channel extends no further than these limits. These simulations use static nodes to mimic surveillance sensor network with high data rate streaming that would be deployed for organisation, parks, and vehicular traffic with nodes that are always powered, as such the energy consumption of the nodes are based on the power output ±11 MHz.

With the improvements made at the sink(s) to receive data directly from sending nodes within range the current simulation results has been compared with the previous results in [87-88] and chapter 4 to determined the level of performances in percentages, that is new results minus the previous results divided by the previous results multiplied by 100 (NR-PR/PR*100). From the formulated solutions and equations derived to improve the degradation at the sink node encountered from the previous work the solutions that obtain better performance will be considered as the most feasible option for the future MC-DCF.

5.5.1 Multiple Sinks with Single Radio

In the previous chapter the effect of the sink received data from sources within range that are sending data to be accepted were examined. It was observed that the more sources sending to the single sink the more delays were encountered. In this scenario the number of sink nodes increased to receive data from sources within the ranges of the sink nodes. No modification to the MC-DCF protocol was made except to increase the number of sinks to three with each having a single radio and the capability to switch channels as in the previous chapter. The simulation last for 500 seconds all nodes send CBR every 2 seconds.

Figure 5-3 show delay impact with the increase in sink nodes that are receiving data packets from sending nodes within range. It has been observed that with three channels there has been a 53% reduction in delay at the sink side comparing to the high level of delay in the previous chapter when only one sink node was used. In Figure 5-3 with two channels sending data from sources, there has been an approximately 32% delay improvement. Single channel and 802.11 DCF show little improvements. This indicates that single channel performance does not improve with increasing sink nodes as the decisions are based on the window size resetting, backing off, wait states and the fact that all nodes are contending for the same medium. MC-DCF with multiple channel switching and single radio interfaces can yield a better performance when using multiple sinks in comparison to single channel which shows a better performance in the previous chapter.

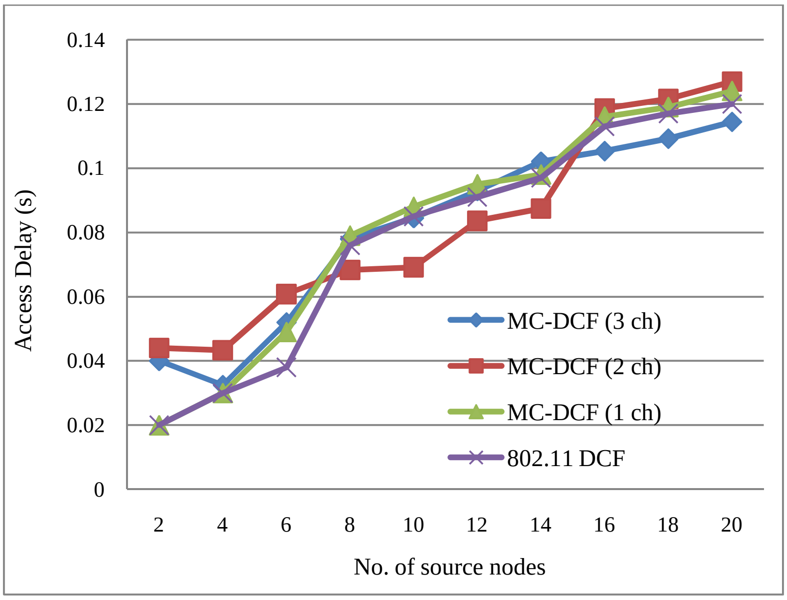

Figure 5-3: Delay impact from source nodes using multiple sinks with single radio interface.

Figure 5-4 shows an improvement of over 41% for three channels with packet delivery ratio when the number of sink increases by three as compare to single sink node in our previous work. With two channels sending data from the sources to the sinks there has been improvement by over 25% comparing to the poor performance resulted with single channel. Similarly where the delay with single channel shows no significant improvement, packet delivery ratio shows no major improvement.

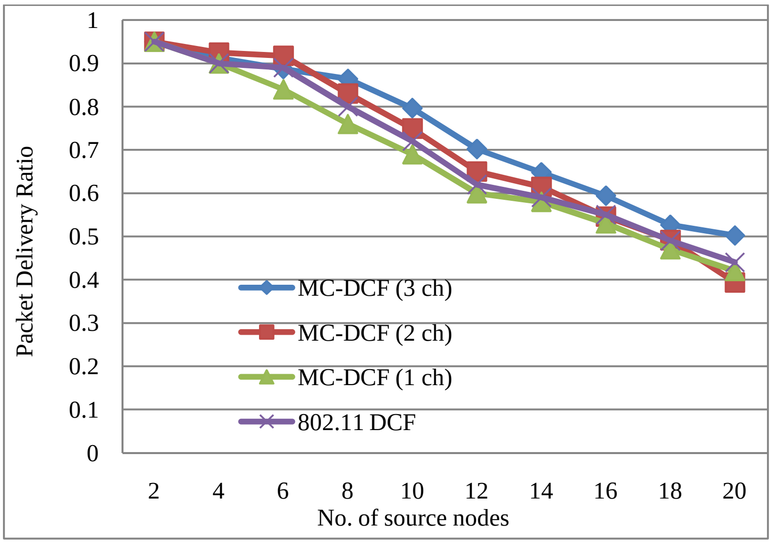

Figure 5-4: Delivery ratio impact from sources using multiple sinks with single radio interface

The aggregate throughput in Figure 5-5 of the overall system with source nodes sending to the sinks have shown that with three channels 38% more data have been delivered to the sink compare to that of single channel. Single channel in all instances has not shown any significant improvement with increasing of sink nodes to receive data from the source nodes.

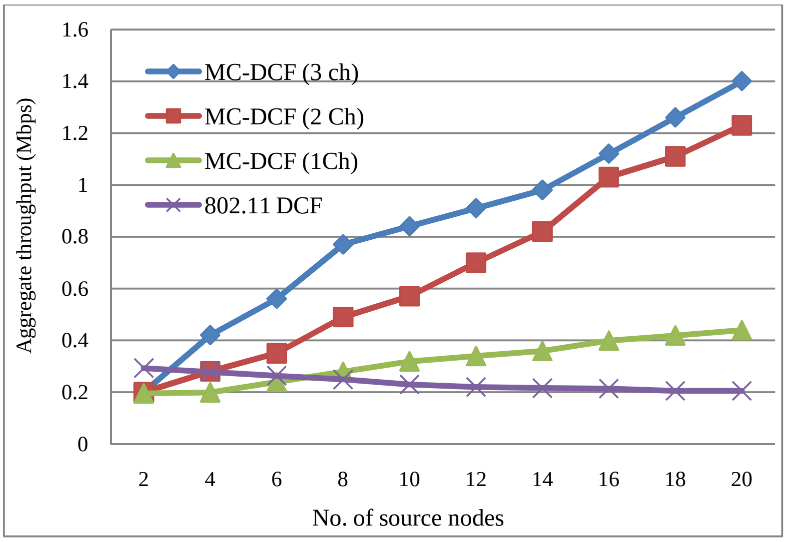

Figure 5-5: Throughput of overall system using multiple sink nodes with single radio interface.

With analysing the impact of MC-DCF with one to three channels in comparison with the original 802.11 DCF, it was observed that increasing the number of sink nodes result in an improvement when two or three channels are used. There was little or no improvement using a single channel or the original 802.11 DCF which only operates on a single channel. The reason for this improvement is that each sink has less data to receive from the senders. The same amount of data simulated in previous work was going to a single sink node. The improvement proved that increasing the sink nodes obtained a better performance as the traffic load has split to be received by more sink nodes. Therefore channel switching by a single radio has less data to retrieve therefore less time is spent to switch between channels from senders and the queuing of packet data has been reduced.

5.5.2 Single Sink with Multiple Radios

In the second set of simulations, a single sink node used and increase the number of sink radio interfaces to three. Figure 5-6 shows sink node with three radio interfaces. Each interface is assign to a channel and three sending nodes assign to each channel to create a one to one mapping against interface. In this case no channel switching is required. Each sender to the sink remains on said channel throughout the simulation. This allows constant flow between sending node and the radio interface.

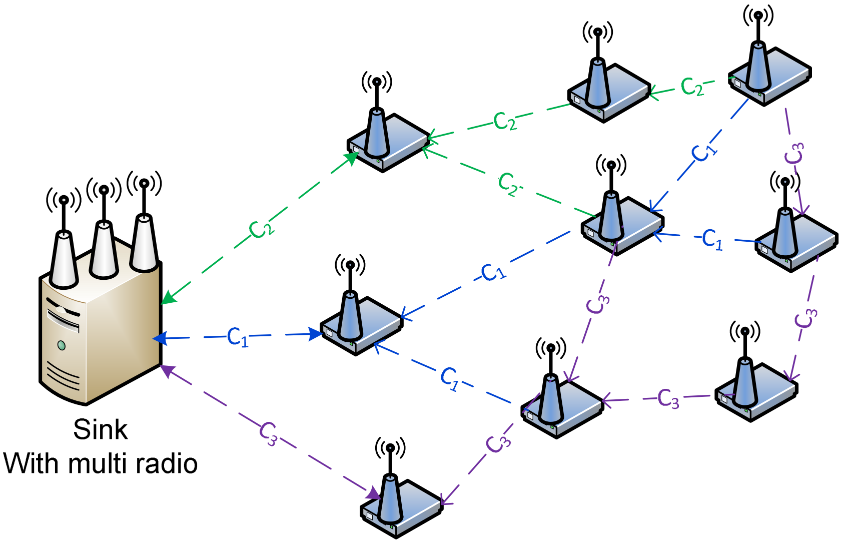

Figure 5-6: Single sink node with multiple radios.

Figure 5-7 shows the impact delay when MC-DCF uses a single sink with three radio interfaces to receive packet data which creates a one-to-one mapping in receiving data from sending nodes. MC-DCF with single radio from previous work had to perform channel switching to receive data when two or more non-overlapping channels are sending data to the sink. The result in previous chapter showed that when two or more channels were used there was poor performance; the repeat of this performance is shown in Figure 5-7, except that only three sources were assigned to send data to the three interfaces, where each interface and each node is assign to one of the non-overlapping channels. However, when the one-to-one assignment is used there have been over 40% successes in improvement for delay.

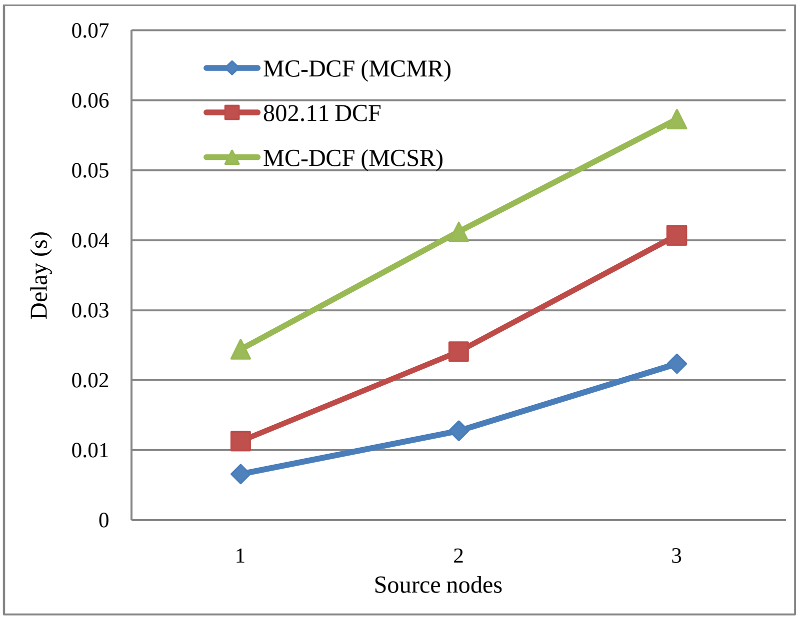

Figure 5-7: Delay impact with multichannel multi-radios communication at sink node.

This outcome indicates that if eliminating radio switching between channels and receives data flowing constantly from senders to the receiving radio interfaces then the performance at the sink can be improved. However this would not be practical when network size increases, as one would need to constantly increase the radio interfaces at the sink in addition, the limitation of non-overlapping channels would not make it feasible as there would not be enough non-overlapping channel to assign to radio interfaces.

The packet delivery ratio in Figure 5-8 shows similar improvement of approximately 46% for MC-DCF operating with multi-radios when compared to MC-DCF operating with single radio in our previous work. Each interface on a sending node is assign to different non-overlapping channels. 802.11 DCF showed little or no improvement as this protocol only design to operate with single channel. As mention before the one-to-one assignments is not ideal for a large network as it would not be practical to have each radio interface assign to a non-overlapping channel from a sending node.

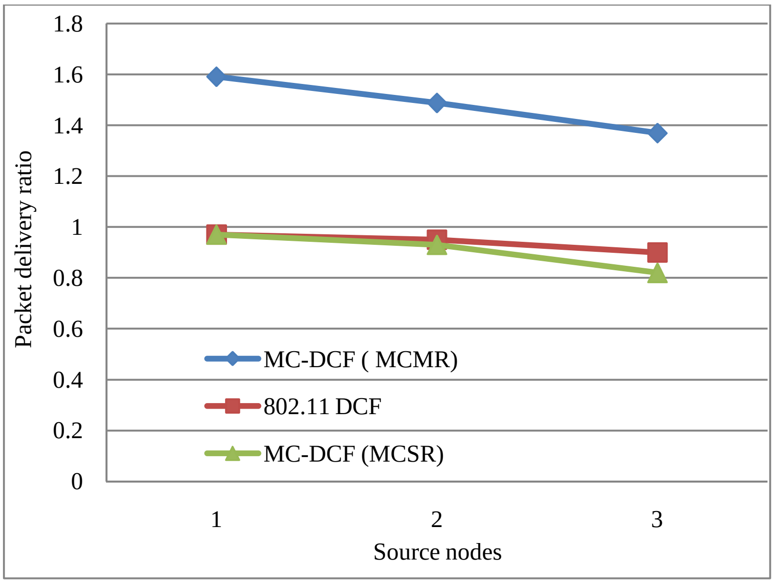

Figure 5-8: Delivery ratio impact with multichannel multi-radios communication at sink node.

Figure 5-9 also showed a 53% improvement in the one-to-one assignment with 3 non-overlapping channels for aggregate throughput. However for small parks and building areas this kind of implementation can be considered.

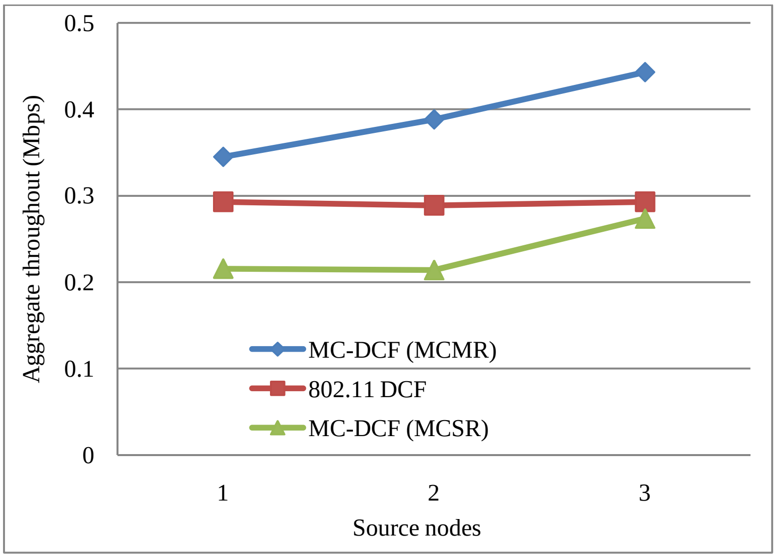

Figure 5-9: Throughput impact with multichannel multi-radios communication at sink node.

The one to one scenario demonstrated above is not practical in all instances but will depend on the size of the network and the number of sending nodes directly to the sink. Ideally there will be more nodes sending to the sink that will create a one-to-many assignment, where many nodes are sending to the same radio interface. Sending nodes can be odd or even in numbers. Some equations are derived to solve these scenarios for our next simulation.

5.5.3 Single Sink with Multi-Radios: Round Robin Method

The third scenario comprises multiple radios, multiple channels with even number of multiple sending nodes. The equations have the capability to simulate odd or even sending nodes to the sink node. Sending nodes in these equations are referred to as transmitter and the radio interface as receiver. G represents an uneven transmitter sending to receiver. As an uneven transmitter G has the capability of sending data to all receivers by switching channels. To identify G to each receiver: G1 represents G when sending to the first receiver, G2 represents G when sending to the second receiver and G3 represents G when sending to the third receiver.

The equations contain only logical states (active (1) and inactive (0)) values. When a node is in its active state its value is equal to one and when it is in an inactive state its value is equal to zero. For example $R_{X1} = \{T_{XA} \mid T_{XC,}\ T_{XG1} = 0\}$; Where the set R_{X1} consist of integer T_{XA} such that $T_{XC,}$ T_{XG1} equal to zero. Therefore when receiver R_{X1} is transmitting to $T_{XA,}$ T_{XA} value is set to one. T_{XC} and T_{XG1} cannot be transmitting to receiver (R_{X1}) simultaneously as such their values are set to zero (inactive state).

Figure 5-10 illustrate a radio interface at the sink (receiver, R_{X1}) accepting data from a node (transmitter, T_{XA} = 1) represented by an unbroken link. Other nodes ($T_{XC,}$ T_{XG1}) being zero are represented by broken links to illustrate their inactive state.

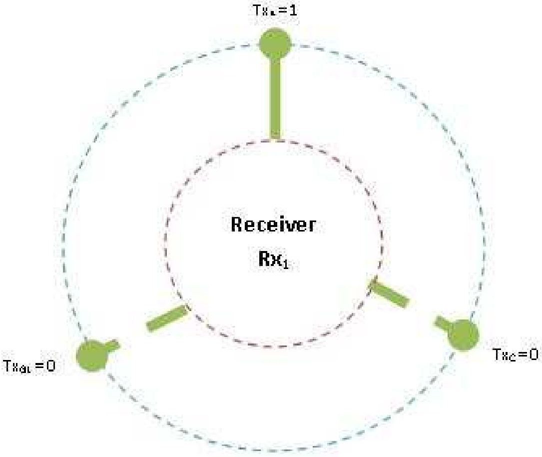

Figure 5- 10: Radio Interface (R_{X1}) Receiving from Node $T_{XA.}$

The following equations for the simulations have been expressed in the tables below.

Even Transmitter to Receiver ratio: (T_X:R_X); T_X = Even Positive Integer, $T_X \geq 4$, $R_X \geq 2$

When there are even senders to the sink node, each radio interface share even number of sending nodes and the radio interface remain on the assign channel with all nodes get even turn in transmitting its data to the sink in a round robin fashion which is explained later in this section. Table 5-2 define the equations.

The equations contains only logical states; Active (1), non-active (0) values

Senders ($T_X = 6$)	**Receivers ($R_X = 3$)**	**Equation**
A = (T_{XA})	1 = (R_{X1})	$R_{X1} = \{T_{XA} \mid T_{XD} = 0\}$
B = (T_{XB})	2 = (R_{X2})	$R_{X2} = \{T_{XB} \mid T_{XE} = 0\}$
C = (T_{XC})	3 = (R_{X3})	$R_{X3} = \{T_{XC} \mid T_{XF} = 0\}$
D = (T_{XD})	1 = (R_{X1})	$R_{X1} = \{T_{XD} \mid T_{XA} = 0\}$
E = (T_{XE})	2 = (R_{X2})	$R_{X2} = \{T_{XE} \mid T_{XB} = 0\}$
F = (T_{XF})	3 = (R_{X3})	$R_{X3} = \{T_{XF} \mid T_{XC} = 0\}$

Table 5-1: Equation for even sender to multiple radios at sink node on 3 non-overlapping channels

Uneven Transmitter to Receive ratio: (T_X:R_X); T_X = Uneven Positive Integer, $T_X \geq 5$, $R_X \geq 2$

The equations in Table 5-3 demonstrate when there are uneven numbers of sending nodes to the radio interfaces at the sink node. When there are uneven numbers of senders only one sender can transmit at a given time; a logical state is considered where the active node sending is equal to one and all other senders are set to zero. In the equation, 7 senders are defined and the odd sender is assigned in a sequential order where it receive equal opportunity to send in respect of which channel it is assign; however the uneven node has the option to switch channels but not during its period of transmission.

Senders ($T_X = 7$)	**Receivers ($R_X = 3$)**	**Equation**
A = (T_{XA})	1 = (R_{X1})	$R_{X1} = \{T_{XA} \mid T_{XC},\ T_{XG1} = 0\}$
B = (T_{XB})	2 = (R_{X2})	$R_{X2} = \{T_{XB} \mid T_{XE},\ T_{XG2} = 0\}$
C = (T_{XC})	1 = (R_{X1})	$R_{X1} = \{T_{XC} \mid T_{XA},\ T_{XG1} = 0\}$
D = (T_{XD})	3 = (R_{X3})	$R_{X3} = \{T_{XD} \mid T_{XF},\ T_{XG3} = 0\}$
E = (T_{XE})	2 = (R_{X2})	$R_{X2} = \{T_{XE} \mid T_{XB},\ T_{XG2} = 0\}$
F = (T_{XF})	3 = (R_{X3})	$R_{X3} = \{T_{XF} \mid T_{XD},\ T_{XG3} = 0\}$

G = (T_{XG1} when sending to 1st receiver, T_{XG2} when sending to 2nd receiver, T_{XG3} when sending to 3rd receiver)	*sequential input to receivers {1 + 2 + 3}	$R_{X1} = \{T_{XG1} \mid T_{XA}, T_{XC} = 0\}$ $R_{X2} = \{T_{XG2} \mid T_{XB}, T_{XE} = 0\}$ $R_{X3} = \{T_{XG3} \mid T_{XD}, T_{XF} = 0\}$ N.B. T_{XG1}, T_{XG2}, and T_{XG3} are switchable communication link from sender G going to each of the receivers. Therefore sender G has the same number of switchable time period to receivers. When G switch to a channel, G waits its turn to transmit then has the option to switch to another channel.

Table 5-2: Equation for uneven sender to multiple radios at sink node on 3 non-overlapping channels

Uneven Transmitter to Receive ratio: (T_X:R_X); T_X = Uneven Positive Integer, $T_X \geq 5$, $R_X \geq 2$

Table 5-4 equations yield the same outcome as Table 5-3 but have been express differently.

- Firstly, begin with senders to Receiver in a ratio of 6:3 which represents 2 transmitters to each receiver (2:1).
- Secondly, multiply the output of ODD transmitter by the quantity of receivers, an even system have been created where G is the sequential sending nodes that can be on any channel, the radio interface at the sink will sense G and updates the number of receiver for data acceptance. However, G is not switch-able to another channel when data is being sent to the receiver in a cycle.

The equations contain only logical states; active (1) and inactive (0) values.

Senders (T_X =7)	**Receivers (R_X = 3)**	**Equation**
A = (T_{XA})	1 = (R_{X1})	$R_{X1} = \{T_{XA} \mid T_{XC}, T_{XG1} = 0\}$
C = (T_{XC})	1 = (R_{X1})	$R_{X1} = \{T_{XC} \mid T_{XA}, T_{XG1} = 0\}$
G = (T_{XG1})	*Sequential time period to receiver 1	$R_{X1} = \{T_{XG1} \mid T_{XA}, T_{XC} = 0\}$

B = (T_{XB})	2 = (R_{X2})	$R_{X2} = \{T_{XB} \mid T_{XE}, T_{XG2} = 0\}$
E = (T_{XE})	2 = (R_{X2})	$R_{X2} = \{T_{XE} \mid T_{XB}, T_{XG2} = 0\}$
G2 = (T_{XG2})	*Sequential time period to receiver 2	$R_{X2} = \{T_{XG2} \mid T_{XB}, T_{XE} = 0\}$
D = (T_{XD})	3 = (R_{X3})	$R_{X3} = \{T_{XD} \mid T_{XF}, T_{XG3} = 0\}$
F = (T_{XF})	3 = (R_{X3})	$R_{X3} = \{T_{XF} \mid T_{XD}, T_{XG3} = 0\}$
G3 = (T_{XG3})	*Sequential input to receiver 3	$R_{X3} = \{T_{XG3} \mid T_{XD}, T_{XF} = 0\}$

Table 5-3: Equation for uneven sender to multiple radios at sink node on 3 non-overlapping channels

These equations allow a round robin fashion; each radio operates as a single-Eulerian cycle, which listens to every node on same channel once in a cycle. When the radio is less than the number of sending nodes, the logics have been derive so that radio operates in a round robin fashion. The round robin technique does not limit the number of radio interfaces, each interface will operate in the same way which will allow the sink node (s) to receive data from senders in a more effective and efficient manner. Take for example 6 sending nodes as illustrate in Figure 5-2 and Table 5-2 with even transmitter to receiver equations, assign to three non-overlapping channels, each radio interface will switch between 2 nodes per cycle. When the radio interface on channel 1 senses the first sending node, it will receive its data packets and then sense the medium for the next node on the same channel. It will switch to that the sending node receives its data and continues in that fashion throughout the simulation period. Figure 5-11 illustrate the round robin fashion where the radio interface(s) at the sink can receive from only one sender at any given time. When the interface is receiving the transmitter is equal to one which is represented by an unbroken link in the diagram and zero otherwise which is represented by the broken link.

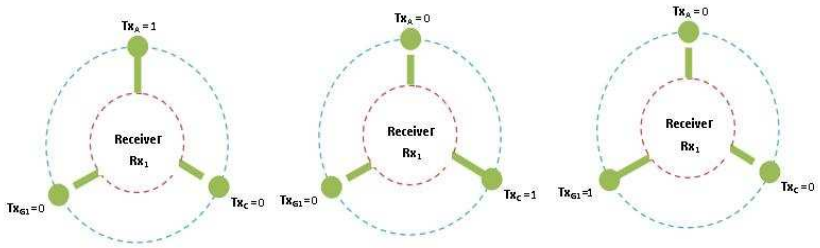

Figure 5- 11: Round Robin Cycle

In the third simulation scenario, a single sink node with three radio interfaces were used; each radio interface is assign to one of the 3 non-overlapping channels and six sending nodes to the sink, using the equations above in a round robin fashion. This assignment is semi-dynamic where two transmitting node is assign to the same channel and each radio interface at the sink switches among sending nodes on the same channel which gives a 2:1 ratio; two nodes transmit to one radio interface.

Figure 5-12 shows the delay impact among the six sending nodes and the radio interfaces at the sink. MC-DCF with the multichannel multi-radio (MCMR) assignment performs significantly better than MC-DCF with multichannel single radio (MCSR). When compared to the outcome with the performance of MCSR in the previous chapter, there has been an improvement of over 55% for delay. This outcome indicates that with multiple radio interfaces MC-DCF can reduce the high delay encountered with single channel as the number of senders need not queue to wait on a single radio interface. Instead senders can be distributed among several interfaces. This also reduces the extensive work of a single interface switching between several sending nodes to receive their data packages.

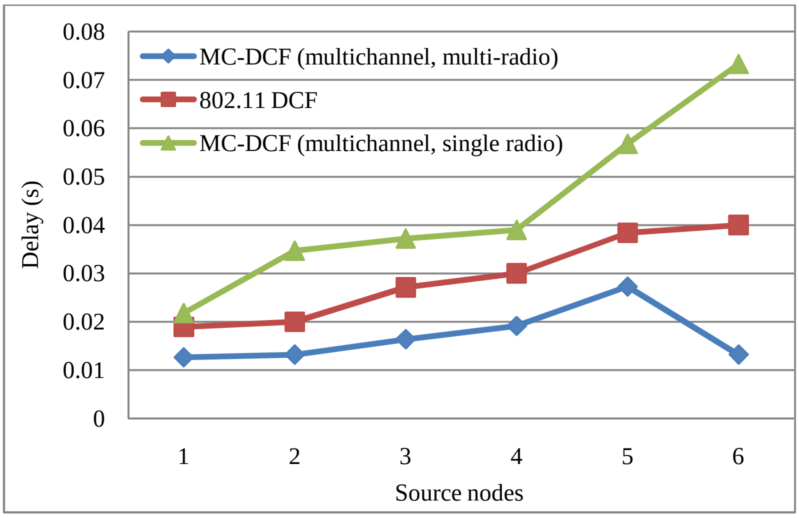

Figure 5-12: Delay impact comparison with one to many communications at sink node.

Figure 5-13 observed a similar trend to that of delay where MCMR obtaining higher packet delivery ratio of over 51% compare to MCSR that perform very poorly from the previous chapter. Therefore, having multiple radio interfaces at the sink node to receive data packets from the three non-overlapping channels have improve the performance packet delivery and reduce the traffic load experience by a single radio interface.

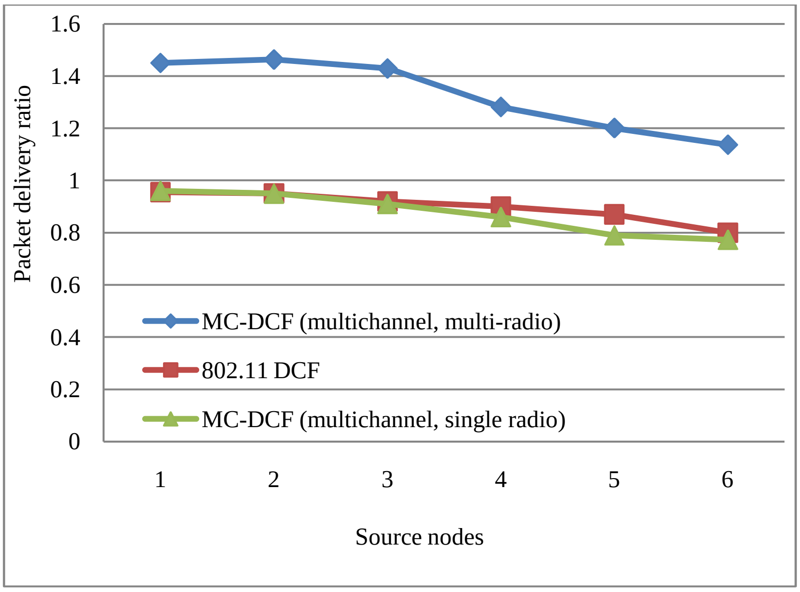

Figure 5-13: Delivery impact comparison with one to many communications at sink node.

Figure 5-14 shows the overall aggregate throughput for the total amount of data delivered to the sink. MCMR show an overall better performance of 49.6% in comparison to that of MCSR offered load.

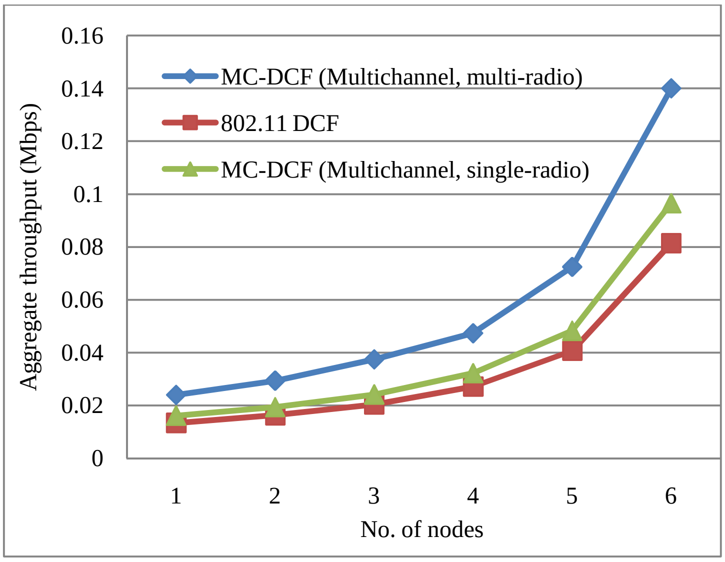

Figure 5-14: Throughput impact comparison with one to many communications at sink node.

The single sink with multiple channels and radio interfaces scenario demonstrated above for MC-DCF has shown improvement in performance over a single sink with multiple channels and single radio interface. There has not been any significant improvement in the 802.11 DCF, as it is a contention based protocol design to operate on a single medium, where all nodes contend for the single medium.

5.5.4 Multiple Sink Multi-Radios

The previous scenarios have simulated and analysed the impact with:

- Multiple sink each with single radio
- Single sink with multi radio
- Single sink with multi-radio in a round robin fashion

Each scenario showed some level improvement for MC-DCF when the sink node(s) obtain data from source nodes, comparing to our previous work where the sink encountered severe degradation when receiving from sources by a single sink with single radio interface that has to constantly switching between sending node interfaces. This scenario analysed the impact of data sending from sources to three sink nodes. Each sink was equipped with three radio interfaces using the three non-overlapping channels in IEEE 802.11.

Figure 5-15 shows sensor network with multiple sink nodes each having three radio interfaces.

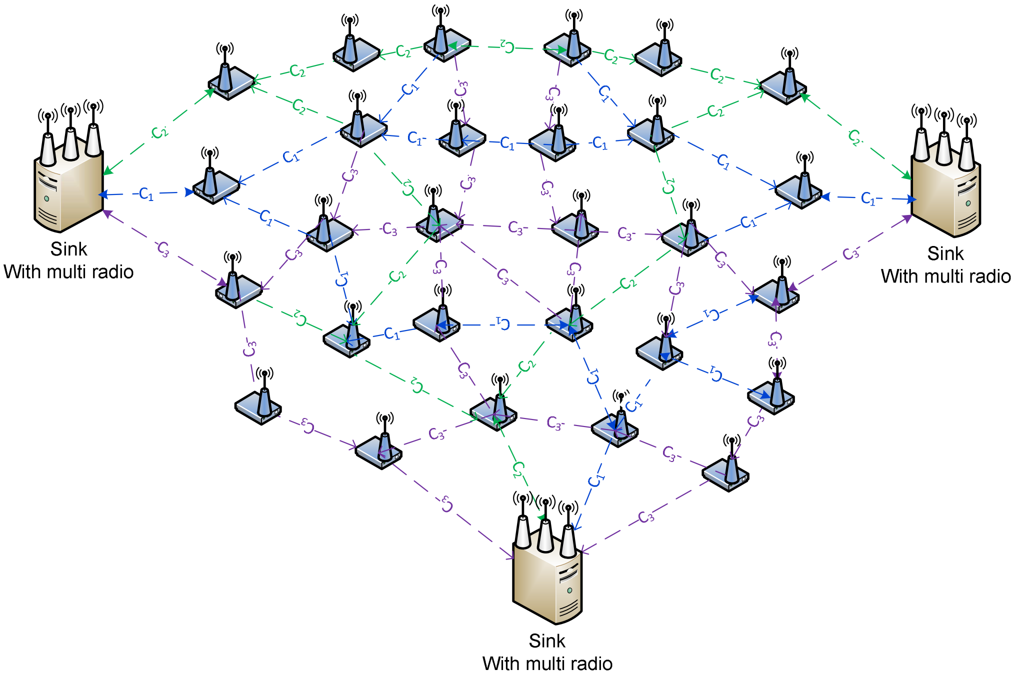

Figure 5-15: Multiple Sink Nodes with Multiple Radios

Figure 5-16 show delay impact with the increase in sink nodes and radio interfaces. It has been observed that with three channels there has been a 96% reduction in delay at the sink side comparing to the previous work where the source node transmitting directly to the sink experience high level due to channel switching by the single radio interface. With two channels sending data from sources, there has been an approximately 87.4% delay improvement. Single channel and 802.11 DCF show little improvements. As mention previously single channel performance does not improve with increasing sink nodes or radio interfaces as the decisions are based on the window size resetting, backing off, wait states and the fact that all nodes are contending for the same medium. MC-DCF with multiple channel switching and multiple radio interfaces have yielded better performance when using multiple sinks in contrast to single channel and 802.11 DCF which shows a better performance in previous work.

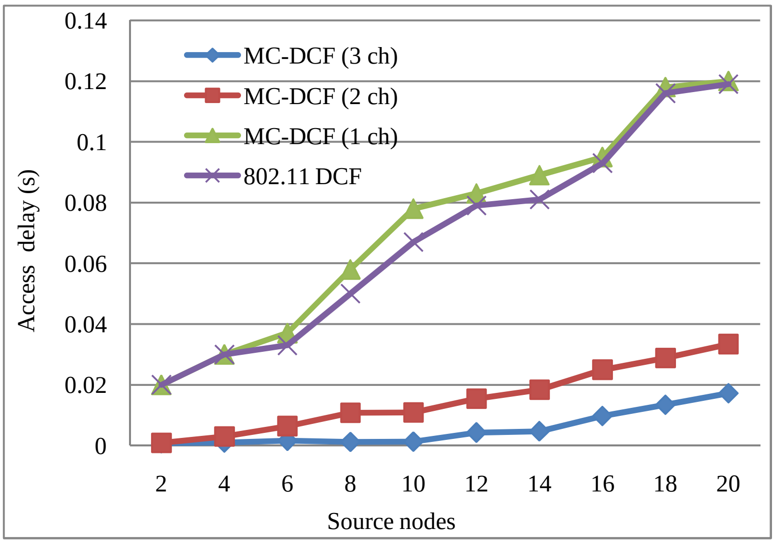

Figure 5-16: Delay impact from source nodes when using multiple sinks with multiple radio interfaces

Figure 5-17 shows an improvement of over 90% for three channels with packet delivery ratio when the number of sink nodes and radio interfaces increase by three as compared to single sink node with single radio interface in our previous work. With two channels sending data from the sources to the sinks there has been improvement by over 81% comparing to the poor performance experienced with single channel. Similarly where the delay with single channel shows no significant improvement, packet delivery ratio using single channel shows no major improvement.

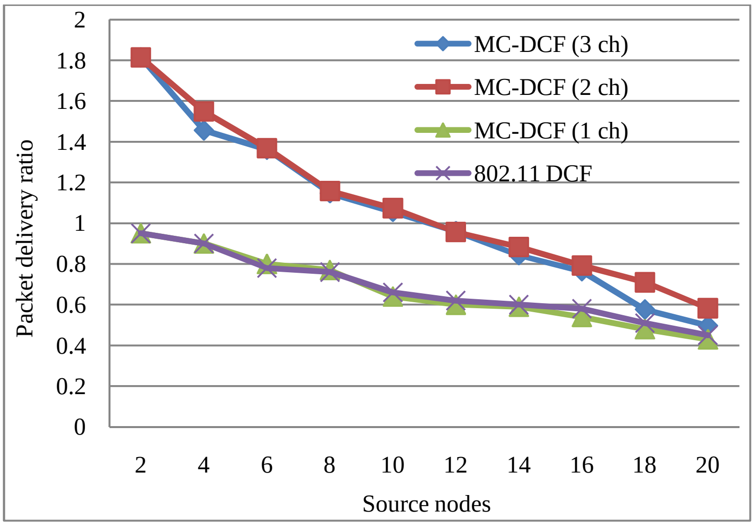

Figure 5-17: Delivery ratio impact from sources when using multiple sinks with multiple radio interfaces

The aggregate throughput in Figure 5-18 of the overall system with source nodes sending to the sinks have shown that with multiple sink nodes, channels and radio interfaces 92% more data have been delivered to the sink compared to that of single sink with single radio and single channel. Single channel and 802.11 DCF in all instances has not shown any significant improvement with increasing of sink nodes receiving data from the source nodes.

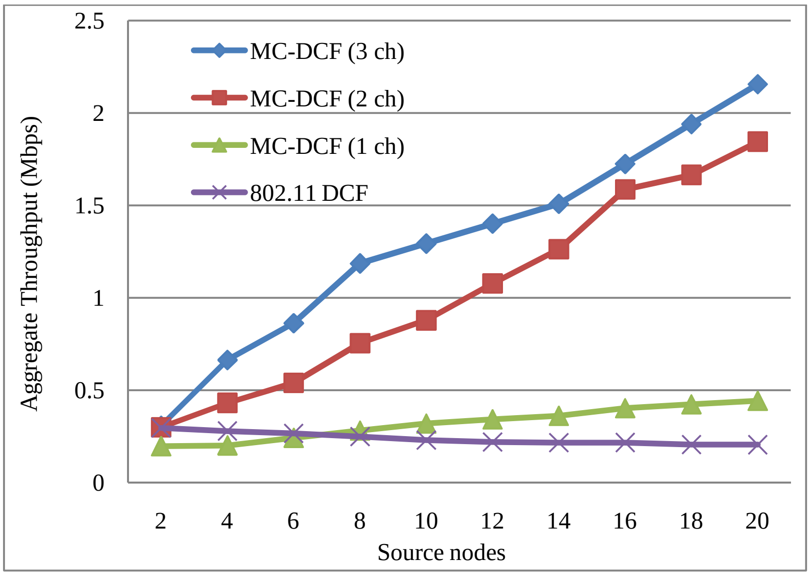

Figure 5-18: Throughput of overall system using multiple sink nodes with multiple radio interfaces.

5.6 Conclusion

This chapter addressed the poor performance encountered by the sink in the previous work. The aim is to have WSN perform at an optimum rate in a multichannel environment of the 802.11 network for high data rate. A WSN was considered, formed by static nodes with increasing the sink node and by assigning multiple radio interfaces at the sink. The multichannel assignment was addressed in two ways: firstly each sink node was equipped with a single radio capable of switching channels to receive data packets, and secondly, each sink node was equipped with multiple radio interfaces with each interface assigned to a distinct channel. The interface switches to receiving nodes on the same channel. However the nodes transmitting to sink remained on the same channel and not allowed to switch channel during transmission.
Solutions were formulated in solving multichannel multi-radio assignment at the sink by using graph technique and a binary vector. A number of equations were derived to solve the odd or even number of transmitting nodes sending data directly to the sink.

From the simulation outcomes it was proven that increasing the number of sink nodes and/or increases the number of radio interfaces in the sink a better performance can obtain which resulted in an overall performance within the network. The multi-radio interfaces assignment in the sink node will be the network to consider for the future, even though when increasing the sink nodes with single interface there have been improvement in performance. The simulation scenario with three sink nodes, each equipped with three radio interfaces using the three non-overlapping channels in IEEE 802.11 is the network to be considered for future static WSN with streaming data. The simulation results shown that an average of over 90% improvement in performance can be achieved. As such this kind of assignment can be considered to be more cost effective and energy efficient in the future.

5.7 Acknowledgements

The work was supported by NAP of Korea Research Council of Fundamental Science and Technology.

Chapter 6

Conclusion and Future Work

6.1 Conclusion Summary

This research determined the feasibility in having 802.11 being considered as a future medium for WSNs to operate high data rate, multi channel environment with streaming data in the 2.4 GHz frequency band that requires timely and efficient delivery. In addition an original model was proposed that addressed shortage of spectrum which limits current capability to introduce new wireless services and improve existing ones. A multi-radio multi channel model was introduced that allows different wireless systems to share multiple channels and switch channels without causing excessive harmful interference to other neighbours. This system was proven from simulations to increase the amount of communications that can take place in a given network. This finding creates the framework in which the world of wireless services and applications, may be revolutionised resulting in less expensive networks transmitting higher data rate than currently exist.

6.1.1 Feasibility Comparison of IEEE 802.11 and IEEE 802.15.4 for WSN

Simulations showed that IEEE 802.11 performed better with high data rate, streaming constant bit rate and at longer range comparing to 802.15.4 which operates better with small data size at much shorter range. This result indicates that 802.15.4 cannot perform well with streaming data even if operating at low data rate and would not be feasible for sensor network with multimedia or surveillance system that rely on image and data over the wireless medium. The 802.11 networks exhibited comparatively higher aggregate throughput when compared to the 802.15.4 indicating its superior performance in a high data rate environment. On the other hand the significantly poor performance of the 802.15.4 network in a high data rate and wide node range environment make it unsuitable for streaming data in a WSN.

It was concluded that 802.15.4 is not feasible for sensor multimedia or surveillance system with streaming data for future multichannel multi-radio systems.
Having investigating the performance between IEEE 802.11 and IEEE 802.15.4 it became feasible to design the 802.11 contention-based protocols for multichannel assignment. The proposed design is a multichannel distributed coordinate function over single radio for WSNs.

Conclusive simulations were conducted to analyse the signal strength with different data rate over the 802.11a/b/g networks, using: access delay, delivery ratio and aggregate throughput metrics to analyse the performances.

6.1.2 Performance Analysis of Proposed MC-DCF - Protocols

802.11DCF, MC-DCF and MMSN Protocols *Figures 4-6, 4-7, and 4-8,* analysed the performance of 802.11 DCF, MC-DCF and MMSN protocols based on number of channels, measured against the three mentioned metrics – packet delivery, aggregate throughput, and access delay. The MC-DCF protocol yielded the highest packet delivery ratio of the three protocols, however, MMSN performed slightly better than MC-DCF in relation to channel access delay and aggregate throughput. However, MC-DCF will outperform MMSN in the 802.11 network, should both protocols operate within the data rates ranging from 2Mbps up to 54Mbps of the 802.11 networks.

802.11DCF and MC-DCF *(1-3 Channels)* Figures 4-9, 4-10 and 4-11 analysed the performance of 802.11 DCF against MC-DCF using one, two and three channels - measured within context of the three mention metrics using the CBR data streams. In this scenario MC-DCF over three channels recorded the lowest level of channel access delay even as the CBR stream increased; conversely when transmitting over one channel the MC-DCF protocol recorded the highest level of channel access delay. The delivery ratio is highest when three channels are used - more packets are delivered compared to one and two channels. A similar trend is seen where MC-DCF with 3 channels has a better aggregate throughput, where more data are delivered to the receiving node.

Impact of Node Density on 802.11DCF and MC-DCF *(1-3 Channels)* Figures 4-12, 4-13 and 4-14 analysed the impact of node density on the performance of 802.11DCF, and MC-DCF using one, two, and three channels - The MC-DCF with three channels recorded the lowest level of access delays as the node density of the network increases. Packet delivery ratio and the aggregate throughput respectively show a comparatively better performance of all the tested protocols - when two or more channels are used. MC-DCF with three channels recorded the highest level of aggregate MAC throughput, of all the tested protocols even as the node density of the network increased. Similar to the packet delivery ratio performance, the 802.11DCF and MC-DCF (Ch1), recorded declines in performance as the density of the network increases.

Sink Node with Single Radio - Channel switching performance was observed at the sink by varying the number of source nodes the sink received data from. Access delay and packet delivery ratio was measured at the sink node. From observation, the more sources delivering to the sink the more delays encountered, and the packet delivery ratio decreases accordingly. The highest rate of decline was evident in the protocols with at two or more channels. This is due to the sink node having to be constantly switching between channels in order to receive data, which incur severe switching delay in addition to the time taken to accept data before switching.

6.1.3 Performance Analysis of 802.11a/b/g Networks

Packet Delay Analysis: 802.11a/b/g Networks - In Figure 4-18 nodes are placed at 50m intervals with data transmitting at a rate of 2Mbps. In this simulation, delays declined over all three networks as the number of channels increased. The most significant decrease in packet delays occurred when three channels were transmitting. When the distance between nodes were increased from 50m to 100m there was a correspondingly dramatic increase in access delays for all three networks, as compared to performance at the 50m node range. The increase in delay that is experienced by all networks indicates that 100m range among nodes results in weak signal, which makes it difficult for transmission and as such degradation of the networks.

Figures 4-20 and 4-21 show the delay that occurs when simulating at 10Mbps over 50m and 100m node intervals. At the 50m range the lowest level of delays occurred, contrary to the pattern in performance experienced at the 100m range where degradation of the networks increased significantly- the 802.11a network accounting for the highest delays. The high delay experienced by 802.11a resulted from it not being backward compatible to 802.11b; in addition to the fact that it was designed to operate at a minimum data rate of 6Mbps. Therefore operating with a data rate of 2Mbps causes possible frequent dropped connections and degradation of service. This conclusively proves that 802.11b cannot operate with data rate higher than 11Mbps. Both 802.11a/g show a better performance than 802.11b, however at 100m range the networks experience high delay which degrades the system significantly.

Aggregate Throughput Analysis: 802.11a/b/g Networks: The results show a similar pattern where the 50m range results in better performance having more data delivered at the receiving nodes. Figure 4-27 shows significant network degradation when operating at the 100m range with aggregate throughput within the range of 0.1 to 1.75Mbps. All network performance at 10Mbps have slight variations with a maximum throughput of 8.8Mbps when operating over 4 non-overlapping channels. Figure 4-27 shows significant network degradation when operating at the 100m range with aggregate throughput within the range of 0.1 to 1.75Mbps. Conclusively, the 802.11b network is not feasible for operating in a high data rate multi channel environment.

Packet Delivery Analysis: 802.11a/b/g Networks: Significantly a lower percentage of packet delivery ratio was evident as the node range increased from 50m to 100m. The 802.11b delivery rate was significantly below 10% at 54Mbps. This is owing to the fact that 802.11b has a maximum raw data rate of 11 Mbps. All networks performed poorly under that is 50% delivery rate when operating at 100m range at the varying data rates of 2, 10 and 54 Mbps. The results are similar to that of the aggregate throughput, in that, the more channels utilised for transmission, the more packets are delivered. The most packets are delivered at the range interval of 50m, and data rate of 10Mbps, proving that contention based network perform poorly when the communication range exceeds 50m.

6.1.4 Multi-Chanel Multi Radio Access: Sink Nodes in WSN

In the earlier simulations the effect of the sink receiving data from sources within range that are sending data to be accepted were examined. It was observed that the more sources sending to the single sink the more delays were encountered. In this scenario the number of sink nodes increased to receive data from sources within the ranges of the sink nodes. No modification to the MC-DCF protocol was made except to increase the number of sinks to three with each having a single radio and the capability to do channel switching.

6.1.4.1 Multiple Sinks with Single Radio: Simulation 1

Delay Impact: Figure 5-3 show Delay impact from source nodes using multiple sinks with single radio interface delay impact with the increase in sink nodes that are receiving data packets from sending nodes within range ….. It has been observed that with three channels there has been a 53% reduction in delay at the sink… comparing to the high level of delay that occurred when only one sink node was used. In Figure 5-3 with two channels sending data from sources, there has been an approximately 32% delay improvement. Single channel and 802.11 DCF show little improvements. This indicates that single channel performance does not improve with increasing sink nodes as the decisions are based on the window size resetting, backing off, wait states and the fact that all nodes are contending for the same medium. MC-DCF with multiple channel switching and single radio interfaces can yield a better performance when using multiple sinks in comparison to single channel.

Delivery Ratio: Figure 5-4 shows Delivery ratio impact from sources using multiple sinks with single radio interface Figure 5-4 shows an improvement of over 41% for three channels with packet delivery ratio when the number of sink increases by three as compare to single sink node in our previous work. With two channels sending data from the sources to the sinks there has been improvement by over 25% comparing to the poor performance resulted with single channel.

Aggregate Throughput: Fig 5-5 shows throughput of overall system using multiple sink nodes with single radio interface. The overall system with source nodes sending to the sinks have shown that with three channels 38% more data have been delivered to the sink compare to that of single channel. Single channel in all instances has not shown any significant improvement with increasing of sink nodes to receive data from the source nodes. With analysing the impact of MC-DCF with one to three channels in comparison with the original 802.11 DCF, it was observed that increasing the number of sink nodes resulted in an improvement when two or three channels are used. There was little or no improvement using a single channel or the original 802.11 DCF which only operates on a single channel. The reason for this improvement is that each sink has less data to receive from the senders.

6.1.4.2 Single Sink with Multiple Radios: Simulation 2

Figure 5-7 shows the impact delay when MC-DCF uses a single sink with three radio interfaces to receive packet data which creates a one-to-one mapping in receiving data from sending nodes. When the one-to-one assignment is used there have been over 40% successes in improvement for delay. The packet delivery ratio in Figure 5-8 shows similar improvement of approximately 46% for MC-DCF operating with multi-radios when compared to MC-DCF operating with single radio in our previous work. One-to-one assignments is not ideal for a large network as it would not be practical to have each radio interface assign to a non-overlapping channel from a sending node. Figure 5-9 also showed a 53% improvement in the one-to-one assignment with 3 non-overlapping channels for aggregate throughput.

6.1.4.3 Single Sink with Multi-Radios: Round Robin Method – Simulation 3

In the third simulation scenario, a single sink node with three radio interfaces were used; each radio interface is assign to one of the 3 non-overlapping channels and six sending nodes to the sink, using the equations above in a round robin fashion. This assignment is semi-dynamic where two transmitting node is assign to the same channel and each radio interface at the sink switches among sending nodes on the same channel which gives a 2:1 ratio; two nodes transmit to one radio interface.

This outcome indicates that with multiple radio interfaces MC-DCF can reduce the high delay encountered with single channel as the number of senders need not queue to wait on a single radio interface. Instead senders can be distributed among several interfaces. This also reduces the extensive work of a single interface switching between several sending nodes to receive their data packages. Figure 5-14 shows the overall aggregate throughput for the total amount of data delivered to the sink. MCMR show an overall better performance of 49.6% in comparison to that of MCSR offered load.

6.2 Conclusion: Discussion and Recommendation

6.2.1 Multiple Sink Multi-Radios - Simulation 4

Each scenario showed some level improvement for MC-DCF when the sink node(s) obtain data from source nodes, comparing to our previous work where the sink encountered severe degradation when receiving from sources by a single sink with single radio interface that has to constantly switching between sending node interfaces. This scenario analysed the impact of data sending from sources to three sink nodes. Each sink was equipped with three radio interfaces using the three non-overlapping channels in IEEE 802.11.

Figure 5-16 show delay impact with the increase in sink nodes and radio interfaces. It has been observed that with three channels there has been a 96% reduction in delay at the sink side comparing to the previous work where the source node transmitting directly to the sink experience high level due to channel switching by the single radio interface. With two channels sending data from sources, there has been an approximately 87.4% delay improvement. Single channel and 802.11 DCF show little improvements. As mention previously single channel performance does not improve with increasing sink nodes or radio interfaces as the decisions are based on the window size resetting, backing off, wait states and the fact that all nodes are contending for the same medium. MC-DCF with multiple channel switching and multiple radio interfaces have yielded better performance when using multiple sinks in contrast to single channel and 802.11 DCF.

Figure 5-17 shows an improvement of over 90% for three channels with packet delivery ratio when the number of sink nodes and radio interfaces increase by three as compared to single sink node with single radio interface in our previous work. With two channels sending data from the sources to the sinks there has been improvement by over 81% comparing to the poor performance experienced with single channel. Similarly where the delay with single channel shows no significant improvement, packet delivery ratio using single channel shows no major improvement.

The aggregate throughput in Figure 5-18 of the overall system with source nodes sending to the sinks have shown that with multiple sink nodes, channels and radio interfaces 92% more data have been delivered to the sink compared to that of single sink with single radio and single channel. Single channel and 802.11 DCF in all instances has not shown any significant improvement with increasing of sink nodes receiving data from the source nodes.

From the simulation outcomes it was proven that increasing the number of sink nodes and/or increases the number of radio interfaces in the sink a better performance can obtain which resulted in an overall performance within the network. The multi-radio interfaces assignment in the sink node will be the network to consider for the future, even though when increasing the sink nodes with single interface there have been improvement in performance. The simulation scenario with three sink nodes, each equipped with three radio interfaces using the three non-overlapping channels in IEEE 802.11 is the network to be considered for future static WSN with streaming data. The simulation results shown that an average of over 90% improvement in performance can be achieved. As such this kind of assignment can be considered to be more cost effective and energy efficient in the future.

6.3 Future Work

After experimenting with multichannel assignments and evaluating MC-DCF performance, it can be confidently said that the results are encouraging. However, these accomplishments need to be followed with further development effort to transform the channel assignment into reality and apply MC-DCF in other contexts beyond multichannel assignments. The work in this thesis opens up research on various interesting issues and directions.

6.3.1 Overlapping Channels

This thesis presented the work on non-overlapping channels in chapters 4 and 5. If transmitters are closer together then channels overlap between the channels may cause unacceptable degradation of signal quality and throughput. However, overlapping channels may be used under certain circumstances. This way, more channels are available. The use of overlapping channels during medium access is an interesting and challenging future research direction.

6.3.2 Energy Efficiency

One of the most important issues in WSNs is the energy efficiency. Although this thesis uses non-overlapping channels and assumes nodes are static and always powered, there is no certainty if multi-channel communication can help to reduce energy consumption in WSNs. Evaluating the energy consumption of the existing multi-channel protocols, together with the impact of channel switching, can be a major research topic.

6.3.3 Real-Time Constraints

In real-time applications, data is delay constrained and has a certain bandwidth requirement. It functions within a time frame that the user senses as immediate or current. For example, scheduling messages with deadlines is important in order to take appropriate actions in real time or set alerts that trigger critical activities.

However, due to the interference and contention on the wireless medium, this is a challenging task. Multi-channel communication can help to reduce the delay by increasing the number of parallel transmissions and help the network to achieve real-time guarantees. Reducing the delay in real time application can be an interesting research area in the future.

6.3.4 Multiple Applications running on the same network

The latest operating systems for WSNs make it possible to have multiple applications running on the same network. This can allow larger amounts of data to be transmitted in the network and dealing with traffic, with different priority levels, in an energy efficient way avoiding collisions and interference which can becomes a major issue. Multi-channel communication can be a topic to be researched for solving the problems that arise with running multiple applications in the network.

6.3.5 Cross Layer Design

The major challenges that WSN need to overcome are:

- The constrained in computational, energy and storage resources because of its limited energy.
- Interference among the transmission
- Redundant information since in most case neighbouring nodes often sense the same events from their environment thus forwarding the same data to the base station.
- Topology changes due to node failure even though most sensor nodes are usually stationary.

With these challenges protocols can no more develop in isolations and as such the invention of cross-layer approach. The idea of cross-layer design can exchange information between them in an intelligent way during communication to improve the performances of the system. Useful cross-layer information and differentiate the channel state as it relates to signal strength, interference level, and channel response estimate in time and frequency domain. The layering approach to network design does not fit in the wireless network as mentioned by [32], in which an in depth analysis of cross-layering approaches for wireless adhoc has been discussed.

Therefore the cross-layer interactions are a technique to boost the performance by effectively adapts to the dynamic environment and interactively communicate with each layer simultaneously to prevent the major challenges that the wireless systems faces. Cross layer design can be a major research area.

6.3.6 Upper Layers Multi-Channel Communication

Network settings is not possible to find a simple rate region, the rate region can reduces the set of feasible rates that congestion control can utilise. The rate region is studied in [33-35]. In WSNs, the local channel contention and interference on the shared communication medium causes network congestion [111]. In [112], the proposal of an interference-aware rate control for WSNs. If multi-channel communications are use to eliminate interference, the effects of congestion can be alleviated and fair rate control could be possible for the nodes that suffer from interference. A congestion control or rate control algorithm that utilises multi-channel communication in WSNs can be a research area.

6.3.7 Test-Bed

Test-beds replicate testing of theories, computational tools and innovations. When compared to WSN simulators, WSN test-bed enables more realistic and reliable experimentation in capturing the subtleties of the underlying hardware, software, and dynamics of the wireless sensor network. WSN test-bed deployment is further enhanced through an increasing collaboration between academia and industry.

WSN test-beds are the basis for experimentation with wireless sensor networks in real world settings; and they are also used by many researchers to evaluate specific applications pertaining to specific areas. A WSN test-bed typically consists of sensor nodes deployed in a controlled environment. WSN test-beds provide researchers with an efficient way to examine and evaluate their algorithms, protocols and applications. WSN test-bed can be designed to support different features depending on the objective of the test-bed. Among the important features of a WSN test-bed it can be designed to remotely configure, run and monitor experiments. Another interesting feature is that the WSN test-bed can be used for repeating experiments to produce similar results for analysis [113]. Selecting the appropriate level of abstraction in simulation model is a complex problem. Thus, it is obvious that the accuracy of a simulator will solely depend on its mathematical model. Accordingly, there is a trade-off between simulator’s accuracy and computational complexity. The more complex the simulation model is the more computational resources and time are required to execute it. This makes the designers of such simulation models tend to make them as simple as possible. It is impossible to take all the various aspects of the wireless channel into consideration when designing a simulation model [114]. Nonetheless, simulation tools are essential in providing affordable environment for the initial design and tuning of wireless sensor networks. Such inherent difficulty in faithful modelling motivates many researches to build their own WSN test-beds.

Among the advantages of a real WSN test-bed over a simulator is that it provides a realistic testing environment and allows users to get more precise testing results [113].

To further appreciate the important role of such WSN budget constraints and cost play one of the most important roles in setting-up the WSN test-bed. WSN test-bed monitoring is concerned with collecting information about a spectrum of parameters including: node states (battery level, communication power), network topology, wireless bandwidth, link state, coverage bounds, and exposure bounds. Based on the collected network states, a variety of management control tasks can be performed. Highlighting the usefulness of test bed and knowing that it is not easy to compare the results of the simulations performed on different simulators due to the different models (e.g., the physical layer, traffic or mobility models) assumed. As emphasised in [115], it would be helpful to have a repository of the standard models not only for simulation codes but also the implementation details on the test-beds. However, experimenting with real test-bed and workloads from a set of different applications is important in early stages of future work to continuously improve MC-DCF design through feedback arising from real running scenarios.

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