

Quality of Service for Wireless Sensor Networks in Smart Grid Applications

by

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Abstract

Monitoring and controlling smart grid assets in a timely and reliable manner is highly desired for emerging smart grid applications. Wireless Sensor Networks (WSNs) are anticipated to be widely utilized in a broad range of smart grid applications due to their numerous advantages along with their successful adoption in various critical areas including military and health care. Despite these advantages, the use of WSNs in such critical applications has brought forward a new challenge of fulfilling the Quality of Service (QoS) requirements of these applications. Providing QoS support is a challenging issue due to highly resource constrained nature of sensor nodes, unreliable wireless links and harsh operation environments. In this thesis we critically investigate the problem of QoS provisioning in WSNs. We identify challenges, limitations and requirements for applying QoS provisioning for WSNs in smart grid applications. We find that the topic of data prioritization techniques at the MAC layer to provide delay bounds in condition monitoring applications is not well developed. We develop six novel QoS schemes that provide data differentiation and reduce the latency of high priority traffic in a smart grid context. These schemes are namely; Delay-Responsive Cross layer (DRX), Fair and Delay-aware Cross layer (FDRX), Delay-Responsive Cross layer with Linear back-off (LDRX), Adaptive Realistic and Stable Model (ARSM), Adaptive Inter-cluster head Delay Control (AIDC) and QoS-aware GTS Allocation (QGA). Furthermore, we propose a new Markov-based model for IEEE 802.15.4 MAC namely, Realistic and Stable Markov-based (RSM). RSM considers actual network conditions and enhances the stability of the WSNs. We show through analytical and simulation results that all of the presented schemes reduce the end-to-end delay while maintaining good energy consumption and data delivery values.

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List of Acronyms

ACK	Acknowledgement
ADC	Analogue to Digital Converter
BE	BackOff Exponent
BEB	Binary Exponential Backoff
BeO	Beacon Order
BI	Beacon Interval
BO	BackOff
CAP	Contention Access Period
CBR	Constant Bit Rate
CCA	Clear Channel Assessment
CFP	Contention Free Period
CH	Cluster Head
CI	Confidence Interval
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	Contention Window Size
DCF	Distributed Coordination Function
EPON	Ethernet Passive Optical Network
FFD	Full Function Device

FIFO	First In First Out
GTS	Guaranteed Time Slot
IFS	Inter-Frame Spacing
ITU	International Telecommunication Union
LQI	Link Quality Indicator
MAC	Medium Access Control
MBOT	Modified Back-off Time
MDP	Markov Decision Process
PAN	Personal Area Network
PD	Partial Discharge
PDF	Probability Distribution Function
QoS	Quality of Service
RF	Radio Frequency
RFD	Reduced Function Device
RSSI	Received Signal Strength Indicator
RT	Retransmission Times
RTS	Request to Send
SF	Super Frame
SNR	Signal to Noise Ratio
SO	Super Frame Order
SPAN	Sub-Personal Area Network
TDMA	Time Division Multiple Access
WMA	Weighted Moving Average
WMSN	Wireless Multimedia Sensor Network
WPAN	Wireless PAN

WSAN	Wireless Sensor and Actor Network
WSN	Wireless Sensor Network

List of Symbols

α	Probability of finding the first CCA busy
α_y	Yielding intensity
β	Probability of finding the second CCA busy
D_0	Size of the MAC buffer
D_i	One hop inter-CH delay
D_{sf}	SF duration
γ	The bit rate in bits per second (<i>bps</i>)
η_i	Number of packets received from end devices during CAP
δ	Number of SF a packet waits in the CH before transmission
θ	Tuning factor
m	Maximum number of BO
μ	The number of packets transmitted from CH during a single D_{SF}
N	Number of nodes in the PAN
n	Maximum frame retries
P_c	Probability of collision
P_{cf}	Probability of channel access failure
P_{cr}	Probability exceeding transmission retry limits
l	Packet length in <i>bits</i>
L	Packet duration

L_{ack}	Duration of ACK packet transmission
L_C	Duration of packet collision
L_S	Duration of successful packet transmission
λ	Packet arrival rate
ρ	Number of packets served in the same SF as the tagged packet
σ	Probability of packet arrival at the MAC layer
t_{ack}	The ACK waiting time
t_{ack-O}	The ACK time out
τ	The stationary probability that a nodes start the first CCA
τ_{TH}	Delay threshold
ϵ	Forwarded packets from lower CHs during the CFP
W_i	BO window at the i^{th} state
W_0	Smallest BO window
φ_i	The occupancy of a buffer B_i in a CH at the i^{th} level
Φ_M	The value of measured data
ψ	Total number of packets received at the CH during a single D_{SF}

Chapter 1

Introduction

1.1 An Overview of the Smart Grid

A Smart Grid is a modern electric power grid infrastructure for enhanced reliability, efficiency, controllability and safety with integration of renewable and alternative energy sources through monitoring, control and modern communication technologies [1].

A smart grid is the use of communications, sensors, computational ability and control to improve the overall functionality, performance and cost of the electric power system. A non smart system becomes smart by communicating, sensing, and exercising control. For a power system, this allows several functions which permit optimization in generation and storage, transmission, distribution, distributed resources and consumer utilization which ensure reliability and optimize or minimize the use of energy, mitigate environmental impact, manage assets, and contain cost [1]. In the smart grid Reliable online information becomes the key factor for reliable delivery of power from the generation unit to the end users. The impact of equipment failure, capacity limitations, natural accidents and catastrophes which generally leads to power failure can be largely avoided by; online power monitoring, control, diagnostics and protection.

The environments of the electrical power system are constantly changing over time as a function of different parameters, e.g. supply demand, energy consumption and environmental conditions. Some of the changes are difficult to predict for example environmental effects and sudden systems malfunctions, other changes are predictable and frequent like the continuous variation of power demand from the customers during season changes. These changes force the generation and distribution grid to behave as a highly dynamic system. Currently, most of the electrical systems available are operated as static systems, because in most cases there is no real-time information about the changing situations of the power grid. The utilities may avoid interruptions by keeping good safety margins in generation, transmission and distribution capacity. In this situation, the technical aspects of the electrical power system remained the same. However, the business environment concerning generation and transmission has changed according to adapt to the new margins. With a rising demand of renewable and green energy sources, the power grid must be able to adapt to small scale and local generation, e.g. solar cells. Furthermore, customers are also getting more discriminatory in terms of their demands; this requires electrical systems to be reliable and flexible, hence, the power grid has to evolve to a smart entity.

In a smart grid, utilities and customers are considered as intelligent nodes in a communication network. These intelligent nodes will be able to distribute real-time information about the current power consumption to both customers and utilities. This information can be useful in many different ways. The customers can get a good view over their energy consumption presented in an appropriate way, e.g. as a function of the time of the day. If this scenario is combined with real-time information of electricity prices, the customer will be able to interpret the energy consumption to an actual cost. Furthermore the customers would have a chance to adapt their energy behaviour e.g., by running

appliances with high power consumption when the electricity prices are low or when the availability of local, renewable electricity is high [2]. In addition to that, in a smart grid, the utilities will be able to get a good balance between demand and supply, this certainly has several advantages. A good balanced system will relieve the tension on the power grid, which leads to a delay of grid additional supply. Off-course without having the knowledge of the circumstances that lead to energy demand peaks, the utilities uses back-up plants when the demand is high. These backup plants are called peak power generators, and in most cases they use fossil fuels to produce energy. Hence, the smart grid will mitigate the need for additional power generation [2].

Based on the above information the existence of an efficient communication system becomes the main factor to the success of the smart grid. Recent developments in wireless communication technologies made them the most successful candidates for the communication between the utilities and control centres and the the utilities and customers and vice versa. Without a doubt ZigBee-based Wireless Sensor Networks (WSNs) are the prime competitors in the area of wireless communications due to their size, cost, low power consumption and etc.. Hence, whenever the term smart grid appears, the concept of WSNs is playing a major role in it. Although WSNs bring forward many advantages to the smart grid automation and control, their utilization in such applications has introduced a new challenge of satisfying the Quality of Service (QoS) requirements of these applications. Consequently, providing QoS support is a challenging issue due to highly resource constrained nature of sensor nodes, variable wireless links and severe operation environments. [3]

Delay aware or delay sensitive operation framework of a WSN is one of the most important aspects in the reliable operation of WSNs, especially in the area of power grid condition monitoring. Some monitoring applications require that the data be transmitted

in near real-time fashion or the entire operation fails.

1.2 An Overview of QoS in WSNs

The meaning of QoS can slightly vary depending on the application area. For example, QoS can indicate the capability to provide assurance that the service requirements of a specific application can be met. QoS can also be defined as the ability of the network to adapt to specific classes of data. The International Telecommunication Union (ITU) Recommendation E.800 (09/08) has defined QoS as: “Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service” [4].

QoS provisions can be classified into hard QoS and soft QoS. Users or applications requiring hard QoS must be provided with strict QoS guarantees. On the other hand, soft QoS approach, the application also has tight QoS requirements but the requirements are flexible to some extent. Hard and soft QoS guarantees can widely be provided through the use of service differentiation. In general service differentiation models can be classified into integrated services and differentiated services. Both models can provide prioritization of data packets, quantify the priority levels and provide required service quality.

Integrated service models typically maintain service on a per-flow basis (i.e. reservation-based approaches); where a flow can either be considered as data-centric or host-centric, data-centric flow could be the data packets generated by triggering sensors in the monitored environment, host-centric flows could be the data packets transmitted between source and destination. As such, integrated services models normally have a several disadvantages which make them inefficient for some WSNs applications. Overall, in wireless mediums it is difficult to provide guaranteed service quality because the channel capacity

is usually varying with time. Another important factor which makes integrated services inefficient in WSNs is that keeping the per-flow states in a network where there are hundreds or even thousands of sensors is really difficult. Finally, integrated service models typically require reliable QoS signalling within the WSN for resource reservation which is very hard to provide in WSNs.

In differentiated service models a per-packet service is maintained, these models can be considered as a reservation-less techniques. The main disadvantage of differentiated service models is that it requires high memory capacity since every node behaves as a source and an intermediate node. Nevertheless, lightweight differentiated service models can be implemented in WSNs. Generally, nodes in a WSN transmit data packets; each data packet can have certain importance. As such, each protocol stack layer can treat the packet according to its priority.

1.3 Motivation

WSNs are likely to become a prevailing technology in the near future due to the special characteristics of these devices and to the great number of applications where they can be implemented. One of the most important applications is their use in condition monitoring and control processes. In fact, WSNs have actually been identified as having the potential to become an integral part of the condition monitoring process. However, in order to achieve that goal, WSNs need to provide a set of features which include a robust QoS support. Unfortunately, based on the available literature, QoS support mechanisms in WSNs are still underdeveloped.

In a complex and demanding application such as smart grid monitoring and control, the demands expected from a sensor node platform supporting such applications also increase. If the platform itself does not directly meet the requirements of the application,

protocols and tools need to be used in order to manage the hardware with the aim of providing the required functionality. Intense research has been carried out in areas such as architecture, protocol design, energy conservation and localization, but QoS in WSNs is not a fully exploited field of research. In critical applications such as patients monitoring, smart grid control and etc., it is essential to guarantee certain levels of QoS.

As the demands from monitoring systems increase, WSN for condition monitoring applications have become more and more bandwidth-hungry and delay sensitive. In order to meet these requirements, WSNs need a well-designed QoS support in each layer of the communication protocol stack, because condition monitoring applications are unlike the traditional end-to-end applications. The variety of applications of WSNs and their different requirements make implementation of a “one-size-for-all” QoS-support mechanism an impossible task. However, well-defined requirements and QoS parameters can be a guide to develop QoS-support for effective and efficient delivery of sensor data.

From the available literature, it is seen that the work on QoS-aware Medium Access Control (MAC) protocols still needs to be improved compared to the work presented on QoS-aware routing protocols in WSNs which seems to be reaching a maturing stage. This necessity becomes obvious in applications where vital infrastructure needs to be monitored in a timely manner and with high reliability.

Most available sensor nodes use the IEEE 802.15.4 MAC protocol to manage their access to the wireless medium. Medium access is done by utilizing scheduling or by using slotted and unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) techniques. When WSNs utilize scheduling to gain access to the medium, it is not that difficult to enforce QoS or provide priority to some nodes on the expense of others. However, there are situations where the use of scheduling techniques may not work efficiently, such as a network with very high number of nodes or a situations where

an overlap in time allocations may exist. On the other hand, in the slotted CSMA/CA mechanism, sensor nodes have equal probability of access the medium [5]. However, the CSMA/CA mechanism is not designed to provide priority to delay critical packets for which they may be delivered to the sink before other non delay critical packets. Therefore, the issue of providing QoS to sensor nodes utilizing the IEEE 802.15.4 mechanism without impacting other performance metrics in the network such as the power consumption and the reliability becomes a real challenge.

Based on the above, some new protocols and algorithms are needed to enhance the performance of the IEEE 802.15.4 MAC protocol to make it more adaptable to QoS requirements of delay critical applications.

1.4 Objectives

The objectives of this thesis are to carry on a critical investigation and review of QoS schemes and mechanisms used in IEEE 802.15.4-based WSNs, to propose and develop adaptive and cross-layer QoS provisioning protocols and algorithms that can provide minimum latency, maximum data delivery ratio and maintain a low energy consumption level to sensor nodes with delay critical data in smart grid condition monitoring systems. To achieve optimum protocol efficiency, cross-layer interaction is considered to exploit the collaboration between the layers of the protocol stack. This is expected to be very challenging because delay, reliability, and energy contradict each other; furthermore, sensor nodes are known to support only simple algorithms. Hence the proposed schemes and algorithms should ensure a desired delay probabilities and packet delivery ratio while minimizing the energy consumption of the entire WSN. In addition to the cross layer design aspect, the protocol is to adapt to traffic variations and varying channel conditions especially in environments like the smart grid environment which is considered

as a harsh environment for wireless communication.

1.5 Contributions

The main research contributions of this thesis are as follows:

1. Present three QoS schemes that aim to address data-prioritization and delay-sensitive data transmission for WSNs in the smart grid. The first scheme; Delay-Responsive Cross layer (DRX). The second scheme, Fair and Delay-aware Cross layer (FDRX). The third scheme is a Delay-Responsive, Cross layer scheme with Linear back-off (LDRX).
2. Propose a Realistic and Stable Markov-based (RSM) analytical model for the IEEE 802.15.4 MAC protocol. The Markov-based model shows that the delay distribution of IEEE 802.15.4 depends primarily on MAC parameters and collision probability in saturated and unsaturated traffic conditions. The model follows the MAC procedure defined by the IEEE 802.15.4 standard in the context of the condition monitoring application scenarios. The proposed model is designed to work with WSNs with star and cluster-tree topologies.
3. Propose an Adaptive RSM (ARSM) QoS scheme which is suitable for WSNs for high and low data rate condition monitoring applications. ARSM builds on the mathematical model of RSM, but it solves the issue of excessive latency by adaptively providing QoS guarantees to delay critical condition monitoring and control applications. ARSM is designed to work best with WSNs with cluster-tree topologies.
4. Propose two QoS schemes for WSNs based on distributed optimization model im-

plemented in the Cluster Heads (CHs) of a cluster-tree or relaying nodes in a mesh topology. The presented QoS schemes can find an optimum delay for specific reliability values. In addition to that, the presented Adaptive Inter-CH Delay Control (AIDC) scheme for cluster-tree topology and QoS-aware GTS Allocation (QGA) scheme in mesh-based WSNs can reduce the end-to-end delay of delay of critical data in smart grid monitoring and control scenarios.

1.6 Thesis Outline

The rest of the thesis is organized as follows:

In Chapter 2, a review of the state of the art is presented. In this chapter the review is classified into four major parts depending on the area where the QoS is considered. In Chapter 3, three different priority and delay aware medium access schemes in WSNs are presented. In Chapter 4, a reliable IEEE 802.15.4 model for smart grid monitoring systems presented. In Chapter 5, an adaptive QoS scheme for WSNs with star and cluster-tree topologies is proposed. In Chapter 6, QoS-aware inter-cluster head scheduling in WSNs with cluster-tree and mesh topologies is presented. Finally, in Chapter 7, the conclusions and future research directions are addressed.

1.7 List of Publications

1.7.1 Journal Papers

1. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “A Survey on Cross-layer Quality of Service Approaches in WSNs for Delay and Reliability Aware Applications”, (manuscript under preparation).

2. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “QoS Provisioning in WSNs for Delay Critical Monitoring Applications”, Submitted to the IEEE/ACM Transactions on Networking.
3. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “A Traffic Adaptive Inter-Cluster Head Delay Control Scheme in WSNs”, Submitted to the IEEE Transactions on Instrumentation and Measurement.
4. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “A Reliable IEEE 802.15.4 Model for Cyber Physical Power Grid Monitoring Systems”, IEEE Transactions on Emerging Topics in Computing, vol. PP, no. 99, pp. 1-1, 2013, DOI. 10.1109/TETC.2013.2281192.
5. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “Priority and Delay Aware Medium Access for Wireless Sensor Networks in the Smart Grid”, IEEE Systems Journal, in press 2013.

1.7.2 Conference Papers

1. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “QoS-aware Inter-Cluster Head Scheduling in WSNs for High Data Rate Smart Grid Applications”, in the IEEE Global Communication Conference, (GLOBECOM 2013), Atlanta, GA, Dec. 2013, (accepted).
2. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “Time Slot Allocation for Differentiated Smart Grid Traffic, in the IEEE Electrical Power and Energy Conference, (EPEC 2013), pp.20-26, Halifax, Canada, Aug. 2013.
3. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “A Traffic Adaptive Inter-cluster Head Delay Control Scheme in WSNs,” in the Proc. of the 18th

- IEEE Symposium on Computers and Communications, (ISCC 2013), pp.29.4.1-29.4.6, Split, Croatia, July 2013.
4. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “ An Adaptive QoS Scheme for WSN-based Smart Grid Monitoring” in the Proc. of the 3rd IEEE International workshop on smart communication protocols and algorithms (SCPA’13), IEEE International Conference on Communications, (ICC 2013) Workshops, pp.3.2.1-3.2.6, Budapest, Hungary, June 2013.
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4. Irfan Al-Anbagi, Melike Erol-Kantarci and Hussein T. Mouftah, “Delay-Aware Cross Layer Data Transmission Schemes for Wireless Sensor and Actor Networks, Research Report TR-2012-03, School of Electrical Engineering and Computer Science, University of Ottawa, January 2012.

Chapter 2

State of the Art

2.1 Introduction

In this chapter, an analysis of the state of the art on QoS in WSNs and existing techniques to achieve delay, reliability and energy bounds in WSNs is presented. To have a wider perspective of the surveyed topic, the survey is divided into four different areas. Each different area tackles QoS provisioning in WSNs from a different perspective. These areas are; WSN applications requiring delay and reliability bounds including smart grid applications, cross layer design considerations, MAC sub-layer design considerations, analytical and optimization models for WSN are discussed and finally a brief overview of the work on routing protocols for QoS in WSNs is presented. The related work presented in this chapter presents a general overview of the work done in this area. The following chapters present related work more relevant to the contents of the chapters themselves.

2.2 Delay and Reliability Sensitive Applications

In this section, the related work that describes providing delay and reliability bounds for WSN data in monitoring applications in general is presented. Even though there are many publications that discuss using WSNs in the smart grid, there are only a few papers that discuss providing a delay sensitive and a reliable framework for WSNs in the smart grid. Furthermore, there are even less papers that particularly discuss QoS provisioning techniques in delay critical smart grid monitoring applications.

Ceken et al. [6], have implemented an energy-aware Time Division Multiple Access (TDMA) based MAC protocol for WSNs. The author have proposed to achieve a relatively better end-to-end message delay results for time critical applications and achieve the lower energy consumption requirement. They have proposed to assign an extra slot to the relevant sensor node to reduce latency of any delay sensitive application. Sensor nodes request extra slot when their queue size exceeds the upper threshold value. They have proposed to make the non-time critical sensor nodes to sleep periodically to reduce the duration of idle listening. They have compared their results with WSN the classical MAC protocol. The authors have proposed their MAC protocol to solve the delay problem in IEEE 802.11 based WSN that use Distributed Coordination Function (DCF), the use of this protocol can achieve the required delay reduction; however, in WSNs the use of DCF only is not efficient, since the number of nodes in a sensor network can be in the order of hundreds of nodes. The authors have not considered using Point Coordination Function (PCF) as an option in their protocol or the combination of PCF and DCF to make use of the scheduling mechanism.

Koubaa et al. [7], have proposed a solution to overcome the limitations of the explicit Guaranteed Time Slot (GTS) allocation in the IEEE 802.15.4 protocol. They have assumed to share the same GTS between multiple nodes, instead of being dedicated to

one node, if that schedule satisfying the requirements of all requesting nodes exists. The time slots of this GTS are dynamically allocated to different nodes in each Super Frame (SF), according to a given schedule. The explicit allocation statically allocates a GTS to only one node in all subsequent SF. Their proposed mechanism have been based on the traffic specification of the requesting nodes, their delay requirements, and the available GTS resources. In the fixed time slots, a node will have a guaranteed service to send its traffic to the Personal Area Network (PAN) coordinator. The runs an admission control algorithm based on this information and the amount of available GTS resources, new allocation request will be accepted if there is a schedule that satisfies its requirements and those of all other previously accepted allocation requests; otherwise, the new allocation request is rejected. The authors have referred to this as the implicit GTS allocation mechanism (i-GAME). They have shown that i-GAME has the advantage to accept multiple flows sharing the same GTS while still meeting their delay requirements. They have also shown that it reduces the utilization of the Contention Free Period (CFP) by reducing the amount of wasted bandwidth of GTSS and maximizing the duration of the Contention Access Period (CAP), since the CFP length is reduced to a minimum. The proposed solution to reduce the delay in IEEE 802.15.4-based WSNs has not considered the impact of the network size on the delay performance. It is known that the use of GTS is limited very much by the number of nodes utilizing these slots and as the number of nodes increase there will be nodes left without GTS and hence they have to wait for the next SF duration and that will impact the performance.

Phan et al. [8], have proposed an opportunistic transmission strategy for WSNs that operates in a strict energy-constrained environment. Their strategy is to allow the node to attempts transmission at good channel conditions whereas meeting the delay constraint for delay-sensitive applications and the buffer size constraint for non-delay-

sensitive applications, under time varying wireless channel. They have used the Markov decision process to find an optimum threshold for transmission decision. Their scheme initiates transmission only when the channel quality exceeds the optimum threshold, so that unsuccessful transmissions causing a waste of energy are avoided whenever possible. The authors have not taken into consideration the actual buffer size when the nodes consider differing transmission for no delay critical data especially when the packet arrival rate becomes high which requires

Shanti et al. [9], have proposed a TDMA-based energy efficient integrated MAC and routing protocol, called Delay Guaranteed Routing and MAC (DGRAM) protocol, which provides deterministic delay guarantee. Their protocol requires a short beacon exchange phase to gather node location information. Then it uses slot reuse technique to reduce latency between two successive medium accesses by a sensor node, with a slot allocation strategy that does not require exchange of control messages, which makes the deployment self-configuring, then each node runs a short beacon exchange phase to learn about the topology of the network. Data packets are then transmitted or received following a logical topology. Their protocol has the routing mechanism built into the MAC, utilizing the coordinated sleep and wake-up cycles. It also allows sensors to go to sleep when they are not communicating to save energy. The authors have presented the method to assign time slots to sensor nodes and show how the slots are reused by nodes that are non-interfering. They have presented delay analysis of DGRAM to prove its delay bound. Their simulation results have shown that their analytical delay bound is always guaranteed by the protocol and that there is no packet loss as long as the event rate is below the designed event rate. The main issue with DGRAM protocol is that the protocol requires each node to know its position relative to the sink. There are several methods that are used for localization in WSNs. However, the authors have not

identified which technique is to be used, and since different techniques may affect the used routing protocol. An other issue is related to the time slot allocation used in the TDMA scheme, the authors have not investigated the effect of the number of nodes on the performance of their protocol. Since the scalability of the network may affect the time slot allocation.

Cheng et al. [10], have proposed a delay-aware network structure for WSNs with in-network data fusion. Their proposed structure organizes sensor nodes into clusters of different sizes so that each cluster can communicate with the fusion center in an interleaved manner. They have also proposed an optimization process to optimize intra-cluster communication distance. The authors have used a time-slot based data aggregation model where a data packet will take 1 time-slot to transmit from one node to another. When the size of the fused data packet increases by a certain factor, it takes more timeslots to transmit equivalent to the increase of the packet size. They have used TDMA at the MAC layer where nodes are assumed to be synchronized at time-slot and time cycle levels. Each parent node will assign dedicated time-slot to its child nodes. To avoid interference, different parent nodes will use different spreading sequences to communicate with their child nodes. The authors have shown through simulations that their proposed network structure can reduce delays in data aggregation processes and keep the total energy consumption at low levels provided that data are only partially fusible. The authors have not considered the effect of packet arrival rate into the aggregation model and on the overall performance of the network. Since packet arrival rate may affect the slot allocation since it is one of the key factors that affect the data fusion in cluster based WSNs.

Ding et al. [11], have proposed a traffic scheduling algorithm focusing on the industrial applications of the WSN and based on the window scheduling algorithm (WSA) of [12].

They have assumed that their algorithm runs during the configuration stage of network system before the system starts to work. The algorithm is based on considering the real-time requirement and data length of time-critical periodic messages to determine proper network and node parameter values and to allocate GTSs to each end node such that the time-critical node releases some GTSs that are not used. The length of the CFP and the D_{sf} can both be reduced, which leads to improved bandwidth utilization and energy efficiency. Since they have used traffic scheduling, the requirement of real-time service is guaranteed. They have run simulations to evaluate the characteristics of the algorithm. One of the major issues in WSNs that use scheduling is that the network should be scalable (i.e. should perform the same when its size increases). The authors have not considered the effect of the network size on the performance of the scheduling algorithm. The number of nodes in each cluster and the number of clusters in the entire network may affect very much the actual number of slots that can be allocated in the CFP.

Ruiyi et al. [13], have proposed an Adaptive Wireless Resource Allocation (AWRA) algorithm with QoS guarantee in communication network of smart grid. The authors have addressed adaptive wireless resource allocation, where they have assumed that if the delay of the packets is greater than the delay threshold, then the packet is discarded, while for non-real-time services, as long as the queue does not overflow, the packet will not be discarded. They have assumed that the queue is infinite and do not consider the discarded packet caused by queue overflow and the problem of retransmission and that the total transmission power of the base station in the sub-channels is average distribution. The authors have proposed that the system of the smart grid contains 19 plots, each plot has 3 sectors and that each sector has N sub-channels and K packets. They have defined an optimization problems based on different stages of base station

tasks. The first stage is detect stage where the base station measures the user's Signal to Noise Ratio (SNR); the second stage is the feedback stage where the user feedbacks the channel state information and the final stage is when the base station collects the feedback information and allocate space, time, frequency resource for the user to transmit data based on certain scheduling criteria.

Kim et al. [14], have developed a delay-optimal anycasting scheme under periodic sleepwake patterns. They have shown that periodic sleepwake patterns result in the smallest delay among all wake-up patterns under given energy constraints. The authors have obtained the anycast forwarding policy and the wake-up pattern for given wake-up rates of nodes which can minimize the expected end-to-end delays from all nodes to the sink. The authors have presented a delay minimization problem where the objective of this problem is to find the optimal joint policy that solves delay-minimization problem for given wake-up rate. Where the global wake-up rate controls the duty cycle of the sensor network, which controls the energy expenditure. They have viewed the problem as minimizing the delays for a given energy budget. The authors have presented that using asynchronous periodic wake-up patterns along with an optimal forwarding policy can minimize the expected end-to-end delay over all asynchronous wake-up patterns. The authors have considered asynchronous sleepwake scheduling where nodes do not synchronize their clocks with their neighbouring nodes. After an event occurs, a sending node needs to predict when a neighbouring node will wake up. They have assumed a random time-offset in the wake-up process of the node due to clock-drift, and that due to this random time-offset, the wake-up process of a node is of stationary increments, as observed by other nodes, and the wake-up processes of different nodes are mutually independent. The authors have shown the relation between the delay and the average wakeup interval; however the behaviour of the energy expenditure as a function of the

wake-up pattern has not been shown to illustrate the trade-off in the delay minimization problem.

Kumar et al. [15], have proposed a solution to overcome the limitations the IEEE 802.15.4 protocol the for low-latency, bandwidth, and energy critical scenarios. They have driven optimal parameters setting to enhance the performance of an IEEE 802.15.4-based WSN. The authors have changed the bit structure of the 8-bit GTS characteristic field, where the device, instead of sending fixed slot length, sends its data and delay specification to the coordinator. The authors have dealt IEEE 802.15.4 CFP GTS allocation limitations by changing the bit structure of 8-bit GTS characteristic field, where the device sends its data and delay specification to the coordinator instead of sending fixed slot length. The coordinator, decides the slot length for the device upon the reception of the reception of the request from the end device. Their solution works on the basis of total cluster load, remaining CAP size, device's data and delay specifications, and device's recent CFP usage. They have made these assumptions to prevent bandwidth under-utilization and the restriction of entertaining at most seven GTS requests. To cancel the constant GTS expiration, they have assumed that the coordinator uses the period bits of the GTS characteristics field and performs GTS expiration dynamically. The authors have used one available reserve bit in the SF indicate the presence of the CFP part instead of using the entire byte in the SF. The coordinator could allocate GTS slots on round-robin to the device, who once declares to have periodic applications. The authors have shown the effect of various MAC parameters on the CFP time allocation. However, they have not tested the actual delay reduction achieved and the power consumption factor when a network implements their solution, nor they have shown the scalability of their solution since they have mentioned that the coordinator considers these factors in to account it does the GTS allocation.

Huang et al. [16], have generalized the multi-parent method to support a multi-cluster model for the network in a network that has multiple Cluster Head (CH) that control scheduling in the network. They have introduced the multi-parent ladder wake-up pattern, and have shown that compared to the single-parent ladder wakeup pattern, the former improves the performance significantly. They have assumed that they can divide the nodes in the network into multiple disjoint groups such that at least one parent from each group can be assigned to any node in the network. Each node in the network has one mother and one father. The CHs are special nodes which belong to both groups and can act as both parents. The authors have formulated this step as a graph coloring problem which is shown to be NP-complete. They have proposed an algorithm where all the CHs cooperate to find a heuristic solution for the graph coloring optimization problem in a distributed manner. They have shown that each CH requires less memory and computational power compared to the case where one CH finds the global solution and that the multi-parent method can improve the performance of various wake-up patterns. Finally they have shown that the running time can be reduced when more CHs are used because the computation load is shared by all the CHs.

Zeng et al. [17], have proposed a measurement architecture using distributed air sniffers, which provides delay measurement, and requires no synchronization or instrumentation. They have considered the placement of the sniffers for efficient delay measurement. The authors have proved the sniffer placement problem is NP-hard and developed two algorithms to solve it. They have demonstrated through testbeds experiments and simulations that their architecture leads to accurate delay monitoring and is effective in detecting abnormal delays.

Karmokar et al. [18], have considered the delay in the finite size buffer and use a technique to estimate the channel conditions. They have used the transmission power

and Acknowledge/Negative Acknowledge (ACK/NAK) feedback of several previous time slots as a history records to estimate the probability of ACK/NAK for the present time slot. They have formed cross-layer optimization problems that merge physical layer and data link layer. They finally have solved using the tools provided by the theory of Markov decision processes (MDP).

From the above reviewed references [6], [7], [8], [9], [10], [11], [13], [14], [15], [17] and [18], it can be seen that these reference discuss achieving delay reduction without impacting other network parameters. It is sometimes desirable to achieve optimization of two or more network parameters using the same protocol as will be seen next. These protocols require careful optimization of the network parameters to achieve the intended goal.

Ngai et al. [19], have considered the design of a generic framework for reliable event reporting in Wireless Sensor and Actor Networks (WSANs). They have assumed that the reliability is related to the delay reporting events, and they should be jointly optimized. The authors have suggested that the non-uniform importance of the events can be explored in the optimization. They have presented delay and importance-aware reliability index for the WSANs where they have integrated three modules to maximize the reliability index; the first is a multi-level data aggregation scheme, which is fault-tolerant with error prone sensors; the second is a priority-based transmission protocol, which accounts for both the importance and delay requirements of the events; and the third is an actuator allocation algorithm, which smartly distributes the actuators to match the demands from the sensors.

Di Marco et al. [20], have presented a cross-layer protocol that combines a semi-random routing, MAC, data aggregation, and radio power control for clustered WSNs. Their protocol controls the combination of a randomized and a deterministic approach

to ensure robustness over unreliable channels and packet losses. They have modelled and solved an optimization problem, whose objective function is the network energy consumption, and the constraints are reliability and latency to adaptively select the protocol parameters by a simple algorithm. The authors have implemented their proposed protocol on a test-bed, and it is compared to existing protocols. Their experimental results have been validated the analysis and shown good performance in terms of reliability, latency, low node duty cycle, load balancing and dynamic adaptation to the application requirements. The authors have not investigated the effect of running the optimization model to minimize either the delay or maximize the reliability with power consumption as the constraint, since these three parameters are more or less interrelated and a decrease in one of them can cause a drastic affects on the others. Another aspect which was not investigated in this paper is the affect of the number of nodes on the performance of the optimization model. This is a pivotal factor to be considered in every TDMA based network.

Di Marco et al. [21], have introduced the TREN protocol by extending the scheme presented in [20] for control applications over WSNs in industrial environments. Their protocol is a cross-layer protocol that embraces routing algorithm, MAC, data aggregation, duty cycling, and radio power control. Their protocol parameters are adapted by an optimization problem, whose objective function is the network energy consumption, and the constraints are the reliability and latency of the packets. TREN uses a simple algorithm that allows the network to meet the reliability and latency required by the control application while minimizing for energy consumption. They have implemented TREN on a test-bed and compared to some existing protocols. The authors have not shown the scalability of their protocol in multilevel network where the number of nodes increases or decreases according to the application especially when their proposed

protocol is based on TDMA technique.

Park et al. [22], have present Breath, an adaptive protocol for WSNs for reliable and timely data gathering. The authors have considered networks where nodes send packets to the sink using multihop routing under certain reliability and delay requirements. Their protocol is based on randomized routing, CSMA/CA MAC and randomized sleep discipline that are jointly optimized for energy consumption minimization in the entire network. The authors have also provided analytical relations of the reliability, delay, and total energy consumption as a function of MAC, routing, physical layer, duty cycle, and radio power. They have used and verified approximations in their model which makes it suitable for WSNs. In their protocol, the authors have solved a mixed integer-real optimization problem where the energy minimization is achieved under the reliability and delay constraints. They have developed a novel algorithm based on the optimization optimization algorithm that allows for rapid deployment and self adaptation of the network to traffic variations and channel conditions, and guarantees the application requirements without heavy computation or communication overhead. The authors have implemented the protocol on a testbed and have shown by analysis and experimental evaluation the benefits of their solution. The authors have described the analytical model that is based on Markov chains for a single hop network; however, they have utilized their model for multihop network. Furthermore, the evaluation of the energy consumption, reliability and the delay for multihop network has not been shown in their paper.

Suh et al. [23], have proposed a MAC protocol for WSNs, Latency and Energy aware MAC (LE-MAC) that minimizes the delay as well as power consumption. They have used a physical carrier sensing feature in CSMA/CA and combined it with a cross-layer technique. They have proposed that when nodes located in routing path between source and sink become aware of the traffic based on the carrier signal and wakeup additional

time during the sleep period for transmitting data over multiple hops. The authors have assumed that nodes located in-route towards the sink and within the carrier sensing range of the sender and receiver prepare to wake up in the sleep period and transmit data. They have also assumed that their scheme can transmit data across K -hops in a single listen/sleep period depending on the extent of the carrier sensing range. In their proposed scheme, they have shown that routing information is important in deciding whether to perform traffic aware wakeup. Therefore, they have assumed that the MAC layer acquires information from the routing agent to know if it is in the routing path towards the sink. If the node is included in the path, it performs the traffic aware wake while other nodes continuously sleep until the next scheduled listen/sleep period. They have compared their protocol with S-MAC on the through simulations and conducted experiment on basic S-MAC with 5 Mica Motes sensor devices arranged in the linear topology and found out that when the data traffic load is low, a sink node waits for 4 seconds in average for receiving the data from the source.

References [19], [20], [21] and [22] discuss achieving delay minimization and the maximization of the reliability at the same time, they also consider energy consumption through carefully utilizing and deriving optimization algorithm. However the above mentioned protocols do not consider reducing the energy consumption along with other network parameters. On the other hand, [23] considered reducing the end-to-end delay and minimizing the energy consumption at the same time.

Kim et al. [24], have proposed two mechanisms for modified IEEE 802.15.4 based WSNs that can provide multilevel differentiated services for each and every device. Their mechanisms can provide the service priority to device which requests the QoS prior to other devices. The authors have presented the mathematical model based on previous works of analysing IEEE 802.11. They have considered the beacon-enabled mode with

slotted CSMA/CA algorithm and assumed the saturation conditions. The mathematical model is based on the discrete-time Markov chain in which each component of an element in state space is representing the situation of the head packet in the queue of a device. Their mechanisms used access probability for the device and the probability that the medium is idle. The authors have obtained the saturation throughput, the saturation delay, and the drop probability. Their first differentiation is by Contention Window (CW), where CW value is set to different CW size according to its priority of the device. They have assigned CW during the network forming phase where every sensor device is assigned with the different priority according to the importance of the function by differentiating CW value. The second method of differentiation is by Backoff Exponent (BE) where they have processed similarly as the differentiation by CW. In network forming phase, every sensor device is assigned with the different priority according to the functional importance by differentiating BE. They have considered a saturated traffic condition which is considered as an realistic traffic condition for WSNs. The second issue which is the assumption of fixed QoS differentiation allocation that is done during the network set-up phase. The authors have not considered the allocation of different CW or BE to every node in the network adaptively which is a more practical situation for WSN monitoring scenarios.

Sthapit et al. [25], have presented a MAC protocol, called medium reservation preamble based MAC (MRPM). Their proposed protocol does not have separate time frames for Sync and data traffics where both the traffics are integrated in a short listen period. An other feature of their proposed protocol is that the reservation of medium in advance by a transmitter through contention before the listen period. Their protocol generates a new period, called contention period, which precedes the listen period to make the reservation of the medium. In contention period, only transmitters wake up and contend

for the medium using CSMA/CA protocol. They have used a short medium reservation preamble (MRP) which is transmitted by winner to acknowledge other contending nodes about the channel access. MRPM have introduced adaptive listening which exploits the physical carrier sensing ability of nodes and dynamically adjust their duty-cycle. Through the use of their proposed carrier sensing capability, sensor nodes that can not interpret transmission but can detect wake up at the appropriate time in the sleep period reduce their multihop delay. The authors have considered the use of Request to Send - Clear to Send (RTS-CTS) handshake as part of their proposed protocol. However, the default IEEE 802.15.4 MAC does not utilize this three way handshake. Therefore, their MRPM could not be used in ZigBee based WSNs without further modifications.

Sun et al. [26], have proposed to use a private wireless network dedicated for power distribution system monitoring. The authors have introduced a QoS support for IEEE 802.15.4 by the differentiated service for data traffic with different priority. They have used additional queues in the MAC to store different priority traffic. Therefore, high priority data will have higher probability of channel access, and can interrupt the service to the low priority traffic by forcing it to BackOff (BO). They have assumed N sensor nodes to monitor power distribution devices and report back to a coordinator using the IEEE 802.15.4 protocol and that all nodes can hear each other. When operational data arrives at any node, it will be pushed into the queue at MAC layer if there is a packet in service. When the emergency data arrived, it will be queued in the high priority queue if there is high priority packet in service. Otherwise, it will interrupt the service of an operational data packet. They have assumed that no operational data will be serviced until the emergency data queue is empty. They have modelled the delay of QoS-MAC and the BO process using the Markov chain queue model for two classes of traffic. They have assumed that the packet arriving rate for all nodes is the same, and set the maximum

number of BO stage as 5, the value of the BE for high priority traffic ranges from 0-3 and for low priority data ranges from 2-5. The authors have not presented the impact of the buffer or queue size on the performance of the network. The queue size of each sensor node will affect the waiting duration of the packet and hence may affect the overall network performance.

References [24], [25] and [26] discuss the issue of providing QoS differentiation by reducing the delay of delay critical data without impacting the overall performance of the network.

2.3 Cross Layer Considerations for QoS in WSNs

Cross-layer approaches for the QoS models in WSNs group resource parameters and performance metrics associated with protocol layers, i.e., the application, network, MAC, and physical (PHY) layers, then maps them to data classes. The main disadvantage of using cross layer approaches is the lack of flexibility due to the coupling between layers. If changes in one layer need to be made, all the other layers with which the former has cross-layer interactions also need to be adapted. However, in condition monitoring applications, timeliness and reliability constraints have significant importance thus the necessity of using cross layer approaches to achieve these goals is reasonable. Many publications discuss cross layer design considerations for QoS in WSNs, several publications are discussed in this section.

Bhuiyan et al. [27], have designed a routing protocol that avoids congestion and meets delay requirements of transmitted data by choosing nodes that are having light loads and incurring low delay during data forwarding towards the Base Station (BS). They considered that all nodes describe their congestion status and delay measurements by broadcasting periodic control data packets to allow neighbouring nodes to utilize these

data during route selection process. Hence the performance of their proposed scheme depends on the successful delivery of these control packets. They also included a congestion mitigation technique in their proposed scheme. This data mitigation is achieved by allowing the MAC sub-layer to always send feedback to network layer regarding its achievable data forwarding rate. The protocol suggests the application layer to lower its rate if the application layer has a higher traffic generation rate. The network layer drops a fraction of packets received from other nodes if the incoming rate is higher than the data forwarding rate of MAC sub-layer. They intended to improve the reliability and the timeliness of data transmitted by the critical nodes by using congestion avoidance and mitigation. They claim to achieve a highly effective method to ensure desirable node density in inaccessible areas, in addition to that, every node is able to measure the end-to-end delay of its packets to the base station and can also route data packets in a delay-aware manner. They used a specific MAC sub-layer approach to ensure high success probability of control data sent by different nodes in the network which are utilized by neighbouring nodes to choose appropriate routes. Their results showed that their proposed protocol is capable of avoiding and mitigating congestion, and performs better than similar known techniques in terms of reliable and timely event detection.

Choe et al. [28], have discussed controlling data reporting functions in communication layers considering parameters from other layers to achieve the information quality at the end system. They have focused on the QoS-aware reporting tree construction scheme and the QoS-aware node scheduling scheme. Their first scheme constructs a data reporting tree based on the conditions of the end-to-end delay and the traffic load to find data reporting paths from each cluster head. In the first scheme, each CH finds the shortest path to a sink, exchanges the path information with adjacent cluster heads and constructs a spanning tree as a back-bone based shortest paths. In the next step they

have changed routing paths from a CHs based on the delay constraints or the amount of traffic generated in a cluster, so that the fewest hop count is considered for tree construction to minimize the delay. They have constructed a balanced tree to reduce the energy consumption of the nodes that are close to a sink or the ones that have heavy children. Their second scheme schedules certain number of nodes that are selected based on the QoS requirements in a cluster to report data to its cluster head in a collision-free manner. Their QoS scheduling scheme provides an adaptive data reporting strategy based on the QoS requirement that is the data collection coverage required by the end system. Their scheduling scheme includes two operations performed in a CH as a slot allocation. The first is selecting data reporting nodes in a cluster, and the second is scheduling the nodes to the particular time slots. An end node can send a slot request message to a CH, and that sends the schedule to the node if the CH can assign the required time slots. They have shown that their schemes provide good throughput performance while providing stable data reporting which is not affected by network density. The main problem with the cluster tree based scheduling schemes is to take into account the actual location and the size of the network which affects the performance of the QoS scheme. The authors have not considered these aspects in their evaluations to show the scalability of their protocol.

Di Francesco et al. [29], have proposed an adaptive and cross-layer approach for reliable and energy-efficient data collection in WSNs based on the IEEE 802.15.4. Their approach is based on an energy-aware adaptation module that meets the application's reliability requirements and then configures the MAC layer, based on the network topology and traffic conditions. Their proposed approach is based on an analytical study of the IEEE 802.15.4 standard which can be integrated into WSNs based on IEEE 802.15.4 without requiring any modification to the standard. The authors have achieved inde-

pendent cross layer interaction by allowing the information coming from one layer to tune the operations of protocols residing in a different layer. Their adaptation module obtains a target level of reliability from the application layer. The adaptation module continuously monitors the performance of the MAC layer, and provides feedback on the current operating conditions by properly tuning the MAC parameters so as to satisfy the required reliability value. In multi-hop networks it maps the end-to-end reliability constraints to the link-level parameters by using the information about the network topology obtained by the routing layer. In their paper their goal has been to satisfy the reliability requirement specified by the application with the help of a distributed and low-overhead algorithm that consumes low energy. Their approach first estimates the current traffic conditions, and changes MAC parameters according to the required level of reliability. They have presented a monitoring and control schemes to address message losses due to various factors. They have shown that their approach can satisfy a target reliability constraint while consuming low energy, and its performance is near-optimal, for both single-hop and multi-hop networks.

Lin et al. [30], have proposed a distributed routing and power control scheme to enable the nodes in the multi-hop network to optimize the overall performance of several delay-sensitive applications under different network dynamics. The nodes achieve this by depending on their locally available information and the limited information exchanges with their neighbouring nodes. The authors assumed that a delay-driven scheduling scheme is utilized at the application layer, and formulated the joint routing and power control problem as a Markov distributed process and created an ideal policy that controls the cross-layer transmission schemes to be selected at each node, assuming that the network dynamics are known. They have also proposed a distributed computation of the ideal policy, which can enable the nodes to independently make decisions in real-time.

Furthermore, they have investigated how nodes can independently learn the network dynamics online, based on their available information. This online learning strategy enables the users to adapt their cross-layer techniques in real time fashion to the changing environment so that the nodes can maximize the usefulness of the delay-sensitive applications. The authors have considered how information exchanged between nodes affect the overall network performance in various network scenarios.

Nandi et al. [31], have proposed a QoS aware MAC protocol for WSNs and its cross layer extension to network layer to provide QoS to delay sensitive WSN scenarios. They have considered both event driven traffic which needs immediate attention and periodic reporting traffic. They have classified the event driven traffic as Class I (delay sensitive) traffic and the periodic reporting is Class II (Best Effort) traffic. They have used MAC layer adaptation by using dynamic contention window adjustment per class. They have also reduced the delay suffered by using three techniques; Difference in Sleep Schedules (DSS) of nodes through dynamically regulating duty cycle based on utilization and DSS delay of class I traffic, Different Inter Frame Spacing DIFS per class, adjusting all of the three proposed schemes simultaneously. They have also proposed a cross layer extension, in this extension the MAC sub-layer uses the next hop information used by the network to better adapt the duty cycle based on DSS delay. They have assumed that the routing protocols can utilize MAC sub-layer parameter DSS delay to select the routes which offer least DSS delay latency to minimizing the overall end-to-end delay. The authors have not considered the idea of adaptively identifying the traffic classes based on the criticality of data which makes their scheme follow a static approach instead of adaptively change the node classification.

Wang et al. [32], have present a hybrid MAC protocol that is suitable for WSNs in terms of energy efficiency, latency, and design complexity. Their proposed protocol

combines channel-allocation schemes from existing contention-based and TDMA-based MAC protocols to allow the realization of trade-offs between different performance metrics. Hybrid MAC uses a short slotted frame structure and a wakeup scheme to achieve high energy efficiency, low delay and improved channel utilization. They have organized the time into non overlapping frames where each frame contains multiple very short wakeup slots and multiple data slots. They have set the number of the wakeup slots based on the density of the network, and the number of data slots based on the potential traffic load in the network and end-to-end delay requirements. they have assumed that Each wakeup slot contains a carrier sensing and wakeup message period, and that each data slot contains carrier sensing and periods for RTS/CTS/DATA/ACK messages. Each node turns on its radio during its own wakeup slot and sleeps during all the other wakeup slots. Nodes randomly select a data slot and announces the data slot number along with the receiver's node identifier using a wakeup message. Upon reception of a wakeup message the node checks the embedded node identifier in the message, the node turns on its radio for the incoming data packet in the specified data slot if it is the intended receiver. If collision takes place in a node's wakeup slot, then it turns on its radio to receive an RTS packet at the beginning of each data slot for an incoming data packet. In each data slot, unicast data transmission follows RTS/CTS/DATA/ACK scheme to avoid collisions id two senders choose the same slot to send data to their receivers at the same time. For QoS reservation, the authors have propose a channel reservation scheme combined with a prioritized channel-access technique to support differentiated transmission to certain flows. They have shown that their protocol outperforms sensor-MAC and routing-enhanced MAC in terms of per-hop latency and delivery ratio and energy performance. They have also shown that their proposed protocol achieves performance improvements in energy consumption, latency, and throughput over existing

MAC protocols.

Shah et al. [33] have proposed a cross-layer framework that used cognitive radio communication to reduce the effects of the propagation conditions in power systems and supports QoS for smart grid applications. Their framework have dealt with the channel impairments by dynamically switching among different spectrum bands to find a channel with the low noise signal. They have formulated a Lyapunov drift optimization with the objective of maximizing the weighted service of application flows belonging to different classes. They have presented a suboptimal Distributed Control Algorithm (DCA) to support QoS through dynamic spectrum access, flow control, scheduling and routing decisions. The authors have used flow control to maintain the service of existing flows by confirming the resources availability and adjusting service attributes of newly admitted flows. They have also performed data scheduling and on-demand routing actions to ensure that the data can be delivered to a destination, while preserving its service characteristics.

Wang et al. [34], have investigated the distribution of end-to-end delay in multi-hop WSNs and have developed a cross-layer analysis framework that uses a stochastic queueing model in realistic channel environments. Their framework considers the heterogeneity in WSNs in terms of channel quality, transmit power, queue length, and communication protocols. They have conducted a case study with the TinyOS CSMA/CA MAC protocol to show how the developed framework can analytically predict the distribution of end-to-end delay. They have proposed to use their frame to identify the relationships between network parameters and the distribution of end-to-end delay and accordingly, to design real-time solutions for WSNs. The authors have suggested that their framework can be extended to model additional QoS metrics such as energy consumption distribution.

2.4 MAC Layer Considerations for QoS in WSNs

The MAC layer controls the sharing of the medium and all other upper-layer protocols are bound to that, it has the ability to significantly affect the overall performance of the WSNs. Therefore, MAC layer becomes a proper choice to implement QoS support. There are numerous publications that discuss the MAC layer design consideration for QoS in WSNs, in this section we will take a look at a few related papers.

Saxena et al. [35], have developed a QoS-based MAC protocol for WSNs. Their MAC protocol have been based on a CSMA/CA mechanism that can adaptively adjusts the CW depending on the application QoS requirements. Their adaptation model depends on the traffic and wireless channel characteristics. They have designed their protocol to dynamically adjust it's duty cycle based on the major application traffic and preserve energy. The authors have performed performance modelling to classify the application traffic into different categories and analyse the overall system performance. They have shown that their protocol achieves improvements for all the QoS parameters under our test cases. The use CW to adaptively control the delay or provide QoS has been addressed previously in this context. The issue with CW size reduction is that the number of channel assessments done are reduced when the CW size is reduced, this reduction may cause some additional collisions in the PAN. The authors have not evaluated and compared their protocol in terms of packet collision rate or reliability which may play a major role in any QoS scheme. Furthermore, the impact of the network size was not considered when the evaluation was performed.

Kim et al. [36], have proposed priority-based QoS MAC (PQMAC) protocol which is designed to maintain energy efficiency and solve the latency problem simultaneously. PQMAC is based on providing classification by type of data and scheduling scheme for fast transmission of event data. They have proposed to provide fast packet transmission

by a priority queue and additional listen time. Sensor node sends high priority data from the high priority queue first. When there is no data in the high-priority queue, the sensor node sends low-priority data from the low-priority queue. The authors have proposed an additional listen time to solve the transmission latency problem in the sleep state. They have suggested that sensor nodes do not send low-priority data to other nodes during the additional listen time which is used only for high priority data. They have suggested that nodes having long listen time or a frequently repeating frame can send data quickly. Their doubling scheme provides more opportunity to send high priority data than low-priority data. This additional sending opportunity for high-priority data is provided by additional listen time. The authors have proposed four data priorities and use them in the doubling scheme. They have suggested that PQMAC uses advanced wakeup scheme and dynamic priority listening to maintain energy efficiency. The advanced wake-up scheme uses the RTS/CTS message that has a priority check field for broadcasting. A dynamic priority listening scheme manages scheduling based on traffic information. The delay reduction scheme proposed by the authors seems to be highly probabilistic which is based on several assumptions such as assuming that a sensor node knows receiving probability of high priority data in advance so that it makes an informed decision. In realistic WSN monitoring scenarios this assumption may not be very accurate since the prediction of high priority data may not be that easy.

Nguyen et al. [37], have proposed a MAC protocol that can minimize the time taken in delivering the first few required event reports in multihop WSNs. Their proposed protocol is based on CSMA/CA mechanism where the first few slots in CW should be contention-free and use a fixed size CW and an increasing probability distribution for picking a transmission slot within the window. The authors have addressed the issue in multihop transmission where the relay nodes have to route different data flows which have

different priority levels which may degrade the QoS given to each data flow because of the random characteristics of CSMA/CA based MAC protocol. They have solved this issue by assigning different DCF inter frame space and CW to different data packets, which ensures that higher priority data packets will be transmitted earlier than the lower priority ones. They have presented a suppression mechanism using implicit acknowledgement through overhearing, based on the broadcast nature of wireless communications that can suppress almost all unnecessary reports at the first hop to solve the problem of latency due to using explicit acknowledgement which is done in later hop. Their suppression mechanism improves the delay performance of sensor network. Based on that, they have proposed that the higher number of hops, the higher level of priority that packet has. The priority information is included into the packet header so that the following relay nodes can read and treat them differently.

F. Shu [38], has investigated the performance of QoS differentiation schemes for the IEEE 802.15.4 CSMA/CA protocol. The author has used different strategies to adjust BO window sizes to prioritize different types of nodes to achieve latency differentiation. The model gave more transmission attempts to the nodes having stricter reliability requirement when busy channels and collisions are detected to achieve reliability differentiation. They have done this by giving high priority to packets of the traffic class having stricter QoS levels for transmission in QoS differentiation schemes. Simulation results showed that the prioritized nodes can achieve less end-to-end delay and higher packet delivery ratio than the normal nodes. The authors have focussed on increasing the packet delivery rate of the high priority traffic class by modifying the MAC parameters. However, it is seen from their results that modifying the BO window size affects the collision rate of non high priority traffic and eventually the packet delivery rate drops drastically especially when the number of nodes is 30.

Yuan et al. [39], propose an architecture that uses WSNs with smart phone platform to perform continuous monitoring of inpatient and outpatient care. The authors have designed a MAC that meet the QoS requirement of three types of context traffic: normal, warning, and emergency traffic. They have used WSNs for short range communication and the smart phones utilize established Wi-Fi communication backbone to relay data on time. They have based their MAC protocol on the 802.11e QoS MAC, which uses prioritized channel contention to provide differentiated service between normal and warning medical information, which is done by extending the 802.11e QoS MAC by adding in a preemptive service scheduling algorithm to provide the highest and preemptive channel access precedence for medical emergency traffic. This highest priority traffic at a node can interrupt the current services of other data at that node. They have also presented the implementation at the physical layer and differential service MAC design that adapts channel provisioning based on the information criticality. They have shown that their scheme provides differentiated services for emergency, warning, and normal traffic. The scheme proposed by the authors assumes no adaptiveness in adding the preemptive service scheduling algorithm, where they have assumed previous knowledge of traffic class classification. Furthermore, the effect of adding preemptive service scheduling on the overall energy consumption of the system has not been presented.

Yahya et al. [40], have proposed a MAC mechanism with QoS support (EQ-MAC) for WSNs. Their mechanism utilizes a hybrid approach of both scheduled TDMA and contention based MAC schemes. EQ-MAC differentiates between short and long messages; long data messages are assigned scheduled TDMA slots where slots are assigned to node which have data to transmit. They have assigned random access slots to short periodic control messages. Their proposal reduces message collisions and reduces the total energy consumed by the radio transceiver, which makes their protocol provide QoS

based on the service differentiation concept. Their scheme provides service differentiation through data prioritization to distinguish between four different priority levels based on traffic importance and criticality. If the packet real time data, or any other critical data that should be processed immediately without any delay, then the sensor node puts this packet into its instant queue of its queuing system to be instantly served. Their scheme is thus based on allowing sensor nodes to do some type of traffic management and provide highest priority traffic a greater chance of acquiring the channel and hence served with minimum delay. The authors have compared their protocol with existing MAC protocols and showed that their protocol outperforms the existing protocols. The main aspect that the authors did not evaluate is the effectiveness of the TDMA scheme which is used for long messages in large networks and how the size of the network affects the time slot allocation of their QoS scheme.

Chen et al. [41], have proposed a new MAC protocol, named Path-oriented Real-time Media Access Control (PR-MAC). Their proposed protocol addresses the two causes of data transmission delay with a schedule algorithm called Bidirectional Pipelining Schedule (BPS) and a multi-channel communication mechanism, respectively. In BPS, each node wakes up periodically for listening where a node wakes up twice one for transmitting data messages from source nodes to the sink, and the other for transmitting control message from the sink to source nodes during one work cycle. Nodes on a multi-hop path wake up sequentially like pipelining with certain offset that is long enough for transmitting or receiving a packet in either direction between sources and the sink. The moment a node wakes depends on its depth in the path where each node maintains a table to record the channels used by and the waking moments of its neighbour nodes. The mechanism of using the common channel differs from that of the special channels, nodes compete for using the common channel. To reduce collision, they have made every node

backs off for a period plus a random time within a contention window at the beginning of a sending slot where the window increases exponentially in the case of contention. When the channel is free, the node exchanges RTS/CTS, when a node receives a packet, it transmits the Acknowledgement (ACK) packet back to sender after a short period. When the event ends or the sink does not get message for a work cycles, the sink sends the nodes a control packet to restore their work pattern to the original. The authors have shown that their protocol reduces the data latency and energy consumption over existing protocols in the case of simultaneous multiple events. The authors have not shown the effect of implementing PR-MAC on the probability of packet collision. The modification of the BO period and the use of BPS may have an impact on the packets lost due to collisions.

Wan et al. [42], have propose a MAC protocol suitable for delay-sensitive applications in WSNs, which can reduce energy consumption without incurring significantly additional latency. The authors have used the wakeup probability to control the number of active nodes within the local area which determines the network connectivity and affects the network performance. They have divide the channel into equal time slots and assigned an initial wakeup probability to each node where each node independently enters active/sleep state based on its own wakeup probability at the beginning of a time slot. The wakeup probability is adjusted to achieve the desirable network connectivity. The authors have implemented anycast data forwarding mechanism instead of unicast to support their opportunistic sleep scheme, where sender anycasts messages to a specified area when it is carrying traffic. Then the best node is chosen to behaves as the forwarder based on the geographical information and the remaining energy of the nodes in the area. The authors have evaluated their protocol using simulations which show that their protocol outperforms SMAC and GAF in terms of balancing the tradeoff between energy

efficiency and the end-to-end delay. The authors have considered assigning or assuming the probability of wakeup to each node in the network. This assumption is not very accurate to describe the operation of a WSN MAC protocol since the wakeup pattern of individual nodes may take a random distribution.

Yigitel et al. [43], have introduced (Diff-MAC), a design and implementation of a new QoS-aware and priority-based MAC protocol for WSNs. Their protocol is designed to support service differentiation and QoS provisioning to deliver heterogeneous traffic. They have proposed to use several features to implement the protocol, these features include: fragmentation and message passing, adaptive contention window adjustment, adaptive duty cycling, intra-node and intra-queue prioritization. Fragmentation and message passing fragments the long video frames into smaller video packets and then reserves the medium to send these packets as a burst which in turn reduces the retransmission cost of long messages in case of MAC failures. Adjustable contention window size is used according to the dynamic traffic requirements to reduce the number of collisions and keep a low delay. Adaptive duty cycle is done based on the dominating traffic class in the network and balances both energy consumption and delay. Intra-queue and intra-node prioritization provided a fair delivery of the data among all sensor nodes and among all traffic classes respectively to avoid bad network performances. They have shown that their protocol is the first all-in-one QoS-aware MAC protocol proposed for WSNs that dynamically adapts the use of its resources to meet the requirements of different traffic classes. They have evaluated the performance of Diff-MAC for three different classes of traffic co-existing in the network: real-time multimedia traffic, non-real-time traffic and best effort traffic, and compared its performance with existing QoS-aware MAC protocols. The main issue with the proposed protocol is that the authors have base their protocol on RTS/CTS operation and have done testing with a IEEE 802.15.4 based plat-

form. However, the IEEE 802.15.4 protocol does not support RTS/CTS mechanism and they have not further commented on the implementation of this mechanism in the IEEE 802.15.4 based platform.

2.5 Analytical and Optimization Models for WSN

There are several important publications that derive accurate analytical models describing the energy consumption, delay and reliability in WSNs. In this section some of these related publications are discussed.

Bianchi [44], has discussed the performance evaluation of the DCF scheme, where he assumed ideal channel conditions (no hidden terminal) and finite number of nodes. The author has provided a simple model that accounts for all the exponential BO protocol details and computes the saturation throughput performance of DCF for both standardized access mechanisms and for any combination of the two methods. He has assumed a constant and independent collision probability of a packet transmitted by each station, regardless of the number of retransmissions already suffered to allow the implementation of a Markovian model. The author also assume a fixed number of stations, each always having a packet available for transmission which means that the transmission queue of each station is assumed to be always nonempty. The analysis is divided into two distinct parts, the behaviour of a single station with a Markov model is derived and stationary probability that the station transmits a packet in a randomly chosen slot time is obtain which does not depend on the access mechanism employed. The author has expressed the throughput of both Basic and RTS/CTS access methods and the combination of the two as function of the computed value by studying the events that can occur within a generic slot time. The model presented by Bianchi has become the bases of the most following IEEE 802.15.4 models that are based on Markov chains. However, due the ap-

proximations the author made (such as the ideal channel and the saturation condition), his model can not directly be implemented in IEEE 802.15.4 based WSNs.

Park et al. [45], have presented an accurate and approximate model and analysis of IEEE 802.15.4 MAC protocol in terms of reliability, delay and energy consumption. The authors have proposed a generalized Markov model of the exponential BO process with retry limits and acknowledgements under unsaturated traffic regime. They have shown that their Markov chain gives an accurate model of the reliability, delay and energy consumption of IEEE 802.15.4. They have proposed a simplified and effective method that reduced the computation complexity while ensuring a satisfactory accuracy. They have used their results to analyse the performance of IEEE 802.15.4 as functions of the MAC parameters and collision probability. They have validated their analysis through simulation. They have proposed certain approximations in their formulation of the reliability, delay and energy consumption. The study in have presented an idle state duration (L_o) which is a variable that controls the model performance. In WSNs, the idle state duration cannot be quantified easily, and therefore, it should not be considered when describing the model. Another point is that the authors have not taken the effects of a finite buffer at the MAC-level.

Buratti et al. [46], have considered a WSN composed of a small number of nodes; each node takes one sample of a given phenomenon and forwards it through a direct link to the sink. They have used the 802.15.4 non-beacon enabled where the nodes compete to access the channel, in order to transmit the data required. The nodes change to idle state when they finish transmission, till the next query is received. The interval between two successive queries is denoted as round. They have provided an analytical model for the description of the transitions between node states (BO, sensing, transmission, idle) of the CSMA/CA 802.15.4 MAC protocol. Their model derives the probability

that a generic node succeeds in the access to the channel and in transmitting its packet. They have evaluated the probabilities as a function of time, starting from reception of the query, till the end of the round. Their model allows the evaluation of the overall success probability for the transmission of a packet in a round, and the mean energy consumed by a node during a round [1]. They have shown that their model predicts the statistical distribution of the traffic generated by the WSN. They have compared their work to existing models, in their model; the statistics are evaluated over time; whereas other work study the asymptotic behaviour of the network. They have shown that in other work the probability to find the channel busy is evaluated regardless of the BO stage in which the node is. They have also shown that their model captures the different probabilities at the different BO stages. The model presented by the authors is based on finite state machine which is known to be quite complicated for the limited resources sensor nodes especially when no approximations are implemented in their model.

Buratti [47], has provided a mathematical model for the beacon enabled mode of the IEEE 802.15.4 MAC protocol. She has considered PAN composed of multiple nodes, which transmit data to a PAN coordinator through direct links or multiple hops. The author has developed a flexible mathematical tool able to study beacon-enabled 802.15.4 networks organized in different topologies. She has considered both the CAP and the contention-free period defined by the standard. She has modelled the slotted carrier-sense multiple access with collision avoidance (CSMA/CA) algorithm used in the CAP portion of the SF. Her model describes the probability of packet successful reception and access delay statistics. She has considered both star and tree-based topologies and provided a comparison between these topologies. The author has shown that the model is a useful tool for the design of MAC parameters and to select the better topology. She has validated her mathematical model through simulation results. Her model differs

from those previously published by other authors in the literature as it precisely follows the MAC procedure defined by the standard in the context of the application scenario described.

Chen et al. [48], have presented an accurate two dimensional discrete Markov chain model for evaluating the 802.15.4 CSMA/CA mechanism. They have focused on the analysis of relationship between throughput and related parameters. The authors have built a Markov chain for the BO counter and have computed the stable distribution probability and success transmission probability in channel collision. They have also given the throughput and energy consumption formula. They have validated their model with simulations of IEEE 802.15.4 at the 2.4GHz scale under different circumstances. The model presented by the authors is based on the model of [44]; however it represents a three dimensional Markov chain instead of a two dimensional model by taking the effect of the BO stage into their model. However, the authors also consider a saturated traffic situation which is not the ideal case to describe the operation of an IEEE 802.15.4 based sensor network

Gallardo et al. [49], have proposed a realistic model where they have modelled the whole network with all of its nodes using a single Markov chain. In doing so they have proposed that assuming independence is not necessary. They have reduced the complexity of the problem, both in processing and memory requirements, by utilizing the models symmetry, which allowed the work with only a few selected representative states. They have compared their method with the conventional independence assumption method. The authors propose to increase accuracy by avoiding the independence assumption. This is done by taking advantage of the fact that the steady state probabilities of many states are equal. In doing so, they have not calculated the probability of all possible states, but only of a few selected representative states. The authors have reduced the

amount of memory needed for their calculations by dynamically allocating memory to store only those elements of the transition probability matrix that are different from zero.

Gribaudo et al. [50], have considered a single hop network topology and have carried out a transient analysis where, upon an event occurrence a number of sensors start contending for the channel to transmit their report. The authors have taken into account the inter-dependencies existing between different sensors that simultaneously contend for the channel. Their model takes into consideration the correlation between collision events which prevented them from assuming independent sensors and which made the fixed-point technique unsuitable for their study. Hence, they have used Hybrid Automata approach to model the WSN which allowed them to give a clear description of the system behaviour. They then have driven a solution algorithm that reduces the complexity of the model and its solution time. They have considered consider next multi-hop networks and extend their model to address this scenario of practical relevance. Their extended model have accounted for the presence of hidden nodes, both with respect to the sender and to the receiver node.

Jung et al. [51], have considered a single-hop wireless network consisting of a PAN coordinator and n sensor nodes. They have assumed that all nodes are within the transmission range of each other and time-synchronized by the PAN coordinator's beacon, and that there are no transmission errors and no channel sensing errors. Data frames arrive at each node according to a Poisson process with λ and that each node can store a single data frame which means that when a node has a data frame to transmit, it cannot accept any new data frames from upper layers. They have constructed a discrete-time Markov chain, which models the operation of the CSMA/CA algorithm in random node and captures the key characteristics of the IEEE 802.15.4 MAC protocol such as a SF structure, acknowledgements, and retransmission schemes with and without a retry limit.

They have verified that the analytic results matched the simulation results. They have further shown that their results have higher accuracy compared to other published work.

Martalo et al. [52], have combined the theory of discrete time Markov chains and the theory of Geo/G/1/L queues to derive a Markov chain-based analytical model for an IEEE 802.15.4 network, which takes into account the presence of buffers at the sources and the relays. The authors have focused on a specific node for single-hop networks. They have further applied their model in evaluating the performance of multihop networks with cluster-tree topology where the relays may contend the shared medium access to the sources. Their Markov chain-based framework evaluates the aggregate network throughput and the packet delivery delay. Their model becomes less accurate because of the approximations they have done to make the multihop analysis tractable. They have not used ACK transmission to confirm successful data packet deliveries, and they have proposed that communications are beaconed enabled. They have evaluated the aggregate network throughput and the packet delivery delay. The authors have not presented the energy consumption evaluation in their model and in their results. Another important point in their model is that they have not highlighted the collision detection method by sensor nodes if the ACK mechanism is not activated in their model

Misic et al. [53], have modelled the Wireless Personal Area Network (WPAN) with uplink transmissions only and have considered network devices with buffers of finite size with specific packet arrival rate. In their model they have assumed that the buffer may be empty, it may contain packets but still have free space to accept new ones, or it may be full and reject new packets. The authors have combined the theory of discrete-time Markov chains and the theory of M/G/1/K queues with service time equal to packet service time. They then have driven expressions for the access probability at the device queue, the probability that the medium is idle on both Clear Channel Assessments (CCAs), and the

probability distribution of the packet queue size. They also have identified the problem of congestion caused by the deferred transmissions from the previous SF, and propose a simple remedy to reduce it. In [54], the authors have identified by modelling the WPAN a number of issues that degrade the performance of IEEE 802.15.4 networks. They have shown that the access probability can be maximized through proper choice of values for the packet arrival rate, network size and packet size.

Misic et al. [55], have considered a star-topology 802.15.4 cluster operating in beacon-enabled mode with both downlink and uplink traffic. They have evaluated the performance of such networks and identify possible performance bottlenecks and quantified their impact. Similar to [53], they have combined the theory of discrete-time Markov chains and the theory of M/G/1 queues to derive the probability distributions of packet service times, which have been validated through simulation. The authors have modelled the relationship between uplink queues, uplink request queues and downlink queues, and have shown that the default parameter values set up in the standard cause deterioration in the performance and rapid change from non-saturation to saturation condition. They have identified problems in the MAC definition that contribute to this performance problem. They have shown that the network coordinator can handle only a small amount of downlink traffic and that the number of nodes and their traffic load should be chosen with the goal of keeping the operating point of the network well away from the saturation point. The analysis presented by the are very complicated and not suitable to be implemented in the low resource sensor nodes since they have employed no approximations and all off the equations model the exact behaviour without much simplification. The other point is that their results predicted by their analysis seem to diverge significantly from their simulation results.

Ramachandran et al. [56], have preformed a performance analysis of the CAP of the

IEEE 802.15.4 SF by modelling it as non-persistent CSMA/CA with BO, where they have developed Markov models separately for the channel and node states, to determine the time a node spends in different states, which are then used to determine the throughput and energy consumption characteristics, where they have used the transceiver characteristics of the commercially available CC2420 IEEE 802.15.4 radio. The authors have suggested and analysed some modifications to the standard that could potentially improve the throughput and energy consumption of WSNs. The authors have presented a number of approximations which makes their model simpler to implement without losing the accuracy when compared with the simulation results. However, their model has considered a saturated traffic condition which limits the implementation of their model to very specific WSN-based applications. Furthermore, the authors have not considered the impact of a finite MAC-level buffer size on the throughput and energy consumption of an IEEE 802.15.4 based sensing node. Our model presented a complete overview and analysis of the effect of a finite buffer in the MAC layer in terms of modelling and simulation.

Ndih et al. [57], have presented a model to address the service differentiation provision in the slotted IEEE 802.15.4 CAP through defining different priority classes, each class has specific values of access parameters and data frame length. The authors have extended the Markov-chain-based analytical model of the IEEE 802.15.4 CAP in [56] by considering two priority classes. Their differentiation model is based on the CW strategy by allowing the high-priority nodes to use $CW = 1$ (class 1), instead of the default $CW = 2$ used by the low priority transmissions (class 2). They have done this by maintaining the same BO procedure parameters, this strategy reduces the duration of idle channel sensing for high-priority nodes so that they gain access to the channel ahead of low-priority nodes, which must observe a longer channel idle time before transmission. The

idea of using different contention window sizes to differentiate traffic classes has been previously discussed in the literature [58, 59, 60, 61]. Furthermore, the authors have not presented a power consumption model in their traffic differentiation analysis, as the size of the contention window impacts the power consumption in WSNs especially in big networks.

Pollin et al. [62], have analysed whether the CSMA/CA scheme meets the design constraints of WSNs. The authors have provided a detailed analytical evaluation of the performance of the CSMA/CA scheme in a star topology network, for uplink and acknowledged uplink traffic. They have considered both saturated and unsaturated periodic traffic scenarios. Their analysis is similar to that of [44] for IEEE 802.11 DCF in the use of a per user Markov model to capture the state of each user at each t time instant. They have presented different assumptions to make the model suitable for IEEE 802.15.4 simplification, hence the coupling of the per user Markov models becomes different. They have shown that the performance predicted by the analytical model is close to that obtained by simulation. The authors have considered two traffic scenarios which are relevant for sensor networks. In the initial scenario, they have assumed a large sensor network that has been deployed to monitor events and upon event detection, all sensors have data to send to the PAN coordinator. They have modelled this scenario by a large number of nodes where each node has a packet to send. In the second scenario, they have assumed that sensor networks are deployed for periodic monitoring purposes. Measurements should be transmitted at regular time intervals, but the measurement update period varies depending on the application instance. They have described guidelines to tune the MAC parameters to increase throughput and power savings. The authors, however, did not take into consideration the transmission retries which when taken results in a three-dimensional Markov-based model. Furthermore, the authors do not consider

the effect of MAC-level buffers on the overall performance of the network.

Sahoo et al. [63], have proposed a hybrid channel access mechanism for the WSN that combines the CSMA/CA scheme of IEEE 802.15.4 and the BO procedure of IEEE 802.11, if collision occurs among the nodes. If the channel is sensed idle upon two successful CCAs, transmission begins immediately. Otherwise, a node defers channel access, remains in the BO state. During the BO procedure, the BO timer is halted, if channel busy is detected and resumes immediately, if the channel becomes idle. They have also presented an extended linear feedback model that has analysed the model for the fixed and binary exponential contention windows to analyse and improve the energy efficiency of WSN, where they have assumed that the nodes in the extended linear feedback model may be in thinking or in backlogged states, alternatively. Nodes in the thinking state has generated a new packet with certain probability to transmit, whereas a node remains in the backlogged state, if it senses the channel busy. They have shown that energy consumption in WSN is increased with increase in size of the contention window and network population. They have also shown that the energy consumption in WSN is reduced by adopting an exponential contention window instead of a fixed one. The authors have suggested to consider an exponential BO mechanism in WSN for better power conservation and higher success probabilities. They have presented that using optimal contention window, they have achieved a reasonable successful probability for the packet transmission. The authors have presented analytical and simulation results to evaluate their model, however, there simulation results seem to be inconsistent with the analytical model results and there are very high differences in the variables that are used to perform these evaluations.

Park et al. [64], have proposed a new Markov chain model of IEEE 802.15.4, and have analysed the throughput and energy consumption in saturation conditions. Their

model have utilised the probability of a device in the channel sensing states instead of the channel accessing states. The authors have validated their energy consumption and throughput results through simulations. They have shown that their analytical results match the simulation results. Furthermore, they have compared their model with the model in [44] by deriving the saturation throughput. The authors however, have not considered the BO state in their analytical model and have not generalized the model for unsaturated traffic conditions. Furthermore, they have not considered the evaluation of power consumption as well as the end to end delay in the network.

Wen et al. [65], have presented an improved analytical model for evaluating the IEEE 802.15.4 slotted CSMA/CA mechanism by introducing the idle state into the Markov chain. They have shown that their model can work well under different system loads without increasing the model complexity and by incorporating a view of several important performance metrics. They have considered throughput, access delay and energy consumption. Furthermore they have performed simulations to validate their analytical model. The authors have presented a two dimensional Markov-based model as opposed to the more realistic three dimensional model where they have not considered the state of the BO counter in their Markov model.

Di Marco et al. [66], have proposed a new generalized analysis of the unslotted IEEE 802.15.4 MAC. The authors have considered the effects induced by heterogeneous traffic due to multi-hop routing and different traffic generation patterns among the nodes of the network and the hidden terminals due to reduced carrier-sensing capabilities. They have modelled the relation between MAC and routing protocols and derived their results on this interaction. They also have studied routing decisions based on packet loss probability or delay lead to an unbalanced distribution of the traffic load across multi-hop paths are studied. They have shown that the routing decisions tend to direct traffic toward

nodes with high packet generation rates, which affects the node's energy consumption. They have also that heterogeneous traffic and limited carrier-sensing range affect the performance and that routing should account for the presence of dominant nodes to balance the traffic distribution across the network.

Zhang et al. [67], have considered a state estimation problem with stringent delay constraints in large-scale WSNs. They have aimed to obtain an optimal state estimate at the sink within rigid delay constraints through the collaboration of a set of distributed sensors and the sink. The authors have designed an estimation method and a scheduling algorithm in multihop WSNs, and proposed an in-network estimation scheme for estimating the state and satisfying delay constraints. In their proposed scheme, every intermediate node on the route calculates an optimal fusion estimate based on the information received from its child nodes in the aggregation tree and its own measurements. Their aggregation scheduling is used to gather maximum sensor information at the sink within stringent delay constraints, to reduce the estimation error through collecting the more information from the sensor networks. The authors have shown through simulations that their approach can obtain significant estimation accuracy gain under different network settings.

2.6 Routing Protocols Considerations for QoS in WSNs

QoS based routing protocols allow sensor nodes to make a trade-off between various network parameters and some QoS metrics before delivering the data to the sink node. In general, all proposed routing protocols focus on various aspects of QoS but there hasn't been a QoS-aware protocols that take into account the main QoS requirements in the condition monitoring context such as reliability, timeliness and also energy efficiency at the same time. This thesis does not consider the network layer to provide service

differentiation. However, a quick overview of the available work related to providing QoS using routing protocols is presented in this section.

He et al. [68], have proposed the SPEED algorithm which is a stateless, localized routing algorithm for WSNs that provides real-time communication, where the authors have provided additional modules to reduce or divert traffic when congestion occurs and to try to balance the network load. In [69], the authors have proposed MMSPEED protocol which takes some ideas from SPEED and extends the protocol to deal with reliability. In [70], the authors have introduced randomized re-routing to detect unusual events in a distributed manner, their protocol dynamically transfers routine data packets to secondary paths in the network and offers a fast track path with QoS guarantees for the packets carrying important data.

Lee et al. [71], have presented an algorithm for Optimized QoS-Aware Placement of relay nodes (OQAP). Their algorithm uses a centralized greedy heuristics and selects to reduce the number of relay nodes required to establish a connected topology and meet the desired QoS requirements. In [72], the authors have investigated using cooperative communications for QoS provisioning in WSNs, and proposed a QoS support adaptive Relay Selection scheme for Cooperative Communications (QoS-RSCC). Sohrabi et al. [73], have used the sequential assignment routing algorithm to select which path to use for sending information to a sink node. They have assumed multiple that paths from each node towards the sink node are available. The authors have computed a QoS metric for each packet routed through the network. In [74], the authors have investigated the use of cooperative communications for QoS provisioning in resource-constrained WSNs. They have also proposed a Multi-agent Reinforcement Learning (MRL-CC) based cooperative communication protocol. Peng et al. [75], have proposed an adaptive QoS and energy-aware routing approach using an improved ant colony algorithm for WSNs to meet QoS

requirements in an energy-aware fashion, balance the node energy utilization to maximize the network lifetime.

2.7 Conclusions

There are numerous papers that address the issue of providing QoS in WSNs in general and providing delay timeliness for delay critical applications in specific. In this chapter a general overview of the state of the art was presented. The review was presented in such a way that the generality was not lost and the topic of the review remained within its confined area of delay and reliability at the same time.

Delay and reliability sensitive applications review of WSNs was presented for general WSN applications that require delay bounds. A critical review of the use of WSNs for smart grid applications was also presented.

Various publications that discuss cross layer approaches in WSNs exist in the literature. In this chapter, to narrow the scope of the review, QoS considerations in cross layer approaches were only considered.

MAC layer approaches for providing QoS in WSNs were widely considered in the literature. In this chapter, a general approach of important work present in this area was considered. Most of the work on MAC layer include protocol optimization to minimize packet collisions and to prioritize channel access in contention based protocols. In scheduling based protocols most of the work reviewed focus on priority based scheduling. In most cases, the use of MAC layer approaches were implemented in conjunction with cross layer schemes. Therefore the work reviewed on the use of MAC layer to provide QoS becomes very much incorporated with other topics presented in this review.

An overview of the state of the art of certain analytical models used to model the IEEE 802.15.4 protocol was presented where several well known analytical models were

addressed.

According to the reviewed material, routing protocols and techniques in WSNs are one of the main layers that are used to enforce QoS in delay critical applications. Therefore, the amount of work related to routing protocols in WSNs is highly diverse. However, since in this thesis, the the work focuses mainly on the MAC layer, no specific work on routing protocols for providing QoS was considered so that the generality of the review on QoS for WSNs is not lost.

In the following chapters more concise review related to the work addressed in this thesis is presented.

Chapter 3

Priority and Delay Aware Medium Access in WSNs

3.1 Introduction

WSNs are considered as potential tools for monitoring and controlling the smart grid. ZigBee-based WSNs are preferred for such applications due to their ability to work in extreme environmental conditions, in addition to having enhanced fault tolerance, low power consumption, self-configuration, rapid deployment and low cost. In environments where high voltages are in use, WSN can also provide necessary insulation.

Despite the advantages of WSNs, they have not been utilized extensively for monitoring critical smart grid assets. This is mostly due to the inherent limitations of WSNs in real-time data delivery. WSNs use low power communication links in dense deployments which introduces low data rates and delays in channel access.

The above mentioned challenges raise reliability concerns in the smart grid. In fact, reliable data delivery has been widely studied in the WSN literature where the term “reliable” generally refers to ensuring data to be delivered from source to destination or

sink. In the context of smart grid, reliability includes timeliness as well, since obsolete data or control signals may be even worse than having no data or signals. For instance, in a scenario where Plug in Hybrid Electrical Vehicle (PHEV) load management is coupled with the status of the electricity distribution system, delayed information regarding the status of the transformers in the substation, may result in unnecessary load control causing inconvenience for consumers, or worse risk, the stability of the grid. Meanwhile, it is also apparent that, not all of the collected data from the substations are significant in control actions. Some data are collected for general monitoring and records purposes and can be processed in a non-real-time manner. The significance of predictable reliability, timeliness and QoS in smart grid communications has been also outlined in the recent studies [76]. In addition, it is well-known that protocols designed in an application-specific manner improve the performance of the WSN [77, 78]. For this reason, the use of WSNs in the smart grid domain and their performance in terms of delay and QoS is considered.

In this chapter, three QoS schemes for WSNs are presented, these schemes aim to address data-prioritization and delay-sensitive data transmission for WSNs in the smart grid. The first scheme; Delay-Responsive, Cross layer (DRX) [79, 80]. The second scheme; Fair and Delay-aware Cross layer (FDRX) [81]. The third scheme is a Delay-responsive, Cross layer scheme with Linear back-off (LDRX) [82].

The main contributions of this chapter are to present novel QoS schemes and provide an exhaustive performance evaluation of these schemes in the smart grid environment and compare their performance to existing schemes. The performance of the presented schemes with different CCA detection methods; namely carrier sensing with energy detection and energy detection methods is evaluated. The impact of priority and delay awareness in medium access techniques on end-to-end delay, delivery ratio and energy

consumption of the WSNs are presented. The performance of the schemes is tested under deterministic and empirical path loss models. Additionally, the applicability of priority and delay aware medium access schemes in various smart grid applications including transformer monitoring, capacitor bank control and fault current indicator which have tight delay requirements are discussed.

3.2 Related Work

In the literature, several studies have proposed using WSNs for monitoring utility assets and power grid equipment [83, 84, 85, 86, 87, 88]. In [84], a WSN system has been proposed to monitor Partial Discharge (PD) activity in high voltage transformers where PD data was collected from individual sensors on the transformers and transmitted to the base station. In [85], the authors have discussed using wireless multimedia sensor and actor networks in various smart grid settings, including electricity production facilities, transmission and distribution system and customer premises. Employing WSN in customer premises for the purpose of pervasive demand response actions have been evaluated in [86].

The performance of WSNs in smart grid assets has been elaborated in [2, 87]. The study in [2], have presented an evaluation of the performance of WSNs in substations, underground transformer vaults and power rooms. The authors particularly focus the impact of noise on the low power wireless links that are being used by IEEE 802.15.4-based WSNs. Meanwhile, the impact of delay on smart grid applications has been initially investigated in [87], considering a WSN that is used for condition monitoring of a wind turbine.

Cross layer protocols have been studied in the general context of WSNs. In [89, 90], the authors have proposed a cross layer protocol to combine the functionalities of medium

access, routing, and congestion control and address receiver-based contention, congestion control, and duty cycling in WSNs.

Reducing the end-to-end delay of a WSN has been also studied for more general applications. In [91] the authors have proposed an adaptive BE management scheme for CSMA/CA of 802.15.4 and investigated its effects on power consumption of the node.

Besides generic delay reduction, QoS has also been studied in the literature where high priority sensor data are aimed to be forwarded with less delay or higher reliability. In [26], the authors have proposed an adaptive mechanism by implementation of the back off exponent management to reduce packet collision. DRX, FDRX and LDRX also use an adaptive mechanism but with different cross layer techniques as will be explained later in this chapter. In [92], the authors have presented a QoS support mechanism in beacon enabled mode using CSMA/CA back-off time. Furthermore, in [93], the authors have proposed a distributed algorithm that meets the application-specific reliability and energy consumption requirements. In [83], priority-based schemes to guarantee time-bounded delivery of high priority packets in event-monitoring networks have been proposed. In [83] the authors have proposed to reduce the number of CCAs performed in high priority nodes from two to one and perform frame tailoring to avoid collision. Different than [83], the DRX and the FDRX schemes implement an adaptive process in modifying CCA duration. Note that they do not modify the number of CCAs.

In addition, the impact CCA methods such as energy detection and preamble detection have been thoroughly investigated in [94, 95]. However, the impact of adaptive CCA duration has not been explored. DRX and FDRX basically aim to reduce the end-to-end delay by adaptively changing the duration of CCA of certain nodes and setting this parameter to default when prioritization is not required.

3.3 The IEEE 802.15.4 Analytical Model

DRX, FDRX and LDRX schemes rely on a Markov-based analytical model to estimate the expected end-to-end delay. In this section, a general analytical model for the slotted CSMA/CA mechanism of beacon enabled mode of the IEEE 802.15.4 [45] is briefly described. The model considers a star topology where all nodes in the PAN contend to acquire the channel and send data to the PAN coordinator. Accurate and approximate models are proposed in [45], both models solve a set of highly non-linear equations using numerical methods. The accurate analysis is found to be computationally demanding and is not suitable for use in sensor devices with limited resources. Therefore, the approximate model is considered for the implementation of the proposed QoS schemes. It is essential to mention here that, in this chapter, the analytical model of [45] is utilized to estimate the end-to-end delay which will trigger the operation of the prioritization and delay reduction schemes, in the next chapter a modified analytical model is presented which can be also implemented to estimate the delay in these schemes for increased accuracy.

A brief description of the model described in [45] (referred to as Park's model in the rest of this thesis) is initially provided. Park et al. have developed a per-node model based on Markov chain for a WSN operating with the slotted CSMA/CA algorithm. The network is further assumed to operate under acknowledged, unsaturated traffic conditions. The system is fully described by three stochastic processes, namely, the BO stage at time $t(s(t))$ the state of the BO counter at time $t(c(t))$, and the state of the retransmission counter at time $t(r(t))$. For the Markov chain to be applicable, nodes are assumed to start sensing the medium independently with a probability τ . With these assumptions in mind, a 3-dimensional Markov chain results Figure 3.1. The model can be described by the tuple $(s(t), c(t), r(t))$. Assuming the stationary distribution of the Markov chain to be $b_{i,k,j} = \lim_{t \rightarrow \infty} P(s(t) = i, c(t) = k, r(t) = j)$ where,

$i \in (-2, m)$, $k \in (-1, \max(W_i - 1, L_S - 1, L_C - 1))$, and $j \in (0, n)$, a closed form formulae is derived for this distribution chain. These derivations are lengthy, therefore they are not presented here, refer to [45] for full derivations. It is worth mentioning that to reduce the complexity of the resulting formulae, Park et al. have applied some approximations such that the final mathematical system becomes implementable on sensor nodes. Figure 3.1 shows the Markov chain model for CSMA/CA algorithm for IEEE 802.15.4.

The approximated formulae of Park's model that are related to derivations needed in the DRX, FDRX and LDRX are presented, and their importance is explain. According [45], the normalization condition of the Markov chain is given by the following equation:

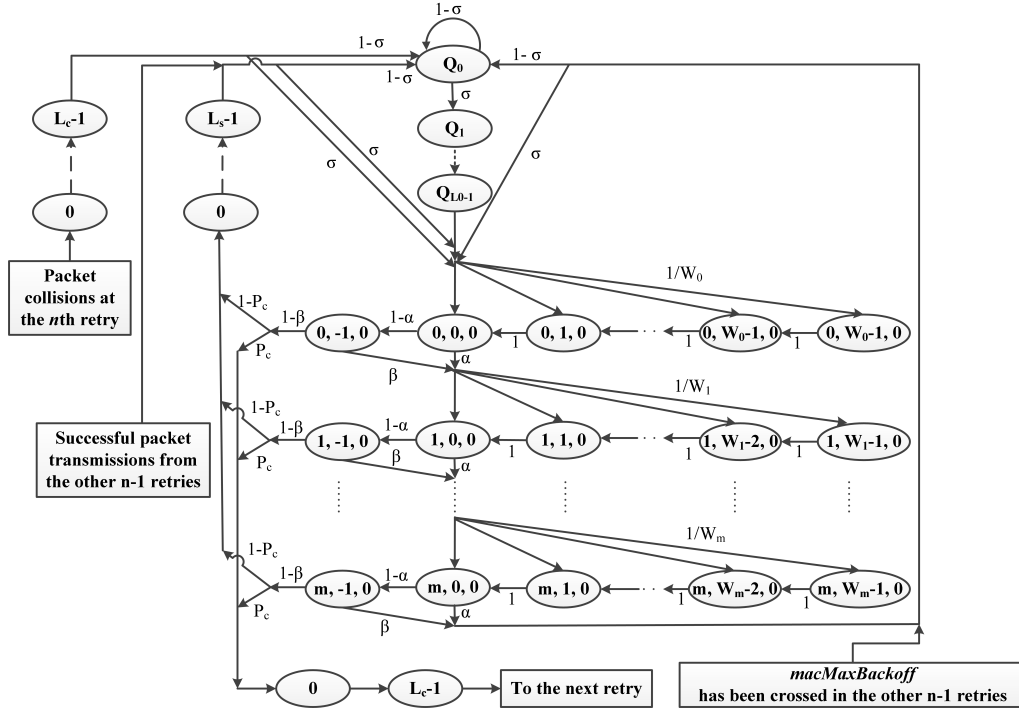


Figure 3.1: Markov chain model for CSMA/CA algorithm for IEEE 802.15.4.

$$\sum_{i=0}^m \sum_{k=0}^{W_i-1} \sum_{j=0}^n b_{i,k,j} + \sum_{i=0}^m \sum_{j=0}^n b_{i,-1,j} + \sum_{j=0}^n \left(\sum_{k=0}^{L_S-1} b_{-1,k,j} + \sum_{k=0}^{L_C-1} b_{-2,k,j} \right) + \sum_{l=0}^{L_0-1} Q_l = 1 \quad (3.1)$$

In Equation (3.1), the first term represents the probability of being in a BO state. The second term refers to the probability of initiating CCA2. The third and fourth terms refer to the packet transmission state and packet collision state, respectively. Finally, the fifth term refers to the probability of being in the idle state when no packets are available. By referring to Figure 3.1 and [45], each term in Equation (3.1) can be described as follows:

$$\sum_{i=0}^m \sum_{k=0}^{W_i-1} \sum_{j=0}^n b_{i,k,j} \approx \frac{b_{0,0,0}}{2} [(1+2x)W_0 + 1+x] (1+y) \quad (3.2)$$

$$\sum_{i=0}^m \sum_{j=0}^n b_{i,-1,j} \approx b_{0,0,0} (1-a)(1+x)(1+y) \quad (3.3)$$

$$\sum_{j=0}^n \left(\sum_{K=0}^{L_S-1} b_{-1,K,j} + \sum_{K=0}^{L_C-1} b_{-2,K,j} \right) \approx b_{0,0,0} L_S (1-x^{m+1})(1+y) \quad (3.4)$$

$$\sum_{l=0}^{L_0-1} Q_l \approx b_{0,0,0} \frac{1-\sigma}{\sigma} L_0 [1+y + P_c(1-x^{m+1})(y^n - y - 1)] \quad (3.5)$$

The approximate probability that a node start sensing the medium independently is given by [45]:

$$\tau \approx (1+x)(1+y)b_{0,0,0} \quad (3.6)$$

where,

$$x = \alpha + (1-\alpha)\beta \quad (3.7)$$

$$y = P_c(1-x^{m+1}) \quad (3.8)$$

From Figure 3.1 and [45], α is given by the following equation:

$$\alpha = LP_c(1 - \alpha)(1 - \beta) + L_{ack} \frac{N\tau(1 - \tau)^{N-1}}{1 - (1 - \tau)^N} P_c(1 - \alpha)(1 - \beta) \quad (3.9)$$

and β is given by the following equation:

$$\beta = \frac{P_c + N\tau(1 - \tau)^{N-1}}{2 - (1 - \tau)^N + N\tau(1 - \tau)^{N-1}} \quad (3.10)$$

finally, and P_c which is also defined as the probability that at least one of the $(N - 1)$ remaining nodes transmits in the same time slot [45], and is given by the following equation:

$$P_c = 1 - (1 - \tau)^{N-1} \quad (3.11)$$

where, W_0 is defined in the standard [5] to be $2^{macMinBE}$.

The state Q in Equations (3.5) and (3.1) is the idle state during which no packets are available for transmission. This state is modelled as Q_i (where $i = 0, 1, \dots, L_{0-1}$) to show that it has a duration specified by L_0 . Q_i models the unsaturated traffic condition.

By substituting Equations (3.2)-(3.5) into Equation (3.1) and using Equations (3.6) to (3.11) a system of non-linear equations is formed and by solving the system an expression for $b_{0,0,0}$ is found.

3.3.1 Performance Metrics

Three metrics are considered to study the performance of the model described in [45] for a WSN with star topology. These parameters are power consumption, reliability, and end-to-end delay. In this chapter the end-to-end delay is used in the operation of the QoS schemes.

Power Consumption

Following [45], the average power consumed in transmitting a packet (E_{tot}) is computed by summing the average power consumed during BO (E_{bo}), channel sensing (E_{sc}), packet transmission (E_t), idle state (E_Q), buffering (E_B), and wake-up (E_w). The power consumed in transmitting a packet from an end node is given by:

$$E_{tot} = E_{bo} + E_{SC} + E_t + E_Q + E_B + E_W \quad (3.12)$$

Each of the terms in equation (3.12) can be computed by knowing the probability of being at a certain state and the amount of average power consumed at that state. For example, if the node consumes an average power of P_{bo} during BO, then:

$$E_{bo} = P_{bo} \sum_{i=0}^m \sum_{K=0}^{W_i-1} \sum_{j=0}^n b_{i,k,j} \quad (3.13)$$

Note that in equation (3.12), since each transmitted packet should be followed by receiving an ACK, the power consumed during that process is considered to be a part of E_t (check [45] for more details).

Reliability

Reliability (R) is defined as the probability of successful packet reception. In slotted CSMA/CA, packets are discarded due to P_{cf} and P_{cr} . Channel access failure takes place when a packet fails to obtain idle channel in two consecutive CCAs within $(m+1)$ BOs. Furthermore, a packet is discarded if the transmission fails due to repeated collisions after $(n+1)$ attempts refer to Figure 3.1. Based on that, the reliability can be found as follows:

$$R = 1 - P_{cf} - P_{cr} \quad (3.14)$$

The same approximations Park et al. used to find R are adopted, the value of R can be given by the following equation:

$$R \approx 1 - x^{m+1}(1 + \tilde{y}) - \tilde{y}^{n+1} \quad (3.15)$$

where, $\tilde{y}$ is the approximated version of y and is given by:

$$\tilde{y} = (1 - (1 - \tilde{\tau})^{N-1})(1 - x^2) \quad (3.16)$$

and $\tilde{\tau}$ is the approximated version of τ

$$\tilde{\tau} = (1 + x)(1 + \tilde{y})\tilde{b}_{0,0,0} \quad (3.17)$$

R can be seen as a function of the busy channel probabilities α and β , the collision probability P_c and other MAC parameters [45].

End-to-End Delay

The average end-to-end delay for a successful pack transmission is defined as the duration from the instant the packet reaches the head of MAC layer queue until an ACK from the destination is received. If a packet is dropped due to either reaching the maximum BOs limits or the maximum retry limits, its delay is not included into the average delay. Similar to [45], the end-to-end delay (D) is resulting from the time spent in BO (D_{bo}) (which can be obtained from [45]), the time wasted due to experiencing j collisions (jL_C), and the time needed to successfully transmit a packet (L_S).

According to [45], the average approximated end to end delay is giving by:

$$\mathbb{E}[\tilde{D}] = \mathbf{P}^T \mathbf{D} \quad (3.18)$$

where,

$$\mathbf{P} = [Pr(A_0|A_t) \cdots Pr(A_n|A_t)]^T \in \mathbb{R}^{(n+1) \times 1} \quad (3.19)$$

The event A_j denotes the occurrence of a successful packet transmission at time $j + 1$ given j previous unsuccessful transmissions, whereas the event A_t denotes the occurrence of a successful packet transmission within n attempts [45].

Therefore based on [45],

$$Pr(A_j|A_t) = \frac{P_C^j (1 - x^{m+1})^j}{\sum_{k=0}^n (P_C (1 - x^{m+1}))^k} \quad (3.20)$$

after simplifications, we have,

$$Pr(A_j|A_t) = \frac{(1 - P_C(1 - x^{m+1}))P_C^j(1 - x^{m+1})^j}{1 - (P_C(1 - x^{m+1}))^{n+1}} \quad (3.21)$$

The value of D is given by: $D = [d_0 \cdots d_n]^T \in \mathbb{R}^{(n+1) \times 1}$ and $d_j = T_S + jT_C + (j + 1)\mathbb{E}[T]$ where, $\mathbb{E}[T]$ is the approximation of the average backoff period, and is given by:

$$\mathbb{E}[T] = 2S_b(1 + \tilde{P}^T \mathbf{T}) \quad (3.22)$$

according to [45] $\tilde{P}$ is given by

$$\tilde{P} = [\tilde{P}(B_0|B_t) \cdots \tilde{P}(B_m|B_t)]^T \in \mathbb{R}^{(n+1) \times 1} \quad (3.23)$$

where, $T = [t_0 \cdots t_m]^T$ and

$$\tilde{P}(B_i|B_t) = \frac{\max(\alpha, (1-\alpha)\beta)^i}{\sum_{k=0}^m \max(\alpha, (1-\alpha)\beta)^k} \quad (3.24)$$

according to [45] $t_i = [(2^{i+1} - 1)W_0 + 3i - 1]/4$. The approximation considers the worst case, i.e., a failure of the second sensing (CCA2), which implies that $T_{sc} = S_b$ and that each sensing failure takes $2T_{sc}$ [45].

Further approximation by not considering all the possibilities of busy channel during two CCAs.

Based on the above equations and on [45], the end-to-end delay can be obtained by the following equation:

$$D = L_S + jL_C + D_{bo} = (1 + j)L + D_{bo} \quad (3.25)$$

where

$$L_S = L + t_{ack} + L_{ack} + IFS \quad (3.26)$$

and

$$L_C = L + t_{ack-O} \quad (3.27)$$

In Equation 3.25, because approximate model is used, L_S is assumed equal to L_C .

3.4 Priority and Delay Aware Medium Access in WSNs

DRX and FDRX schemes aim to address data-prioritization and delay-sensitive data transmission for WSNs in the smart grid. DRX scheme [79] uses the application layer

data prioritization to control medium access of sensor nodes. DRX first performs delay estimation, if the estimated delay cannot meet the delay requirements of the smart grid application, then channel access of the node is fast-tracked by reducing CCA duration. FDRX [81] incorporates fairness into DRX. Similar to DRX, FDRX initially executes delay assessment, if the estimated delay is higher than the delay requirements of the application, then the node is given higher priority to access the channel. To provide fairness, a node periodically yields to other nodes in the PAN. Hence, FDRX provides fairness by periodically allowing other nodes in the PAN to contend fairly to access the channel. In this section, the DRX and FDRX schemes are presented. Comparisons with previously proposed QoS supporting mechanisms [26, 92, 83] are included. α_y of FDRX and different CCA durations of DRX are further evaluated.

3.4.1 DRX and FDRX Schemes

A WSN that aims to monitor and control delay critical data in a smart grid environment is considered as an example to implement the DRX and the FDRX schemes. The data collected by certain sensors are assumed to have high priority and should be delivered with minimum end-to-end delay.

Both the DRX and FDRX schemes include an adaptation module which facilitates the interaction of the application layer with the MAC and physical layers. They aim to reduce the end-to-end delay by estimating the delay of critical data, and then insuring that this data is delivered to the destination with minimum delay. Each node in the PAN initially implements the delay-estimation algorithm that estimates the expected delay based on the model described in Section (3.3). Thus, a node makes a decision based on the delay estimation algorithm, by making the MAC layer respond to specific delay requirement of the application.

If a node finds out that the estimated delay is higher than a predefined threshold τ_{TH} then the application layer places a flag in the application layer header indicating that lower layers should treat the packet accordingly. Thus, upon the arrival of those packets to the MAC layer, it requests the physical layer to make changes in its parameters.

In DRX, the MAC sub-layer requests the physical layer to reduce the CCA duration from 8 symbol periods to 4 symbol periods (i.e. from 128 μs to 64 μs). In doing so, the physical layer senses the channel in half of the regular CCA duration and reports the results to the MAC layer. Thus, this node can acquire the channel and transmit its data with higher probability compared to other contending nodes. If the node finds the channel busy, it invokes the BO algorithm as described in [5]. To avoid any possible coexistence problems, no devices are assumed to be transmitting at the same frequency band other than the IEEE 802.15.4 nodes. Algorithm 1 describes the DRX scheme, initially the application layer evaluates the captured data and decides if the level of the monitored parameter value Φ_M is beyond an acceptable threshold Φ_{TH} (i.e. higher or lower than normal limit values). These values can vary from one application to an other, in the smart grid, values of Φ_{TH} are taken from [96]). The algorithm invokes the delay estimation process $E[D]$. If the estimated delay is found to be higher than the threshold τ_{TH} value (different delay thresholds for different smart grid applications are obtained from [96] and used later in the performance evaluation section) then the CCA duration is divided by two, otherwise the algorithm does not make any changes to the physical layer parameters and transmits the data using regular CCA duration process.

FDRX includes an improvement to the DRX scheme. The DRX scheme aims to reduce the end-to-end delay without taking other nodes in the PAN into consideration. The proposed FDRX scheme can achieve the delay reduction and additionally allow other nodes to transmit fairly. Similar to the DRX scheme, the FDRX scheme initially

Algorithm 1 DRX Algorithm

```

//Measure the data//
if  $\Phi_M \geq \Phi_{TH}$  then
  // Invoke delay estimation algorithm //
   $E[D]$ 
  if  $E[D] \geq \tau_{TH}$  then
    // Insert a flag in the application layer header//
     $APP_{Header} = APP_{Header}^*$ 
     $CCA_{duration} = CCA_{duration}/2$ 
     $MAC - CSMA/CA()$ 
  else
     $CCA_{duration} = 8symbol durations$ 
     $MAC - CSMA/CA()$ 
  end if
else
   $CCA_{duration} = 8symbol durations$ 
   $MAC - CSMA/CA()$ 
end if
(Execute IEEE 802.15.4 CSMA/CA Algorithm)

```

implements the delay-estimation algorithm described in Section (3.3). Based on the resulting values of the delay estimation, the MAC layer responds to the delay requirement of the application. The main difference between the DRX and the FDRX schemes is that the latter yields to other nodes in the PAN periodically to allow them to transmit. Thus, FDRX is fairer to other nodes.

In the FDRX scheme, the MAC sub-layer requests the physical layer to reduce the CCA duration from 8 symbol periods to 4 symbol periods. This request is done based on a predefined duration (yielding intensity α_y). The value α_y varies from zero to one, zero means the node is not yielding to other nodes (corresponds to DRX) and one means that the node uses the default IEEE 802.15.4 MAC settings. The fairness property is added to ensure that a node only utilizes this scheme for a short period of time and then inverts back to default to allow other nodes to transmit.

3.4.2 DRX and FDRX Performance Evaluation

To evaluate the performance of the proposed schemes, the DRX and FDRX schemes are implemented with the QualNet [97] network simulator platform. The two schemes are tested with different number of nodes and traffic conditions. Furthermore, to investigate the performance of the DRX and the FDRX schemes in realistic smart grid environments, smart grid specific shadowing deviation and path loss properties are investigated. In addition to that, the simulation parameters are selected similar to that of the analytical model described in Section (3.3). A beacon enabled star topology having N nodes and a coordinator is used. Nodes are assumed to be operating in the 2.4 GHz band with a maximum bit rate of 250 kbps. All nodes are assumed to have Constant Bit Rate (CBR) traffic. Initially, one node is assumed to receives high priority packets during the simulation time. The transmission range is set to 20 m and all the nodes are in the same PAN. Each simulation is run for 300 seconds and each result represents an average of 10 runs. In the initial simulations, the delay threshold τ_{TH} is set to 0.400 second (following actual delay bound requirements presented in [96]). All nodes are assumed to transmit with sufficient power, (i.e. all nodes in the PAN can hear each other). The noise factor is assumed to be constant throughout the entire simulation. Table 3.1 shows the default parameters used in the simulations, the remaining parameters are taken from [5]. The performance of the presented schemes is compared with an existing QoS supporting scheme [92] in terms of end-to-end delay and the packet delivery ratio. The scheme presented in [92] reduces the BO duration of a contending node to make it BO for a shorter period then the rest of the nodes. The authors reduce the BO time by reducing the value of the BE. The results are also compared with [83] where the authors reduce the number of CCA performed in high priority nodes from two to one and perform frame tailoring to avoid collision. Throughout this thesis, the choice of the number of nodes is

Table 3.1: Initial Simulation Parameters

Parameter	Value
Transmission power (dBm)	3.5
Noise factor (dB)	10.0
Contention window	2
Packet size (Byte)	120
Beacon order	1
SF order	1

selected based on actual smart grid scenarios (i.e. the number of nodes vary from 10 to 50 nodes in most cases).

Figure 3.2 shows the relation between the average end-to-end delay and the number of nodes in the default IEEE 802.15.4 MAC settings, the Modified Back Off Time (MBOT) scheme of [92], the single CCA scheme [83], the FDRX and the DRX scheme. An obvious reduction in the end-to-end delay in the DRX scheme against the default IEEE 802.15.4 MAC settings and MBOT scheme is observed. Furthermore, there is a slight improvement in the delay when using DRX compared to the single CCA scheme [83]. The significance of this delay reduction is illustrated more clearly in a smart grid case study. The DRX scheme is seen to have higher impact on delay reduction compared to the FDRX ($\alpha_y = 0.5$) scheme, $\alpha_y = 0.5$ implies that FDRX is yielding 50% of the time. This higher delay reduction is because the DRX scheme allows the node to utilize the channel more often and does not share the resources with other nodes in the PAN. On the other hand, FDRX is considered to be fair because it yields-off to other nodes to allow them to transmit their data; hence it is observed that the delay reduction is less than the DRX scheme. The FDRX scheme performs slightly better than MBOT scheme.

Figure 3.3 shows the percentage of data packet received by the PAN coordinator (packet delivery ratio) from an individual node versus the number of nodes for the default IEEE 802.15.4 MAC settings, MBOT scheme, the single CCA scheme, the FDRX scheme

and the DRX scheme. The packet delivery ratio drops as the number of nodes increase since the number of collisions is proportional to the number of nodes in the PAN. As seen in the figure, the DRX scheme performs better than the default IEEE 802.15.4 MAC settings, the single CCA scheme and MBOT scheme. The FDRX scheme has slightly higher percentage of delivery ratio than the default IEEE 802.15.4 and MBOT scheme. Again, DRX performs better in terms of packet delivery ratio, because that node transmits at higher rate compared to other nodes in the PAN. The FDRX scheme comes next in terms of the packet delivery ratio because it is yielding to other nodes.

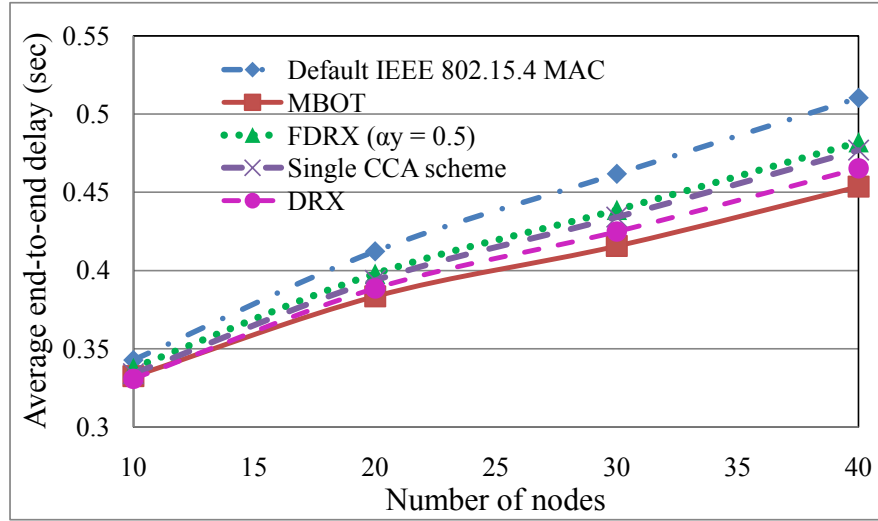


Figure 3.2: Average end-to-end delay of DRX and FDRX.

To show the effect of different CCA durations and why it is divided by two in the proposed schemes, the effect of reducing the CCA symbol duration on the average end-to-end delay is investigated. Figure 3.4 shows the effect of changing the CCA symbol duration from the default value to the DRX value. The average end-to-end delay starts to increase as the symbol duration increases. The results presented in Figure 3.4 assist in selecting an optimum value for the CCA symbol period that will minimize the end-to-end delay and maintain acceptable packet collision rate in the entire PAN. The effects

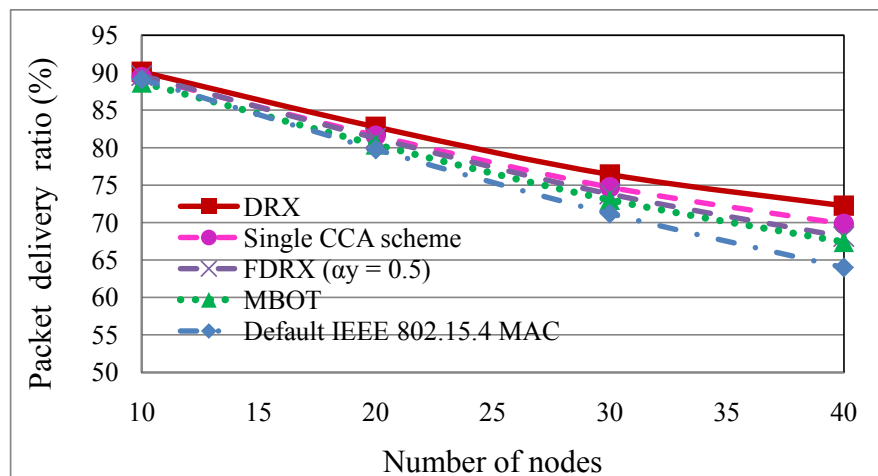


Figure 3.3: Packet delivery ratio of DRX and FDRX.

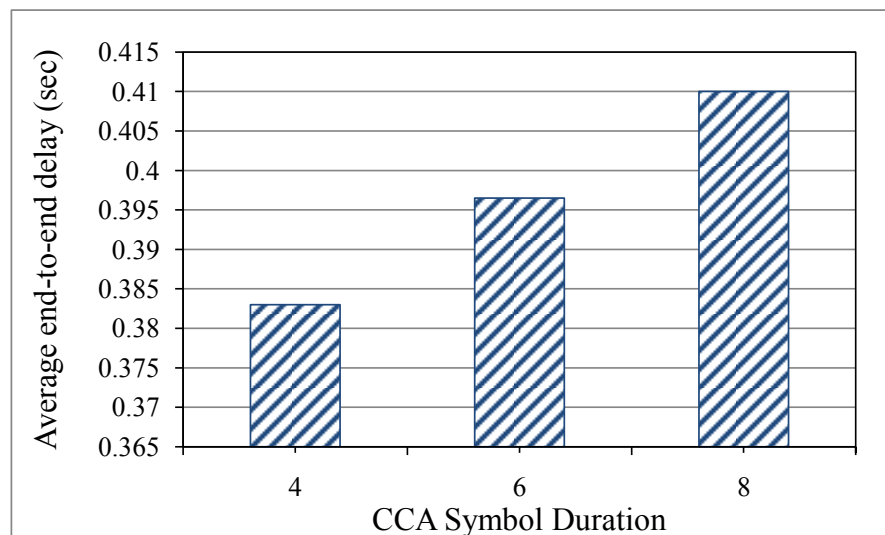


Figure 3.4: Effect of the CCA symbol duration on the average end-to-end delay.

of α_y of the FDRX scheme on the performance of the WSN is further investigated. This investigation assist in optimizing the value of α_y to obtain certain delay bounds, packet delivery ratio as well as packet collision rates. Figure 3.5 shows the effect of yielding intensity, α_y , on the average end-to-end delay of a particular node implementing the FDRX scheme. As α_y increase, the average end-to-end delay also increases for all

number of nodes. This is because when α_y approaches one the scheme converges to the default setting and as it approaches zero it converges to DRX. Hence, based on the application and the delay bound requirements, certain values of α_y which guarantees delay reduction and fairness at the same time are selected.

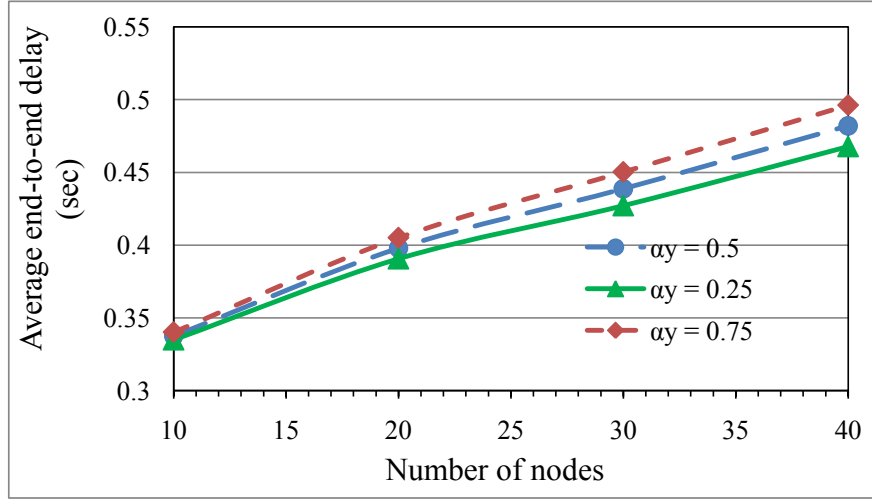


Figure 3.5: Effect of α_y on the average end-to-end delay.

Figure 3.6 shows the effect of α_y on the packet delivery ratio of a particular node implementing the FDRX scheme. The results presented in this figure agree with general behaviour of the FDRX protocol, i.e. as α_y increases the packet delivery ratio decreases. This is because the node implementing FDRX at lower α_y values will acquire the channel more often than the rest of the nodes and hence have a higher packet delivery ratio.

The effect of the DRX and FDRX schemes on the energy consumption of sensor nodes are studied. The energy model of the MicaZ nodes is assumed to be used. In Figure 3.7, the energy consumed in the transmit mode is slightly higher for DRX and FDRX schemes than the default settings since nodes implementing these schemes will have the opportunity to transmit more often than their neighbouring nodes. However, the increase in energy consumption is not significant (only 0.9%) compared to the increase

in the packet delivery ratio and the reduction in the end-to-end delay. The effect

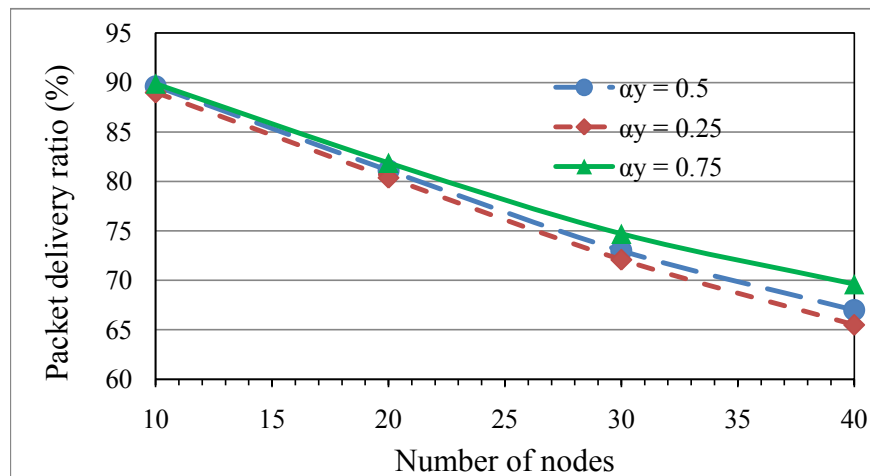


Figure 3.6: Effect of α_y on the packet delivery ratio.

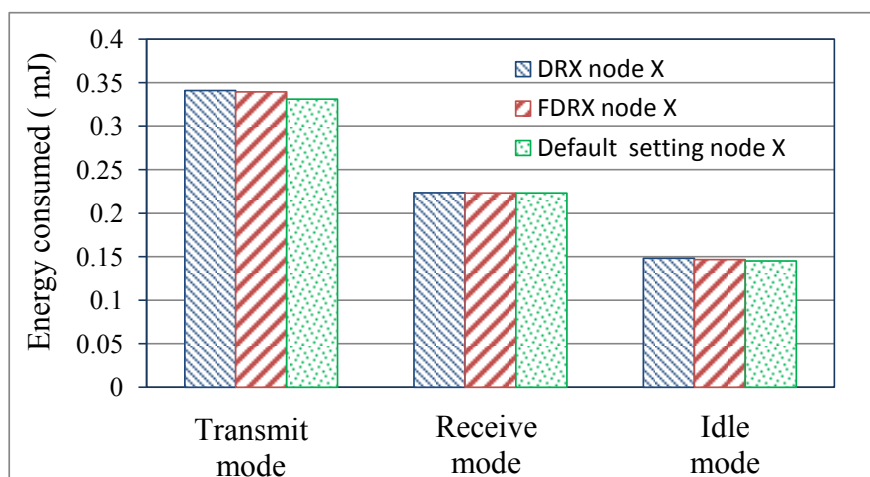


Figure 3.7: Energy consumption of DRX and FDRX.

of different α_y on the energy consumed in a node implementing the FDRX scheme is also investigated. The value of α_y can be adjusted according to the power requirements of individual nodes. Figure 3.8 shows the effect of α_y on the energy consumed in the transmission mode. Again, as α_y approaches 1 performance close to the default settings is obtained. In the previous set of results the effect of the DRX and the FDRX schemes on

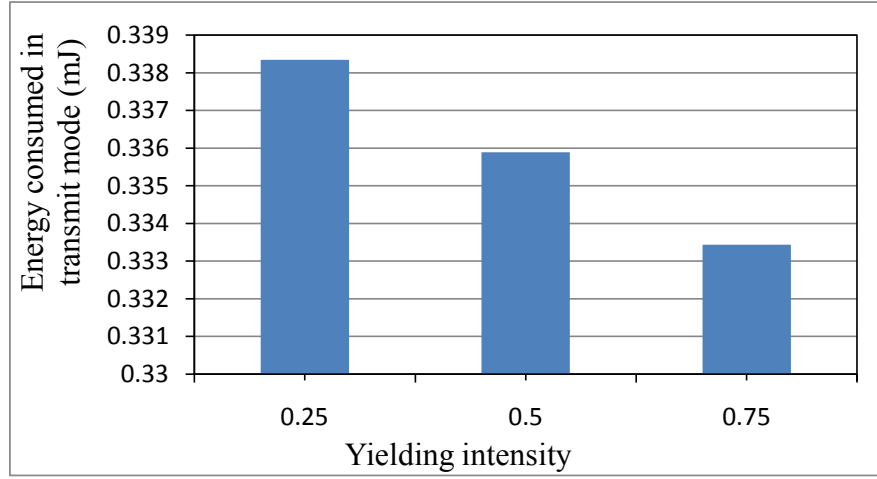


Figure 3.8: Effect of α_y on the energy consumed.

the performance of the node implementing these schemes is investigated. In the next set of results, the effect of implementing these two schemes on the overall WSN performance in terms of the number of packets being lost at the sink due to collision is tested. The same assumptions made in Section (3.5) are used. Furthermore, to have a wider perspective, the impact of two CCA methods; namely, CCA with energy detection and CCA with carrier sensing and energy detection on the network performance is compared.

Figure 3.9 shows the number of packets lost due to collision as seen by the PAN coordinator in the entire WSN. In this set of simulations, carrier sensing with energy detection method is used. As the number of nodes increase the number of packets lost due to collisions also increase, as expected. Furthermore, as the number of nodes increase the packets lost in the DRX scheme becomes higher than the default IEEE 802.15.4 MAC settings. This slight increase of packet lost due to collisions is experienced by nodes that do not implement the DRX scheme since they fail to have their data transmitted to the PAN coordinator due to packet collisions. In the worst case scenario when the number of nodes is 40 the difference in the number of packet lost due to collision at the PAN coordinator is approximately 6%. However, for lower number of nodes (10-20 nodes) the

difference between the packet lost due to collision is negligible. Figure 3.10 shows the

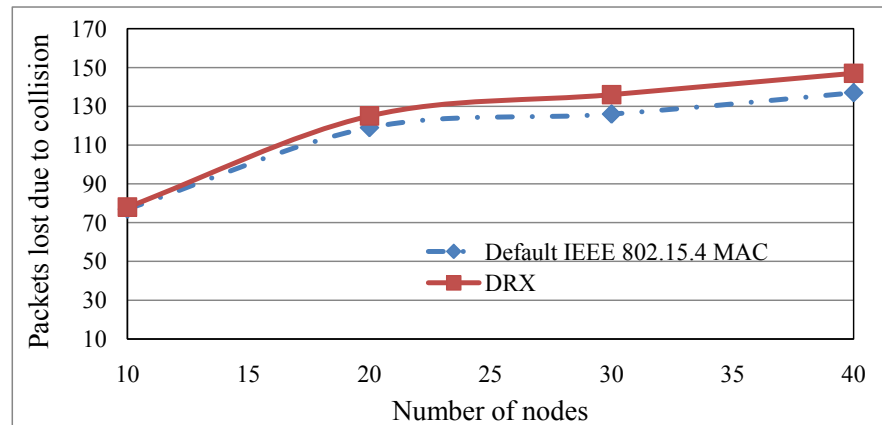


Figure 3.9: Packets lost due to collision in DRX using carrier sensing with energy detection.

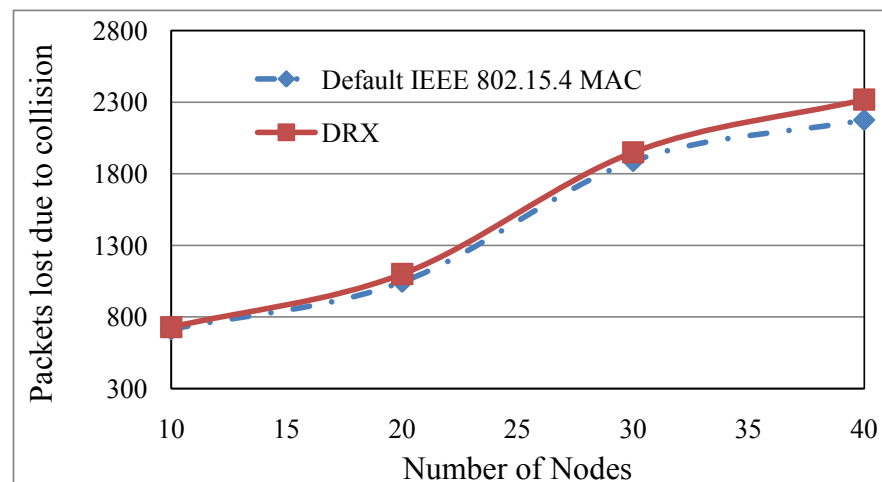


Figure 3.10: Packets lost due to collision in DRX using energy detection method.

number of packets lost due to collision at the PAN coordinator in the entire WSN. In this simulation, the energy detection method is used. As the number of nodes increase the packet loss also increases and the difference is negligible at lower number of nodes. However, the number of packets lost is very much higher than that of the carrier sensing

with energy detection method (Figure 3.9). This agrees with the theory explained in Appendix (A) and presented in [95].

Figure 3.11 and Figure 3.12 show the number of packets lost due to collision at the PAN coordinator in the entire WSN in the FDRX scheme for different yielding intensities with energy detection and carrier sensing methods, receptively. The trend of the results presented in these figures agree with the general results presented previously. It is worth to note that if the application requires certain bounds on the data delivery from the entire WSN, certain values of α_y can be chosen to maintain certain levels of packet collisions and end-to-end delay at the same time.

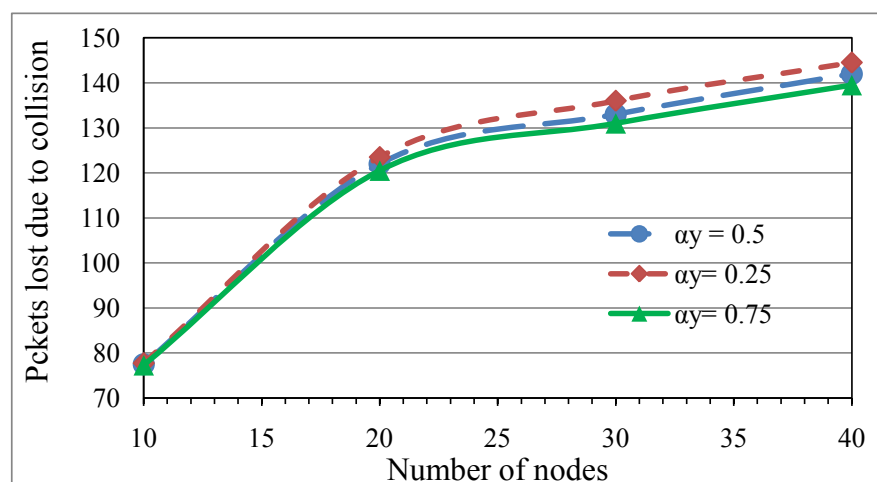


Figure 3.11: Packets lost due to collision in FDRX using energy detection method.

The performance of the DRX and the FDRX schemes in real smart grid environment is investigated by taking the effect of the path loss models in to consideration. The path loss is defined as the difference (in dB) between the transmitted power and the received power, which represents the signal level attenuation caused by free space propagation, reflection, diffraction and scattering.

There are three types of path loss models, namely, empirical models which are based

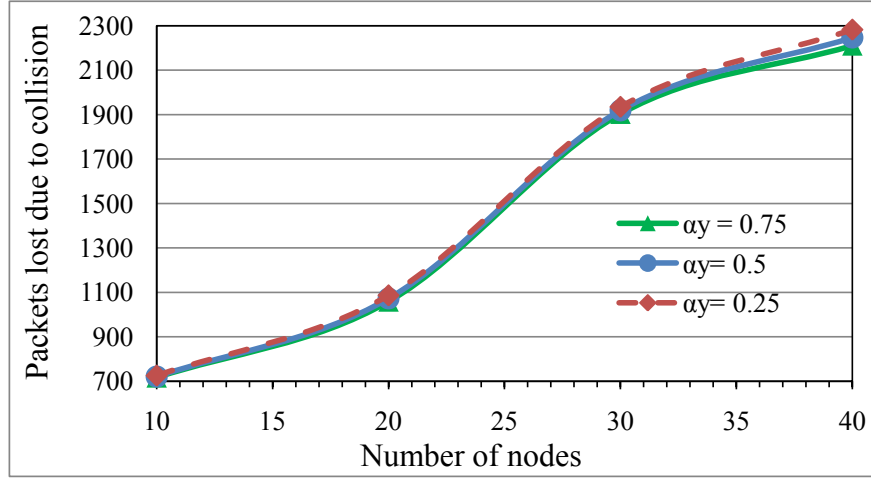


Figure 3.12: Packets lost due to collision in FDRX using carrier sensing with energy detection method.

on data measurement, deterministic models which depend on the geometry of the site and finally semi-deterministic models which are based on empirical models in addition to deterministic models. The performance of the DRX and FDRX schemes is investigated in both empirical and deterministic path loss models. For the deterministic path loss model, the two-ray path loss model is considered for an outdoor environment (i.e. transformers in a substation) where there is normally two signal path, one is direct from sensor node to the sink and the other is reflected through a metal object or through the ground. The other deterministic path loss model that is considered is the Telecommunication Industry Association/American National Standard Association (TIA/ANSI) Joint Technical Committee (JTC) path loss model for the Personal Communication Service (PCS) bands for indoor areas, recommended by a technical working group of the for 1900-MHz PCS bands [98]. The parameters for path loss calculations in the indoor as well as the outdoor environments are taken from [98].

For the empirical path loss model, the work presented in [2] is followed, where the authors have conducted experiments with actual sensor nodes operating in the 2.4 GHz

industrial, scientific and medical band with an effective data rate of 250 kbps. The work in [2] is performed to measure the Link Quality Indicator (LQI) and the Received Signal Strength Indicator (RSSI) with certain radio propagation parameters for different electric-power-system environments. Their experimental studies showed that their results provided more accurate multipath channel models than Nakagami and Rayleigh models. The DRX and FDRX schemes are simulated in similar environments to that of [2], namely, outdoor 500-kV substation environment, indoor main power room and underground transformer vault. The following values are used for channel propagation parameters; outdoor substation (path loss = 3.51, shadowing deviation = 2.95), indoor main power room (path loss = 2.38, shadowing deviation = 2.25) and underground transformer vault (path loss = 3.15, shadowing deviation = 3.19). The channel is assumed to have lognormal shadowing model with shadowing mean of 2.25 dB and all sensor nodes are operating in Non-Line of Sight (NLOS) mode.

Table 3.2 shows the number of data packets lost due to collision at the sink considering three different electrical power environments for the default settings, the DRX and the FDRX schemes. In this scenario, 15 nodes are used and overloaded the nodes with CBR traffic to test the scheme in extreme traffic conditions. The DRX and FDRX schemes outperforms the default IEEE 802.15.4 settings. The results for the JTC path loss model is close to the indoor empirical path loss model and that two ray model is somehow close to the outdoor 500-kV substation model for this simulation scenario.

3.4.3 Case Study

As a case study, three critical smart grid monitoring applications that have strict end to end delay requirements are considered. These applications are capacitor bank control, fault current indicator and transformer monitoring [96]. The functional requirements

Table 3.2: Data packets lost due to collision in different electric power environments

Path Loss Model	Propagation Environment	Default Set-tings	DRX	FDRX $\alpha_y = 0.5$
Empirical Model	Outdoor 500-kV substation	169	163	165
Empirical Model	Indoor main power room	165	159	162
Empirical Model	Underground transformer vault	162	160	160
JTC Model	Indoor commercial	163	158	159
Two-ray Model	Outdoor	172	166	167

for these applications are obtained from [96]. The performance of a WSN with priority and delay-aware medium access schemes are evaluated for those smart grid applications. For these set of results a WSN with 40 nodes in a star topology is considered where sensor nodes monitor certain parameters such as current or voltage and transmit their data to a PAN coordinator. The PAN coordinator is assumed to be connected to a high speed network e.g. Ethernet Passive Optical Network (EPON), hence the delay from the PAN coordinator to the user is negligible. The WSNs are simulated using the default IEEE 802.15.4 MAC settings, the DRX and FDRX schemes. In Table 3.3, the default IEEE 802.15.4 MAC setting has higher latency than the functional requirements of all applications, while both DRX and FDRX schemes succeed in reducing the latency below the functional requirements. DRX and the FDRX schemes are able to reduce the end to end delay by 60 ms and 35 ms respectively.

Table 3.3: End-to-end delay values for critical smart grid applications

Smart Grid Application	Functional Requirements (Min Latency)	Default Set-tings	DRX	FDRX $\alpha_y = 0.5$
Capacitor bank control	500 ms	510 ms	450 ms	475 ms
Fault current indicator	500 ms	510 ms	450 ms	475 ms
Transformer monitoring	500 ms	510 ms	450 ms	475 ms

3.5 LDRX Scheme

In this section, the LDRX scheme [82] is described. LDRX scheme addresses the delay and service requirements of the smart grid monitoring applications. The LDRX scheme is designed to operate in cluster-tree WSN topology which is suitable for monitoring large smart grid assets such as electrical substations or large installations as shown in Figure 3.13. LDRX scheme can easily be extended to cluster-tree topologies with any size and depth. The LDRX scheme is shown to have greater impact on delay reduction compared to the DRX and FDRX schemes.

It is important to mention that these schemes are implemented in a smart grid monitoring as an example of a delay critical application. These schemes can be implanted (without any modifications) in many other delay critical applications such as patient monitoring, military monitoring applications, industrial monitoring and etc.

The LDRX scheme achieves data prioritisation and delay reduction by modifying the IEEE 802.15.4 MAC and it operates as follows; the application layer checks the measured data and if it measured data triggers an alarm, the application layer marks the data frames with sequence of bits indicating high priority, Figure 3.14 shows a flowchart describing this process. Upon the arrival of the frames at the MAC sub-layer and at the edge of the BO period boundary the MAC sub-layer checks for the data priority as

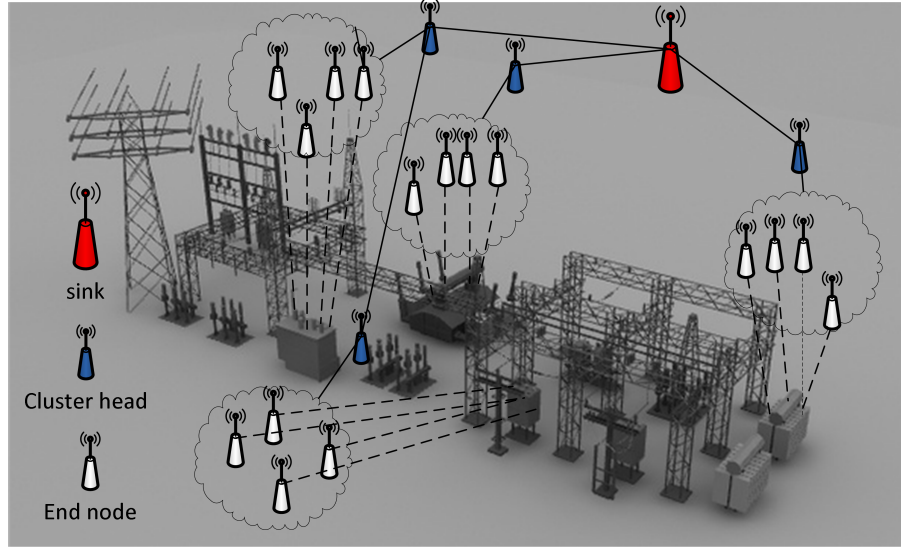


Figure 3.13: WSN-based substation monitoring proposed for LDRX.

shown in Figure 3.14. If the data is marked with high priority it initiates the LDRX schemes otherwise it uses the default IEEE 802.15.4 MAC. As in Figure 3.15, LDRX implements a random delay on a period from $[0 \text{ to } (2BE - 1)]$ instead of $[0 \text{ to } (2^{BE} - 1)]$. The linear back-off period is in any case shorter than the exponential back-off period. Based on this, the node with high priority data (referred to as “tagged node”) will exit the back-off period before other nodes in the PAN and start sensing the channel. Then the tagged node starts sensing the channel before other nodes and it does that in a shorter duration compared to other nodes (i.e. uses DRX on top of the LDRX). If the tagged node finds the channel idle it reduces the CW until it is zero and then transmits its packets. Otherwise it repeats the BO process until it reaches maximum number of BOs where it declares failure and drops its packets. It is essential to mention here that if all the nodes are allowed to use linear BO period then that will deteriorate the network performance especially when the number of nodes is high. This degradation of the performance is due to the limited linear BO interval which leads to having more nodes selecting the same BO interval and colliding during channel sensing.

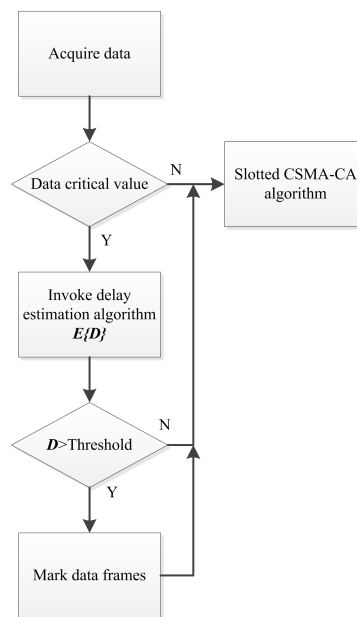


Figure 3.14: LDRX application layer process.

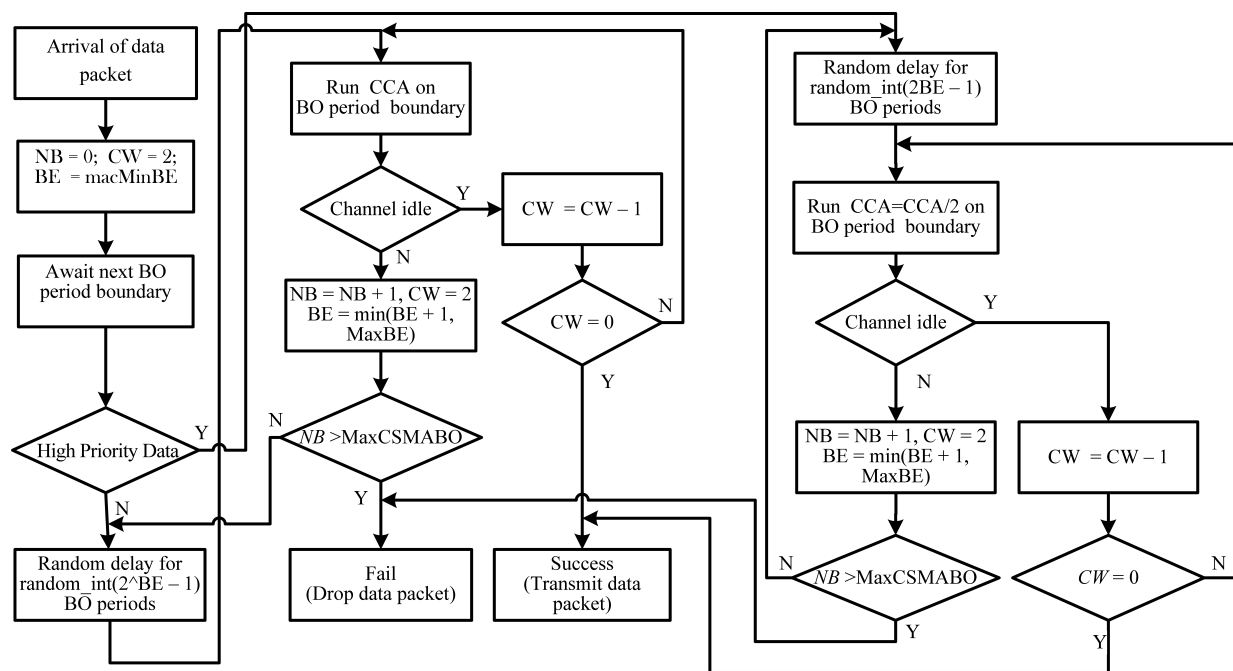


Figure 3.15: LDRX flow chart.

In LDRX the general analytical model for the slotted CSMA/CA mechanism of the beacon enabled mode of the IEEE 802.15.4 presented in Section (3.3) is also utilised to

estimate the end-to-end delay $E[D]$. However, the model described in [45] is proposed for a star topology. In this section, the delay estimation model is modified to make it suitable for a cluster-tree based WSNs.

3.5.1 The Proposed Scenario

A cluster-tree WSN is deployed to monitor number of transformers in a substation and transmit the measured data to a sink. This sink is assumed to be connected to a high speed EPON to provide a near real time monitoring and control access from remote locations.

A cluster-tree WSN topology is commonly used in situations where the extension of the communication range is needed. In a cluster-tree topology, the traffic generated at the sources (end nodes or leafs) flows towards the sink (root), through a series of intermediate nodes also known as Cluster Heads (CHs) or relays. In particular, each CH receives packets coming from a specific cluster of end nodes. For example, the scenario in Figure 3.13 is considered where a substation with a number of transformers is to be monitored with a WSN. The use of star WSN topology in this substation layout is not convenient since the transmission range of sensor nodes in a single hop WSN is limited to 10 to 20 m. As shown in Figure 3.13, multi-hop tree routing is used to transport data from the source node to the sink node. The function of CHs is to collect data from end nodes and forward it to the next level CH in the tree until the sink is reached. Furthermore, these CHs also forward traffic from other CHs in the direction of the sink. In a cluster-tree topology, the communication between CHs is done either based on contention or based scheduling. The latter is based on granting a minimum service guarantee all along the path through which the data is relayed where the CHs utilize the GTS of the CFP in the SF [5]. Note that not all CHs in the network can hear

each other (because they are placed far apart); therefore, the use of contention between CHs will lead to collision due to the hidden terminal problem. The CHs are chosen based on their location in the network and based on available resources. In the LDRX scheme, the following assumptions are followed:

- CHs communicate with each other using GTS duration; the time slot allocation is controlled by CHs to avoid beacon frame collisions [99].
- All end devices generate packets at the same rate and these devices use CSMA/CA scheme to transmit to their CHs (i.e. end devices use CSMA/CA in intra-CH communication).
- The traffic received by a CH in an upper level is equal to aggregate of traffic from CHs at lower levels.
- All CHs have an M/G/1/L queues, the difference between CHs is in the packet arrival rate.
- Every node in the network knows its location and knows how many hops it is away from the sink.
- The tagged packet leaves its the CH during the same SF.

To extend the delay estimation model of equation (3.25) to the cluster-tree topology, the above-mentioned assumptions are used. Equation (3.25) is used to estimate the delay from any end node to its CH. Since CHs are assumed to communicate with each other using the GTS and all end nodes know their locations then the delay between CHs is known to all the nodes in the network. Therefore the total end-to-end delay of any end node in the cluster-tree topology is assumed to be equal to the sum of the end-to-end delays along the path to the sink node. The total estimated end-to-end delay D_{total} is

dependent on the number of nodes in the local PAN and the location of that PAN in the tree, the value of D_{total} is given by the following equation:

$$D_{total} = D + \sum_{j=0}^{h-1} D_{int}j \quad (3.28)$$

h is equal to the number of levels from the end node for which the delay to be calculated to the sink. The delay between CHs as well as with the sink node is given by the following equation:

$$D_{int} = \sum_{j=0}^{h-1} [D_{prop}j + D_{sf}j] \quad (3.29)$$

D_{prop} is the propagation delay between CHs, its value depends on the channel bit rate and the packet length (L). D_{sf} is included to account for the delay of the packets in the next CHs when they miss the current SF due packet aggregation from lower level CHs.

In the cluster-tree topology where there is synchronization between CHs, no power is assumed to be consumed in (BO, channel sensing, and retransmissions). For simplicity, E_B and E_w are assumed to be equal to E_Q . The total power consumed is:

$$\tilde{E}_{tot} = E_{tot} + \sum_{i=0}^{h-1} [E_t i + E_Q i] \quad (3.30)$$

In the cluster-tree topology no packets are assumed to be lost in the transmission between CHs due to the employed synchronization and beacon collision avoidance mechanisms. Hence, the reliability from the low level CHs to the parent CH is 100% (i.e. the total reliability of the cluster-tree network is equal to R).

3.5.2 LDRX Performance Evaluation

To evaluate the performance of the LDRX scheme the network scenario presented in Figure 3.13 is simulated using QualNet simulator. It is initially assumed that there are 10 nodes in each cluster and there are 4 clusters with 4 CHs and a single sink node at the control room. The clusters could be 2 hops or 1 hop away from the sink. All sensor devices operate in the 2.4 GHz band with data rate equal to 250 kbps, sensor nodes are assumed to generate traffic with Poisson distribution. For increased accuracy, simulations are run for 300 seconds and an average of 10 simulation runs is taken. All nodes within a cluster use CSMA/CA to gain access to the medium. All nodes within a cluster are assumed to transmit with sufficient power, which means that all nodes in a single cluster can hear each other.

Figure 3.16 shows the analytical and simulation results of the end-to-end delay as a function of the traffic generation rate for the default IEEE 802.15.4 MAC and the LDRX scheme. The number of nodes in a single cluster is varied to investigate the performance of LDRX scheme for different cluster sizes. There is a significant reduction in the end-to-end delay when LDRX scheme is used for all traffic and network conditions. Simulation and analytical results of the LDRX scheme agree for all packet generation rates.

Figure 3.17 shows the analytical and simulation results of the end-to-end reliability as a function of traffic generation rate and for different number of nodes in a single cluster for the default IEEE 802.15.4 MAC and the LDRX scheme. The reliability drops from 100% (for 30 nodes) as the traffic rate increase. This happens because more nodes within a single cluster are contending to transmit their data thus leading to more collisions. In addition, there is no significant change in the reliability between the two schemes (i.e. the default IEEE 802.15.4 MAC and the LDRX). Simulation and analytical results of the LDRX scheme agree for all packet generation rates. This is a good indication

that our proposed scheme succeeds in reducing the delay without affecting the system performance.

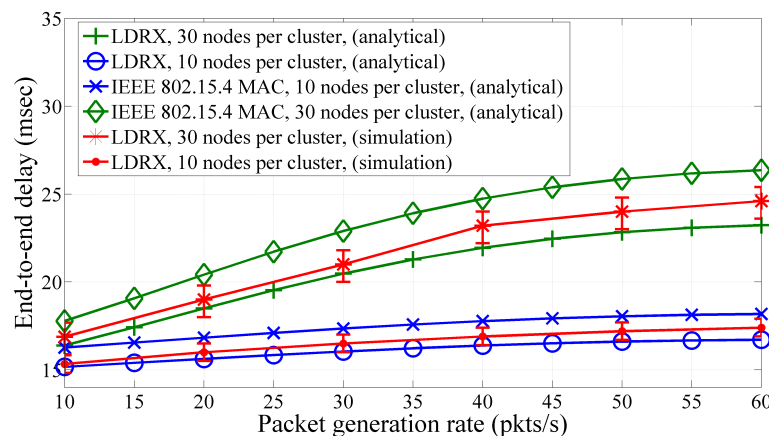


Figure 3.16: LDRX end-to-end delay.

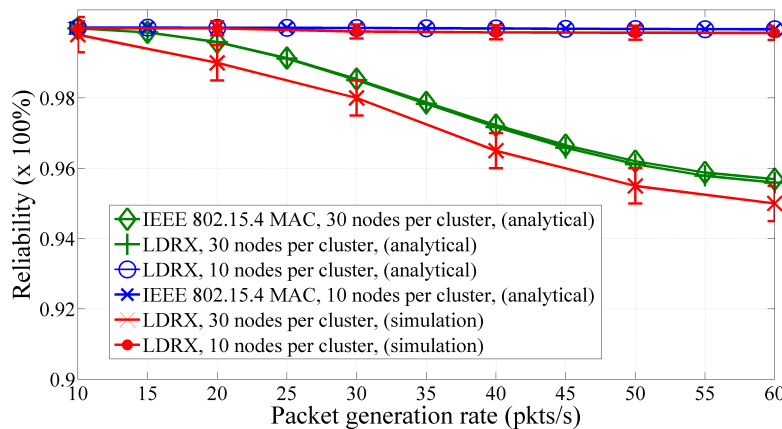


Figure 3.17: LDRX end-to-end reliability.

Figure 3.18 shows the analytical and simulation results of the total power consumed by a single node as a function of the traffic generation rate for different number of nodes in a single cluster. As the packet generation rate increases the power consumed in transmitting a single node increases. Furthermore, a node implementing the LDRX scheme does not have a difference in the power consumed when compared to a node

implementing the default IEEE 802.15.4 MAC setting. This shows that LDRX does not increase power consumption while reducing end-to-end delay. The simulation and the analytical results of the LDRX agree for all traffic conditions.

Figure 3.19 shows the simulation results of the end-to-end delay against the percentage of nodes generating high priority traffic in a single cluster for different cluster sizes. As the percentage of nodes generating high priority traffic increases the end-to-end delay increases in a linear fashion for all cluster sizes. This increase in the end-to-end delay is expected since higher number of nodes tries to utilize the LDRX scheme as they generate high priority traffic which leads to higher number of collisions and thus reducing the delay. However, in the worst case scenario when all the nodes (100% of the nodes) generate high priority traffic the end-to-end delay reaches its maximum values, which is the end-to-end delay of the default IEEE 802.15.4 MAC protocol.

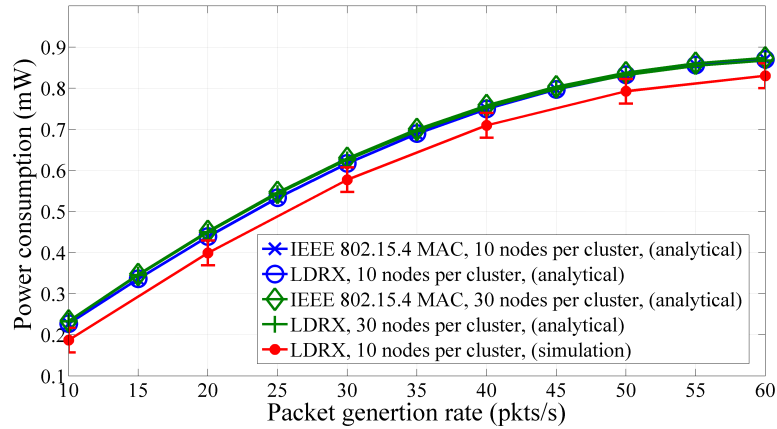


Figure 3.18: LDRX total power consumed.

Figure 3.20 shows the simulation results of the end-to-end delay of the LDRX, DRX and FDRX schemes for different traffic generation rates. The LDRX scheme outperforms the DRX and FDRX schemes for all traffic rates, this shows that LDRX is more suitable than previously proposed WSNs QoS schemes in reducing the end-to-end delay and

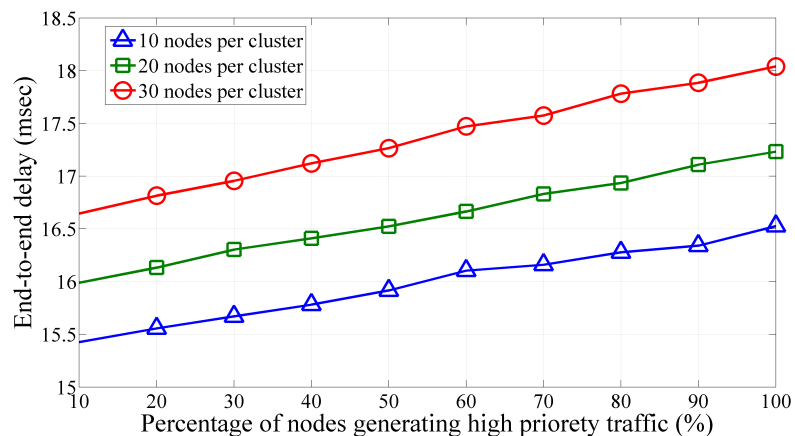


Figure 3.19: Number of nodes generating high priority traffic.

providing service differentiation to high priority traffic.

In Figure 3.21, both the number of nodes per cluster and the packet generation rate are varied, the end-to-end delay for both the LDRX scheme and the default IEEE 802.15.4 MAC is observed. Analytical results show that the LDRX scheme outperforms the default IEEE 802.15.4 MAC protocol for all cluster sizes and traffic conditions.

Figure 3.22 shows the channel utilization for different number of nodes in a cluster and for different packet generation rates. Analytical results show that the channel utilization does not significantly change when a node implements the LDRX scheme and the default IEEE 802.15.4 MAC protocol.

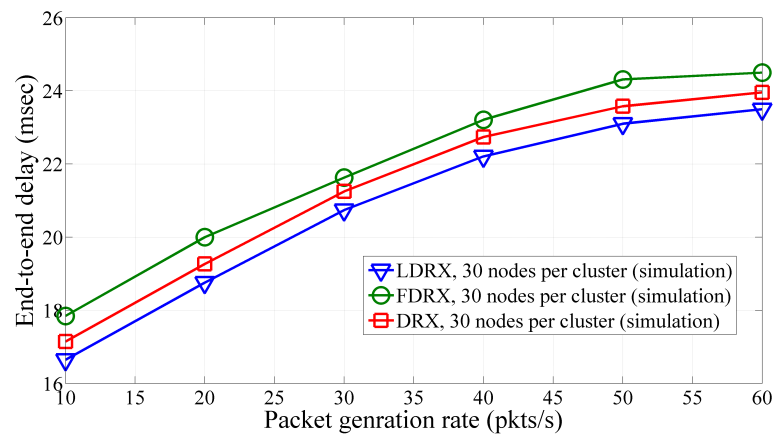


Figure 3.20: LDRX vs. DRX and FDRX.

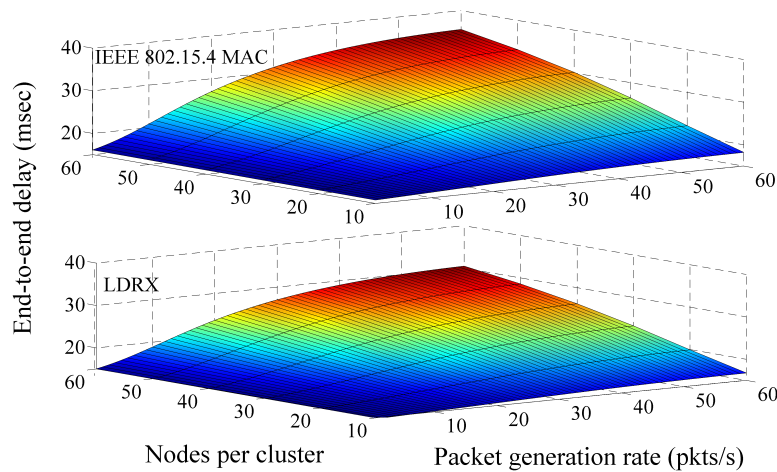


Figure 3.21: LDRX end-to-end delay versus cluster size and packet generation rate.

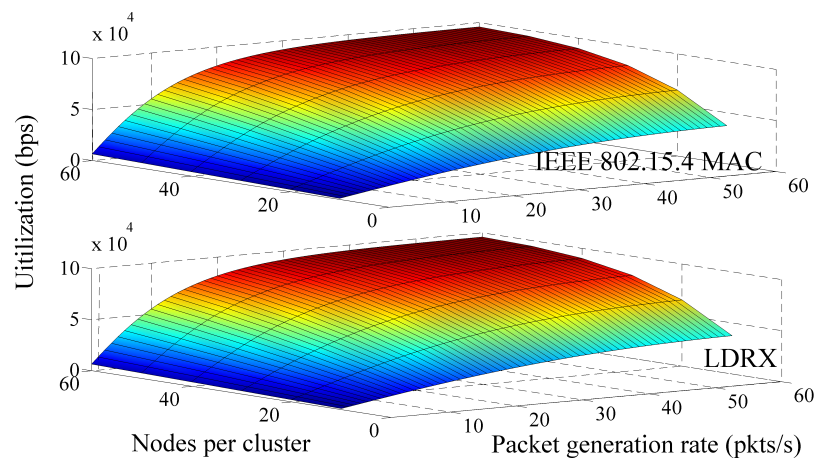


Figure 3.22: LDRX utilization versus cluster size and packet generation rate.

3.6 Conclusions

In this chapter, priority and delay-aware medium access techniques that respond to the delay requirements of smart grid applications by predicting the end-to-end delay and creating cross layer measures were presented and evaluated. These schemes achieved delay-responsiveness by modifying the parameters of the physical layer of the IEEE 802.15.4 protocol.

The first scheme, namely, DRX, first estimates the end-to-end delay. If the packet is from a critical smart grid application that has high priority and if the estimated delay cannot meet the delay requirements of this application, then DRX reduces the CCA duration, in order to allow the high priority packet to access the medium before other contending packets. The second approach, FDRX, incorporates fairness into delay-sensitive data transmission by yielding other nodes periodically.

A delay mitigation scheme was also presented for general WSN-based monitoring applications. The proposed scheme, namely, LDRX, is tailored for a WSN with cluster-tree topologies which is suitable for monitoring assets distributed over wide spread locations, such as monitor a number of transformers in a substation. The cluster-tree topology is the best topology suitable for monitoring large areas with metal structures or multiple buildings or obstacles due to transmission range limitations and path loss factors of ZigBee based WSNs.

Simulation and analytical results showed that the DRX, FDRX and LDRX schemes adaptively reduced the end-to-end delay of high priority data packets while maintaining constant reliability and power consumption compared to the default IEEE 802.15.4 MAC protocol. Results also showed that in the worst case scenario (i.e. when all the nodes in the cluster generate high priority traffic), the LDRX can perform as good as the default IEEE 802.15.4 MAC protocol. Finally, the LDRX scheme is shown to out performs the

DRX and FDRX schemes.

The delay reduction achieved by DRX, FDRX and LDRX enhance the smart grid operation in situations where sudden changes in loads or the generation cycle take place. The performance of DRX and FDRX schemes were further evaluated by taking shadowing and path loss of actual electric power systems into consideration. The results of this evaluation showed that the DRX and the FDRX outperformed IEEE 802.15.4 with the default settings in the considered smart grid environment. A case study was presented to show the effectiveness of the DRX and the FDRX schemes in reduction of the latency of actual smart grid functional requirements.

In the next chapter an analytical model for WSN with star and cluster-tree topologies is presented. The model introduces improvements to Park's model used in this chapter.

Chapter 4

A Realistic and Stable Model for IEEE 802.15.4

4.1 Introduction

Using WSNs for monitoring and controlling smart grid assets require careful design of QoS provisioning models due to the delay and reliability-sensitive nature of the collected data [100]. Certain smart grid monitoring applications require a WSN that can handle high traffic volumes over a broad area. Providing QoS support to critical WSN monitoring applications is a challenging issue due to the highly resource constrained nature of sensor nodes, unreliable wireless links and harsh operation environments.

Choosing optimum network parameters to achieve certain QoS guarantees requires a precise and realistic analytical model that takes into consideration the factors that control the delay, throughput, and power consumption of the WSNs. In the past few years, several publications focused on QoS-aware protocol design in the smart grid [101, 102, 103, 104]. Furthermore, several models with different mathematical approaches have been proposed to describe the performance of WSNs under certain traffic conditions

[64, 45, 62, 55, 47, 105]. Some of these analytical models become too complex and impractical in the resource-constrained sensor nodes [62, 55, 47]. On the other hand, other models tend to use approximations that lead to inaccuracies in the model itself by not considering certain important factors such as traffic patterns. In addition to that, few of those models tends to address QoS provisioning for delay and reliability critical monitoring applications.

In this chapter, a Realistic and Stable Markov-based (RSM) model is presented for an IEEE 802.15.4-based WSNs [106]. The model addresses the inaccuracies in previous analytical models, and addresses issues that were not covered previously in this context. Smart grid calls for WSN deployments in large scale installations where star topology becomes inefficient. WSNs can be extended for a larger coverage via cluster-tree or mesh topologies. It is not straightforward to use the analytical model of a star topology [106] or other available models to cluster-tree WSNs. In [107] the model of [106] is extended to contention-based cluster-tree WSNs. The use of contention based cluster-tree topology requires that all the nodes in network hear each other to avoid collision and packet loss. However, the use of WSNs for smart grid applications may require positioning the nodes in clusters that are far apart, hence, contention based schemes may not work well due to the hidden terminal problem.

In this chapter, an RSM model for the IEEE 802.15.4 MAC protocol is presented. The model includes star topology as well as contention based and schedule-based cluster-tree topologies. Furthermore, comprehensive performance evaluations is performed for all of the proposed topologies under different traffic and network conditions that are suitable for smart grid applications. In addition to that, a SF structure is proposed, the SF structure is suitable for the presented QoS model and the proposed application. Furthermore, the accuracy of the presented model is investigated by performing simulations

in environments that are consistent with the analytical model and mimic the electrical substation environment.

The main contributions of this chapter are developing a Markov chain-based QoS model for star and two cluster-tree WSN topologies that can be widely deployed in smart grid environments and performing comprehensive performance evaluations while considering realistic traffic generation patterns that are suitable for monitoring applications in the smart grid.

4.1.1 Related Work

Markov-based performance evaluation of the IEEE 802.15.4 MAC sub-layer has been presented in several studies. The majority of these studies are based on the model derived in [44]. The work presented in [44] has assumed saturated traffic conditions; which makes this model an unrealistic WSN situation. Later studies, for example [62, 55] and [108] have solved the saturation traffic model problem by modelling the IEEE 802.15.4 MAC with unsaturated traffic conditions.

In [45], the authors have presented a generalized model for the IEEE 802.15.4 MAC sub-layer. The authors proposed certain approximations in their formulation of the delay, reliability and energy consumption. The work presented here is differentiated from [45] by considering the idle state, traffic arrival and packet buffering at the MAC sub-layer. The work presented in [45] has proposed an idle state duration (L_0) which is a variable that governs the model performance. In realistic WSN applications, the idle state duration, cannot be quantified easily. Thus, the model presented in this chapter does not depend on this parameter. Another major difference is that the model presented in this thesis is designed to be less dependent on the network traffic conditions by including the effect of a finite buffer at the MAC-layer. This feature makes the model more stable even

when the traffic changes its pattern. Furthermore, in [109], the authors have presented a model for the IEEE 802.15.4 MAC sub that models and optimizes the performance of a single hop star WSN. They have also interoperated packet copying delay due to hardware limitations in to their model. The effect of a finite MAC buffer is also modelled in the RSM model. However, a different approach is followed in deriving and describing those buffers in chapter. This work is differentiated by eliminating the idle state duration and presenting the model for two types of cluster-tree topologies.

In [108], the authors have used a Markov-based model to analyse the characteristics of the IEEE 802.15.4-based WSN in terms of packet delay, energy consumption and throughput under unsaturated, unacknowledged traffic conditions.

In [110] the authors have proposed an optimization tool that applies some classical operative research instruments to a Markov-chain based model. They have showed that their technique was suitable for the performance analysis of a generic cluster-tree IEEE 802.15.4-based network. In this proposed model, power consumption optimization is specifically considered while considering the effect of both packet arrival rate and the MAC-level finite buffer. Furthermore, in [110], the power consumption metric has not been considered. In addition, the model proposed has assumed certain approximations to the traffic generation pattern which makes their model lose its generality.

In [111], the authors have studied the delay performance in a WSN with a cluster-tree topology. They have proposed a heuristic scheme to find the time-line allocations of all the CHs in a WSN in order to achieve the minimum and balanced packet drop rate for traffic originated from different levels of the cluster-tree.

The use of reliable and timely WSNs for industrial applications has been discussed in [112, 113, 114, 115, 80, 79]. Furthermore, QoS provisioning in smart grid monitoring application has been discussed in [79, 86, 26, 81]. The performance of wireless commu-

nication technologies for WSNs has been compared in [116] and IEEE 802.15.4 has been found satisfying performance for indoor scenarios.

4.2 The Realistic and Stable Model

In this section a mathematical model for star-based and cluster-tree based WSN topologies is presented. The model for the star topology is initially described and then the extension for two cluster-tree topologies is discussed and finally the performance of each model is investigated. All of the three models follow the following assumptions:

- All of the nodes in the WSN operate in the beacon-enabled mode of IEEE 802.15.4 protocol.
- Packets arrive at the MAC sub-layer with an arrival rate of (λ packets per second (pkts/s)) with Poisson distribution. The arrival rate is assumed to be the same for all end nodes.
- The MAC-level ACK packets are used to increase the reliability.
- In the star topology, the coordinator node is the sink while in the cluster-tree topology the root node is the sink.
- A single packet fits into the SF period. That is, a packet should be delivered to the coordinator or to the next hop in one transmission round.
- In both the star and cluster-tree topologies, all nodes have M/G/1/L queues and the buffer available at each node is assumed to be of a First In First Out (FIFO) type with no flow priority. Furthermore, the packet processing time in the buffer is negligible.

4.2.1 Star Topology

The modifications to the model in [45] (Park's model) are described. A brief description of Park's system model analysis was presented in Chapter 3. The improvements for the star topology are discussed here and the modifications for the two cluster-tree topologies are presented next.

The derivation of the RSM model begin with Equation (3.1) which is the normalization condition of the Markov chain. According to [45], a node remains in the idle state when no packets are generated. The node remains in the idle state for a period of L_0 before checking the availability of packets. That is, even if a packet is available, a node does not leave the idle state before having the L_0 period elapsed. Sending the packets every L_0 is considered to be as unrealistic as it does not resemble real WSN situations. Therefore, it is proposed that the node should leave the idle state whenever a packet is generated. In addition to that, the effect of a MAC layer finite buffer is added in the model. The buffer is modelled in Figure 4.1 by the B_i ($i = 0, 1 \cdots D_{0-1}$) states. The model in this figure shows that Equation (3.1) should be updated as follows:

$$\sum_{i=0}^m \sum_{K=0}^{W_i-1} \sum_{j=0}^n b_{i,k,j} + \sum_{i=0}^m \sum_{j=0}^n b_{i,-1,j} + \sum_{j=0}^n \left(\sum_{K=0}^{L-1} b_{-1,K,j} + \sum_{K=0}^{L-1} b_{-2,k,j} \right) + Q + \sum_{l=0}^{D_{0-1}} B_l = 1 \quad (4.1)$$

It is assumed that $L_S = L_C = L$. The first three terms in Equation (4.1) are similar to the first three terms in Equation (3.1). The forth term of Equation (4.1) represents the RSM idle state and is derived as follows:

By referring to Figure 4.2 and Equation (3.5), the probability of being in the idle state is derived as follows: By examining the first state Q_0 in Park's model we have:

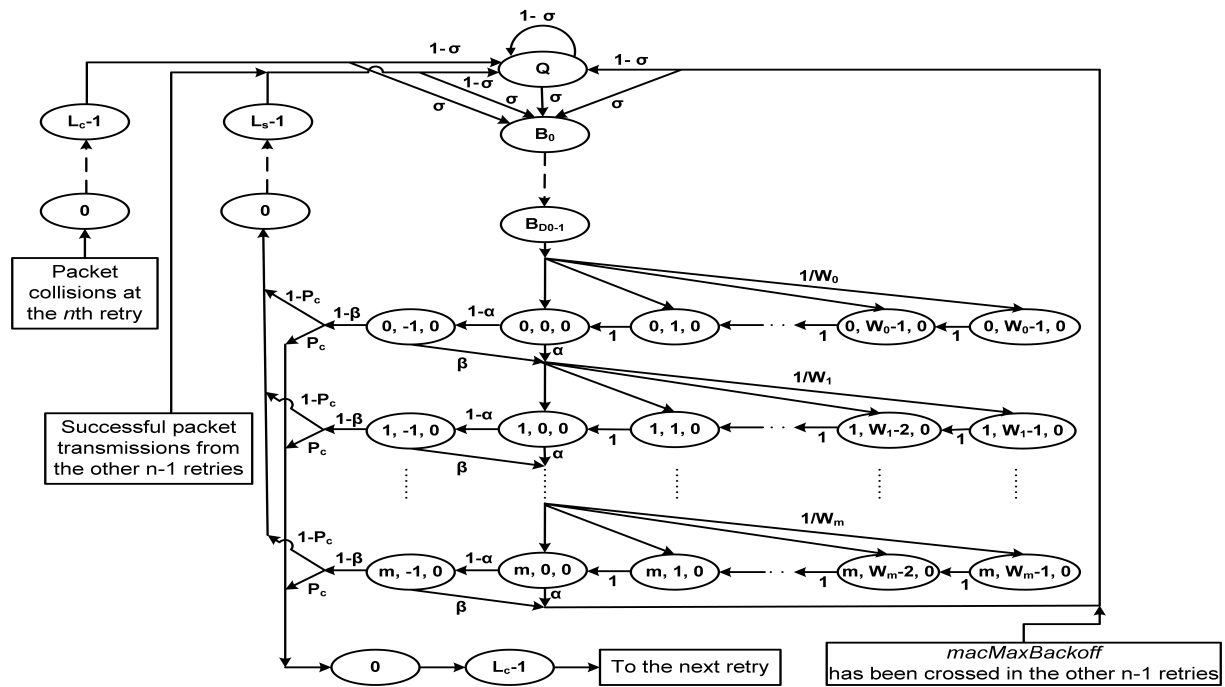


Figure 4.1: RSM Markov-based model

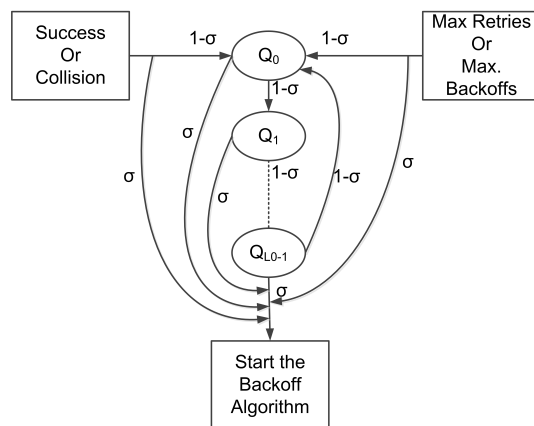


Figure 4.2: Modelling the idle state in RSM.

$$Q_0 = (1 - \sigma)Q_{L_0-1} + (1 - \sigma) \left[\sum_{j=0}^n (\sigma + (1 - \sigma)\beta)b_{m,0,j} + \sum_{i=0}^m P_c(1 - \beta)b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1 - P_c)(1 - \beta)b_{i,-1,j} \right] \quad (4.2)$$

By referring to Figure 4.2, the following equation is generated:

$$Q_1 = (1 - \sigma)Q_0 \quad (4.3)$$

and

$$Q_2 = (1 - \sigma)Q_1 = (1 - \sigma)^2Q_0 \quad (4.4)$$

From Figure 4.2 we have got,

$$Q_{L_0-1} = (1 - \sigma)Q_{L_0-2} \quad (4.5)$$

Therefore,

$$Q_{L_0-1} = (1 - \sigma)(1 - \sigma)Q_{L_0-3} = (1 - \sigma)^2Q_{L_0-3} \quad (4.6)$$

From Figure 4.2 and generalizing the relation for Q_{L_0-1} , the following relation is obtained:

$$Q_{L_0-1} = (1 - \sigma)^{L_0-1}Q_0 \quad (4.7)$$

From Equation 4.2, the following equation is obtained:

$$Q_0 = (1 - \sigma)[(1 - \sigma)^{L_0-1}Q_0] + (1 - \sigma) \left[\sum_{j=0}^n (\sigma + (1 - \sigma)\beta)b_{m,0,j} + \sum_{i=0}^m P_c(1 - \beta)b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1 - P_c)(1 - \beta)b_{i,-1,j} \right] \quad (4.8)$$

solving for Q_0 ,

$$Q_0 = (1 - \sigma)^{L_0} Q_0 + (1 - \sigma) \left[\sum_{j=0}^n (\sigma + (1 - \sigma)\beta) b_{m,0,j} + \sum_{i=0}^m P_c (1 - \beta) b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1 - P_c) (1 - \beta) b_{i,-1,j} \right] \quad (4.9)$$

and

$$Q_0 [1 - (\sigma)^{L_0}] = (1 - \sigma) \left[\sum_{j=0}^n (\sigma + (1 - \sigma)\beta) b_{m,0,j} + \sum_{i=0}^m P_c (1 - \beta) b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1 - P_c) (1 - \beta) b_{i,-1,j} \right] \quad (4.10)$$

Finally, the following equation is obtained:

$$Q_0 = \frac{1 - \sigma}{1 - (1 - \sigma)^{L_0}} \left[\sum_{j=0}^n (\alpha + (1 - \alpha)\beta) b_{m,0,j} + \sum_{i=0}^m P_c (1 - \beta) b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1 - P_c) (1 - \beta) b_{i,-1,j} \right] \quad (4.11)$$

From Figure 4.2:

$$\sum_{l=0}^{L_0-1} Q_l = Q_0 + Q_1 + Q_2 + \cdots + Q_{L_0-1} \quad (4.12)$$

and

$$\sum_{l=0}^{L_0-1} Q_l = Q_0 + (1 - \sigma)Q_0 + (1 - \sigma)^2 Q_0 + \cdots + (1 - \sigma)^{L_0-1} Q_0 \quad (4.13)$$

hence

$$\sum_{l=0}^{L_0-1} Q_l = Q_0 [(1 - \sigma) + (1 - \sigma)^2 + \cdots + (1 - \sigma)^{L_0-1}] \quad (4.14)$$

finally the following equation is obtained:

$$\sum_{l=0}^{L_0-1} Q_l = Q_0 \sum_{l=0}^{L_0-1} (1-\sigma)^l \quad (4.15)$$

and using:

$$\sum_{i=0}^{x-1} y = \frac{y^x - 1}{y - 1} \quad (4.16)$$

Using Equation (4.16) and substituting Equation (4.15) into Equation (4.11) we have got:

$$\sum_{l=0}^{L_0-1} Q_l = Q_0 \frac{(1-\sigma)^{L_0} - 1}{(1-\sigma) - 1} \quad (4.17)$$

and

$$\begin{aligned} \sum_{l=0}^{L_0-1} Q_l = \frac{(1-\sigma)^{L_0} - 1}{(1-\sigma) - 1} \times \frac{1-\sigma}{1-(1-\sigma)^{L_0}} \left[\sum_{j=0}^n (\alpha + (1-\alpha)\beta) b_{m,0,j} + \right. \\ \left. \sum_{i=0}^m P_c(1-\beta) b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1-P_c)(1-\beta) b_{i,-1,j} \right] \quad (4.18) \end{aligned}$$

finally,

$$\begin{aligned} \sum_{l=0}^{L_0-1} Q_l = \frac{1-\sigma}{\sigma} \left[\sum_{j=0}^n (\sigma + (1-\sigma)\beta) b_{m,0,j} + \right. \\ \left. \sum_{i=0}^m P_c(1-\beta) b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1-P_c)(1-\beta) b_{i,-1,j} \right] \quad (4.19) \end{aligned}$$

From Equation (4.19) it is seen that the idle state duration is completely dependent on packet arrival probabilities and not on a predefined duration (which completely disappears from Equation (4.19)). Therefore the L_{0-1} idle states of Figure 4.2 can be augmented into a single idle state as shown in Figure 4.1.

The derivation of the last term in Equation (4.1) is shown below.

By referring to Figure 4.1 and [45], the following equation for B_0 is written as:

$$B_0 = \sigma Q + \sigma \left[\sum_{j=0}^n x b_{m,0,j} + \sum_{i=0}^m P_c (1 - \beta) b_{i,-1,n} + \sum_{i=0}^m \sum_{j=0}^n (1 - P_c) (1 - \beta) b_{i,-1,j} \right] \quad (4.20)$$

In Equation (4.20), the first term is derived from Figure 4.1, the second term represents the sum the probabilities of finding the medium busy m times in any of the n transmission retries, the third term represents the probability of experiencing a collision in any of the m BO stages of the n^{th} transmission retry, and the fourth term represents the probability of a successful transmission at any BO stage in any transmission retry. By following Park's approximations, Equation 4.20 is rewritten as follows:

$$B_0 = \sigma [Q + x^2(1 + y) + y^{n+1} + (1 - P_c)(1 - x^2)(1 + y)] b_{0,0,0} \quad (4.21)$$

Finally, $\sum_{l=0}^{D_0-1} B_l = D_0 B_0$. It is seen that all of the terms in Equation (4.1) are represented in terms of $b_{0,0,0}$. Therefore, this equation is solved to derive an expression for $b_{0,0,0}$. Therefore, by knowing the $b_{0,0,0}$, a system of non-linear equations in terms of α in Equation (3.9), β in Equation (3.10), and τ in Equation (3.6) is formed and then the non-linear system is solved to find the network operating point.

To evaluate the performance of the WSN with the modifications introduced to Park's model, three performance metrics are considered, namely, power consumption, reliability, and end-to-end delay.

Star Topology Performance Metrics

In the Star topology, Equation (3.12) is followed to calculate the power consumption in transmitting a packet from an end node to a coordinator (E_{tot}) and Equation (3.15) to calculate the Reliability of packet transmission (R) and finally Equation (3.25) to calculate the end-to-end delay of packet transmission from an end node to the coordinator. These equations are derived in [45]. However, the modified model described in Figure 4.1 and described above is used to update the calculations of a star topology performance parameters.

4.2.2 Cluster-tree Topology

In this section, a model for the cluster-tree based WSN is presented by extending the star topology model derived above. A cluster-tree WSN topology is widely used when extended communication range is desired. In cluster-tree topology, two situations are considered when deriving the model. The first situation is when all the CHs at the same level can hear each other (i.e. no hidden terminal problem). In this situation the CHs are assumed to use CSMA/CA to access the channel. The second situation is when the CHs cannot hear each other because they are placed far apart. This situation is more common in real WSNs scenarios. Therefore, the use of contention will not be the best solution to provide channel access because of the hidden terminal problem. Hence, proper and careful scheduling is used between CHs to allow them to transmit based on specific timing and granting a minimum service guarantee all along the path through which the data is relayed (that is, using GTSs).

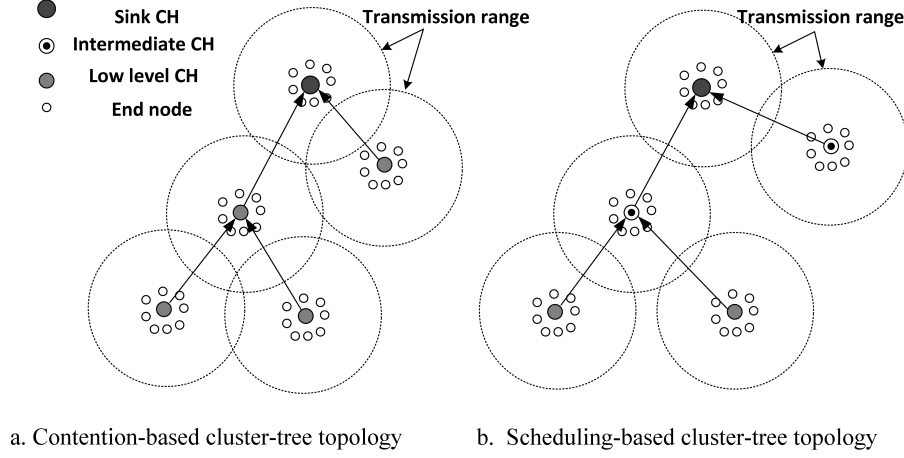


Figure 4.3: The proposed cluster-tree topology for the RSM model.

Contention-based cluster-tree model

By grouping the end nodes and the CHs at various hierarchical levels, one obtains the cluster-tree network depth [99]. For example, the network in Figure 4.3-a is a particular cluster-tree network with a depth equal to 3 and the following hierarchical levels: the first level contains 20 end devices or sources, the second level is composed of two CHs and each of these CHs is having its own end devices and finally the last level contains the sink. The topology described in Figure 4.3-a uses multihop tree routing to transfer data from the source to the destination. CHs collect packets from sensor nodes belonging to their respective clusters, in addition to relaying packets, and forward them to the next level CHs in the tree until reaching the sink. In this scenario, the communication between the nodes and their respective CHs is assumed to be contention-based. Furthermore, communication between the CHs themselves is also based on contention. For the proposed contention-based cluster-tree WSN scenario, the following additional assumptions are followed:

- CHs communicate with each other using contention (CSMA/CA).
- Each cluster is having a finite number of end devices contending to send data to

its CH.

- The traffic received by a CH in an upper level is equal to the aggregate of traffic from CHs at lower levels.
- All CHs have M/G/1/L queues, the difference between CH's queues is in the packet arrival rate.

In the study of the CSMA/CA cluster-tree based WSN, the following metrics are utilized to evaluate the performance:

Total End-to-End Delay The total end-to-end delay to transmit a packet in the contention-based cluster-tree topology is assumed to be equal to the sum of the end-to-end delays along the path from the source node to the sink. The total end-to-end delay in contention-based cluster tree WSN (D_{CCT}) is dependent on the number of nodes and packet arrival rate in each level and its value is given by the following equation:

$$D_{CCT} = \sum_{j=0}^{h-1} D_j \quad (4.22)$$

where, D is the end-to-end delay in each network level (from an end node to a CH, from a CH to a CH or from a CH to the sink), and h is equal to the number of levels starting from the end node for which the delay is to be calculated to the sink.

End-to-End Reliability The end-to-end reliability is defined as the probability of successful packet reception from any end node in the network to the sink node. The end-to-end reliability (R_{e2e}) is equal to the product of the reliabilities along the path to the sink node:

$$R_{e2e} = \prod_{j=0}^{h-1} R_j \quad (4.23)$$

where, R is the reliability from an end node to a CH, a CH to a CH or a CH to the sink.

Power Consumption The average power consumption (E_{total}) of transmitting a packet in a cluster-tree topology is equal to the sum of all power consumptions along the path from an end node to the sink. Furthermore, in all intermediate nodes, the power consumed in transmitting a packet is equal to the power consumed in receiving a packet. The total power consumption is given by the following equation:

$$E_{total} = \sum_{j=0}^{h-1} E_{tot,j} \quad (4.24)$$

where, E_{tot} is the average power consumed in transmitting the packet from an end node to a CH, a CH to a CH or a CH to the sink. The power consumed in receiving a packet in intermediate nodes is included in E_{tot} by doubling the power consumed in transmitting packets in intermediate nodes.

Scheduling-based Cluster-tree model

The cluster-tree model considered here is assumed to have one sink (which is also a CH) and other CHs form a multilevel wireless backbone with the cluster-tree topology. Each cluster-tree topology is assumed to have h levels. The CHs are classified into three categories based on their location in the network. These CHs are; sink CH which is the root of the tree and at the highest level, intermediate-level CHs which have one or multiple child CHs (at a lower level) and low-level CHs which are not connected to any CHs at the lower levels.

The 15.4b Task Group [117] have proposed two general methods to avoid beacon frame collisions. These methods are the time division approach and the beacon-only period approach. In the time-division approach, each CH schedules its SF during the

inactive period of the other coordinators. This is achieved by setting an offset in time for the beacon frame transmission in each CH. This approach requires minor modification to the current IEEE 802.15.4 MAC protocol. There are several limitations associated with this approach. These limitations can be summarized as follows: the first is the constraints in the duty-cycles, since a duty cycle is dependent on the number of interfering CHs (i.e. interfering CHs must operate in different time windows), the second, is that direct communication between sibling CHs (CHs connected to the same parent) is not possible, because each of these CHs operates in a time window different from its adjacent clusters. In the beacon-only period approach, the SF structure is modified by introducing a period at the beginning of each SF, during this period, CHs transmit their beacon frames [99]. Each CH should select a proper time slot so that its beacon frame does not collide with the ones from adjacent CHs. This approach allows multiple clusters to share the active period, so it is more scalable than the time division approach. The main disadvantage of this approach is that the beacon-only period depends on the size of network and the parent-child relationship. Most importantly, in this approach, the GTS mechanism cannot be implemented, since transmission from nodes belonging to different clusters may collide [5].

Figure 4.3-b shows the cluster-tree topology with the three CH categories. Each CH is assumed to communicate with its sensors using the CAP (i.e. using CSMA/CA) this is a practical situation because generally the end devices connected to a single CH are located geographically close to each other within the same PAN. The CH collecting data from end devices is referred to as a parent CH. Each parent CH forwards the data from end devices to upper level CHs until the sink CH is reached. In a typical WSN, most traffic is from the sensors to the sink. The traffic in the opposite direction is assumed to be mostly for control signalling and ACK transmission. Therefore, their effect on the

data traffic transmission delay is not significant and hence can be neglected. Therefore, the traffic transmissions from the sensors to the sink is only considered.

The traffic from the end nodes to their parent CH is identified as a local traffic and the traffic between CHs as the forwarded traffic. No co-channel interference between the transmissions in neighbouring clusters is assumed to be present. It is also assumed that there is a time synchronization between communicating CHs so that when one CH is transmitting at a frequency channel, the intended receiving CH should tune its radio to receive at the same frequency channel. With the cluster tree-topology, communicating CHs have strict parentchild relationship, which makes time synchronization between them much simpler than in the mesh topology. All the children CHs listen to the beacons from their parent CHs and synchronize with them. Furthermore, the time synchronization between CHs does not have to be re-performed for each individual packet transmission but only when the CHs should switch from the receiving mode to the transmitting mode. The effect of time synchronization on the packet transmission delay is assumed to be negligible.

Each type of CH identified above is assigned with a unique SF structure based on its depth in the tree. Figure 4.4 shows the proposed SF structure for the three types of CHs. Each BI specifies both the CAP for contention-based transmissions, GTSs for contention-free transmissions and inactive period where the node is in either idle state or sleep mode to save power [5]. The CAP of each SF is allocated for intra cluster transmission (i.e. from end devices to their parent cluster head). The CAP of all the low-level CHs is assumed to be longer than the CAP of intermediate CHs and the sink CH. This assumption is made to allow longer CFP to the intermediate and sink CHs, since these devices are expected to handle higher inter-cluster traffic rates compared to the low level CHs. Another reason for allocating longer CAP to the low level CHs is that these

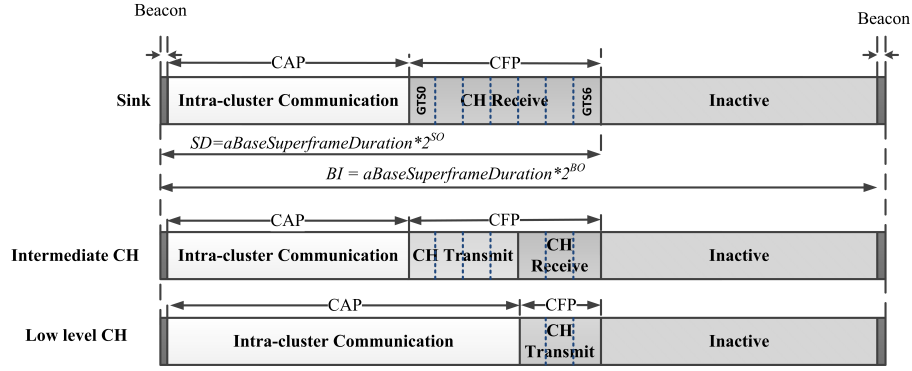


Figure 4.4: The proposed SF structure used in the RSM model.

clusters are assumed to have higher number of nodes compared to the upper level clusters and thus having longer CAP will reduce the delay from the end devices to the parent CH. Furthermore, the CFP period of all intermediate level CHs is divided in to two periods, one is CFP for transmitting to upper CHs (GTS_{TX}) and the other is for receiving from lower level CHs (GTS_{RX}), in doing so, intermediate CHs are guaranteed not to transmit and receive at the same time and hence avoid collision [118, 119, 120]. It is assumed that the CFP period of the low level CH is completely allocated for transmitting and the CFP period of the sink CH is completely allocated for receiving from intermediate CHs. To avoid beacon frame collisions between neighbouring CHs, the beacon frame collision avoidance approach described in [117] is used. In this approach the time is divided such that beacon frames and the SF duration of a given coordinator are scheduled in the inactive period of its neighbour coordinators. This approach is implemented by carefully selecting the duty cycle of each CH in the network. This is done by selecting a specific Beacon Order (BeO) and SO [117]. Each CH is assumed to maintains a buffer (B_i) to store its received packets, which can be either from its end devices directly connected to it or from child CHs at lower levels, this buffer is assumed to accommodate all of the incoming traffic. The following additional assumptions are followed in this model:

- Each cluster is having a finite number of end devices which contend to send data

to their CH.

- The traffic received by a cluster head in an upper level $(h + 1)$ is equal to the aggregate of traffic from cluster heads at lower levels (h) .
- Each cluster is modelled with the same Markov model described above.

In the study of the scheduling-based cluster-tree WSN, the following metrics are used to evaluate the performance of the model:

Total End-to-End Delay The total end-to-end delay to transmit a packet in the scheduling-based cluster-tree topology is assumed to be equal to the sum of the end-to-end delays along the path from the source node to the sink node. The total end-to-end delay in scheduling-based cluster-tree WSN (D_{SCT}) is dependent on the number of nodes and packet arrival rate in each level (h) and its value is given by the following equation:

$$D_{SCT} = D + \sum_{j=0}^{h-1} D_{int}j \quad (4.25)$$

where, D is the end-to-end delay from the end device to its parent CH and is given by Equation (3.25). D_{int} is the inter-cluster head delay and is calculated as follows:

The inter-CH (i-CH) transmission delay D_{int} is considered to compute the end-to-end delay from a node to the sink. To simplify the calculations of D_{int} , the CHs are classified into two categories based on their distance (in number of hops) from the sink; first level CH and intermediate level CH. First level CHs are one hop away from the sink, higher level CHs are at a distance of more than one hop from the sink. The delay from the first level CHs to the sink is initially computed then the D_{int} between higher level CHs is computed.

Table 4.1: Time Slot Allocation for Each Type of Cluster Head.

CH type	CAP	GTS_{TX}	GTS_{RX}	μ_i	ψ_i
Low-level	12	4	0	17	0
Intermediate-level	8	4	4	17	17
Sink	8	0	8	0	34

The actual occupancy of B_i at an i^{th} level is assumed to be φ_i . The value of φ_i is therefore given by the following relation:

$\varphi_i = \eta_i + \epsilon_i$, η_i can be obtained directly from λ and the reliability R . Let μ_i and ψ_i be the maximum number of packets that can be transmitted and received from and into an i^{th} level CH during a single (D_{SF}) respectively. The values of μ_i and ψ_i depend on the packet length and the GTS duration. Based on the SF structure described in [5] a GTS and a CAP time allocation is proposed for each type of CH in the network as shown in Figure 4.4. Table 4.1 shows the time slot allocation used in the RSM model for each type of CH in Figure 4.4. For simplicity, it is assumed that all the packets in B_i experience the same D_{int} .

Let $\pi - 1$ be the occupancy of B_i when the measurement of the end-to-end delay is initialised. Similar to [111], the one hop D_{int} (in time slots) is therefore given by:

$$D_{int} = \delta D_{SF} + \mu_i \quad (4.26)$$

The value of δ can simply be found by the following equation:

$$\delta = \left\lceil \frac{\varphi_i}{\mu_i} \right\rceil - 1 \quad (4.27)$$

Based on Equation 4.27 and [111], the average single hop delay of all the packets incoming

to B_i (D_{SH}) is giving by the following equation:

$$D_{SH} = \frac{\sum_{a=1}^{\varphi_i} \left[\left(\left\lceil \frac{a}{\mu_i} \right\rceil - 1 \right) D_{SF} + \mu_i \right]}{\varphi_i} \quad (4.28)$$

As in [111], a special case is considered where the CH is the sink, in this case, D_{int} of the tagged packet in time slot is:

$$\tilde{D}_{int} = \delta D_{SF} + \rho \quad (4.29)$$

then,

$$\rho = \pi - \delta \mu_i \quad (4.30)$$

Therefore, as in [111], the average single hop delay of all the packets incoming to B_i ($\tilde{D}_{SH}$) in the last hop is giving by the following equation:

$$\tilde{D}_{SH} = \frac{\sum_{a=1}^{\varphi_i} \left\{ \left(\left\lceil \frac{a}{\mu_i} \right\rceil - 1 \right) D_{SF} + \left[a - \left(\left\lceil \frac{a}{\mu_i} \right\rceil - 1 \right) \mu_i \right] \right\}}{\varphi_i} \quad (4.31)$$

End-to-End Reliability To calculate the end-to-end reliability for scheduling-based cluster tree topology, no packets are assumed to be lost during buffering at the CHs. Furthermore, since a scheduling mechanism is used between CHs, then ideally there are no packets lost during the communication between CHs. Hence the reliability of packet transmission is equal to the reliability of packet transmission from the end node to its local CH. Based on these assumptions Equation and 3.15 is used to calculate the end-to-end reliability for packet transmission from an end node to the sink.

Power Consumption Since a scheduling mechanism is used between CHs, then there is no power lost during BOs, channel sensing, retransmissions due to collisions during the

communication between CHs. The power consumed during buffering stage is assumed to be negligible. Furthermore, the power consumed in transmitting a packet is equal to the power consumed in receiving a packet. Hence the total power consumed in transmitting a packet from an end node to the sink in scheduling based cluster-tree topology is given by:

$$\tilde{E}_{total} = E_{tot} + \sum_{j=0}^{h-1} 2E_tj + E_wj \quad (4.32)$$

where, E_{tot} represents the power consumed in transmitting the packet from an end device to its local CH and is given by Equation (3.12), E_t is power consumed in transmitting a packet and E_w is power consumed during the wakeup process.

4.3 Simulation and Analysis

To validate the analytical results of RSM, QualNet [97] network simulator is used to simulate a beacon-enabled WSN of star and cluster-tree topologies. All of the simulation parameters are set similar to the mathematical model environment. Poisson traffic arrival is used and the number of nodes is varied in a (20 m x 20 m) area. All of the sensor nodes are assumed to be operating in the 2.4 GHz band with a maximum bit rate of 250 kbps. Each simulation is run for 300 seconds and each simulation is repeated 10 times. All nodes are assumed to transmit with sufficient power, which means that all nodes in a single PAN or cluster can hear each other. The noise level is assumed to be constant throughout the entire simulations (i.e. constant noise factor). The Acknowledgement mechanism is activated to improve the reliability of the system. The power consumed during the buffering state as well as the BO state is assumed to be equal to the power consumed during the idle state. Initial simulation parameters are set similar to Table 3.1.

The rest of the parameters are acquired from the IEEE 802.15.4 standard document [5] and the actual specification document of MicaZ platform. In all of the presented results the proposed model is refereed to as “RSM” model.

4.3.1 Star Topology

Figure 4.5 shows the end-to-end delay of packet transmission from the tagged node to the coordinator against the number of nodes for different λ values and a buffer size of 512 B. When λ changes in Park’s model the end-to-end delay fluctuates drastically, whereas the RSM model shows a more stable behaviour with different λ values. This is a more realistic model which in fact represents a stable WSN system because the designer and the operator of WSN want a system which is independent of the traffic arrival rates. Simulation results of $\lambda = 50$ pkts/s agree very much with the presented analytical results.

Figure 4.6 shows the reliability of packet transmission from the tagged node against the number of nodes for different λ values and a buffer size of 512 B. It is seen that there is an extreme fluctuation in the reliability when λ changes in Park’s model. On the other hand, the RSM model results show very stable performance with varying λ . This happens because the nodes in the RSM model tend to shortly buffer the packets before contending for the channel access and this apparently reduces the collision rate drastically and makes it almost independent of λ . A simulation of $\lambda = 50$ pkts/s agrees with the RSM model.

Figure 4.7 shows the total power consumed in transmitting a packet from the tagged node against the number of nodes for different λ values and buffer size equal to 512 B. It is seen from the figure that there is an obvious fluctuation in the total consumed power when λ changes from (10 to 90) pkts/s in Park’s model. On the other hand, the RSM model results show a clear stability in terms of the total power consumption and that the

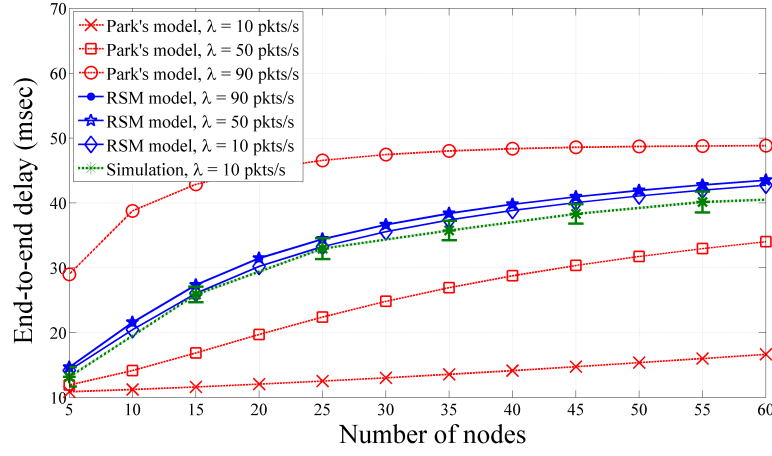


Figure 4.5: RSM end-to-end delay in a star topology.

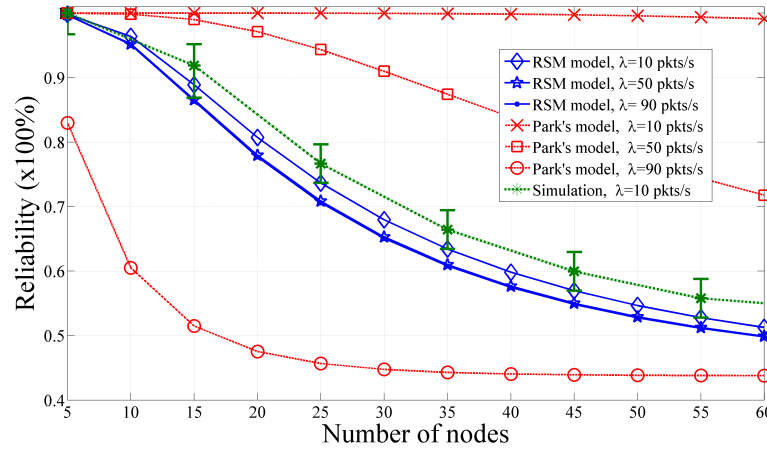


Figure 4.6: RSM reliability in a star topology.

power consumed is independent of the probability of traffic arrival. This indeed is what is required from a model to be realistic and stable. It is also seen that the simulation results for $\lambda=50$ pkts/s agree with the RSM model.

4.3.2 Cluster-tree Topology

Contention-Based Cluster-tree

For the cluster-tree topology, the same scenario described in Section 4.2 is followed.

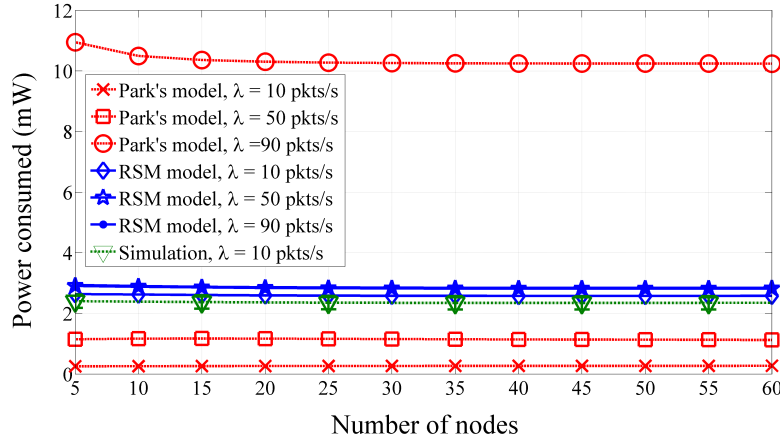


Figure 4.7: RSM total power consumption in a star topology.

Figure 4.8 shows the end-to-end delay of packet transmission from the tagged node as a function of λ for different MAC buffer sizes. This delay is measured from the end device (leaf node) with the highest depth to the sink node. It is shown that as λ increases the end-to-end delay slightly increases then the delay reaches saturation. For a buffer size of 512 B the increase of the end-to-end delay with λ is more significant compared to the cases where the buffer is equal to 1 kB and 2 kB. This happens because with higher MAC buffers the nodes tend to buffer the arriving packets before transmitting them, and hence decrease the gradient of the delay with λ . This takes place because as the buffer size increases the contention among nodes decreases, which leads to less collisions and hence delay is decreased. There is a good agreement between simulation and analytical results for all buffer sizes.

Figure 4.9 shows the reliability of packet transmission from the tagged node as a function of packet arrival rate for different buffer sizes. It is shown that as the MAC buffer increases the total end-to-end reliability increases. This is attributed to the buffers that reduce the contention, which leads to fewer collisions. As a result, the total reliability is increased. The simulation and analytical results agree for all buffer sizes.

Figure 4.10 shows the total power consumed in transmitting a packet from the tagged node in the cluster-tree network. The power consumption is dependent on the number of relays between the end node and the sink. The total power consumption decreases as the MAC buffer sizes increases. This reduction in power consumption takes place because the nodes experience less number of retransmissions as they experience less number of collisions.

Figure 4.11 shows the throughput of the tagged node as a function of the number of nodes and packet arrival rate for the RSM model with MAC buffer size of 2 kB (Figure 4.11-a) and the default IEEE 802.15.4 MAC (Figure 4.11-b) and for a cluster of 10 nodes. It is seen that for low number of nodes, the default IEEE 802.15.4 MAC achieves higher throughput compared to the RSM model with 2 kB MAC buffer. However, for higher number of nodes (20 nodes and higher), the RSM model achieves better throughput. This is because as the number of nodes increase higher collisions take place leading to lower throughput in the default IEEE 802.15.4 MAC, whereas higher MAC buffer sizes mitigate the contention in the RSM model. It is also seen that as the packet arrival rate increase the throughput slightly increases and then abruptly drops. On the other hand, it is seen that the throughput with the RSM model increases slightly and reaches steady state as the packet arrival rate increase.

Figure 4.12 shows the energy efficiency of a tagged node as a function of number of nodes and packet arrival rates for the RSM model with 2 kB MAC buffer (Figure 4.12-a) and the default IEEE 802.15.4 MAC (Figure 4.12-b). The energy efficiency is calculated as the ratio of energy spent in successful transmission of a data packet to the total energy consumed by a node multiplied by the packet success rate. It is seen that as the number of nodes increase the energy efficiency decreases because the nodes experience higher retransmissions and BOs due to collisions. However, it is seen that the energy efficiency

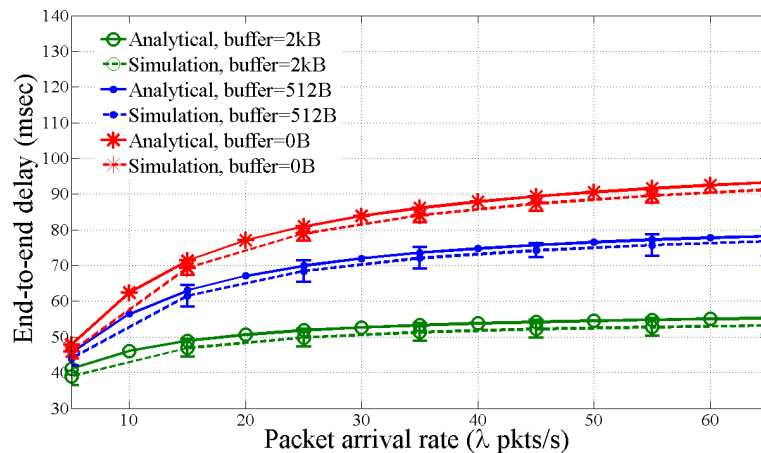


Figure 4.8: RSM end-to-end delay in a contention-based cluster-tree topology.

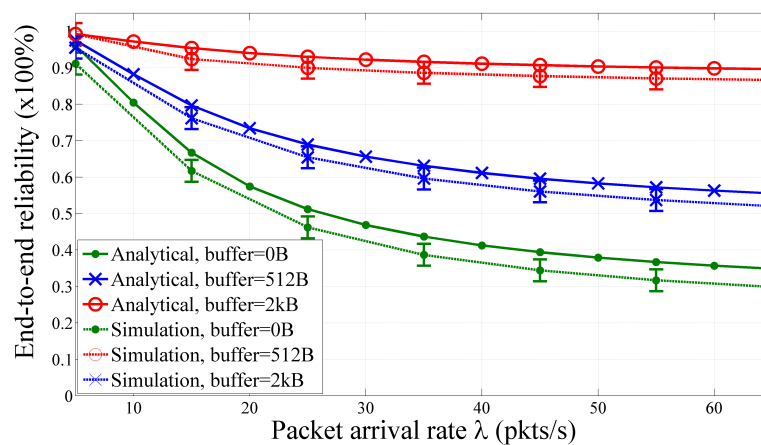


Figure 4.9: RSM end-to-end reliability in a contention-based cluster-tree topology.

is higher with the RSM model for all number of nodes. It is also seen that the energy efficiency drops sharply in the IEEE 802.15.4 MAC as the packet arrival rate increases. In contrast, in the RSM model with a 2 kB MAC buffer the energy efficiency does not drastically drop as the packet arrival rate increases.

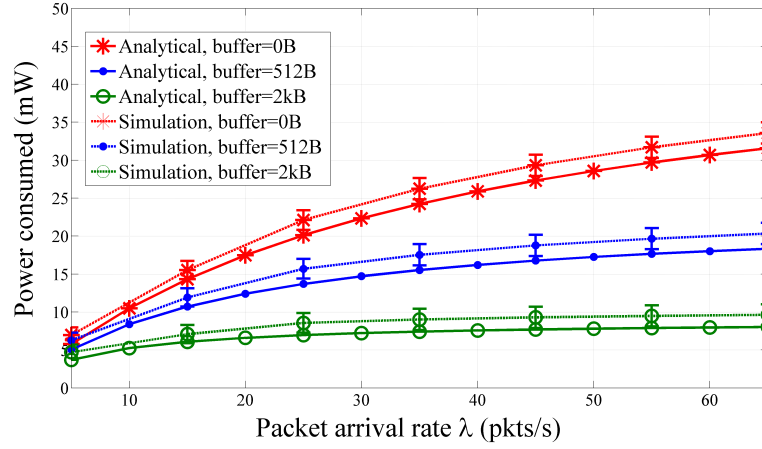


Figure 4.10: RSM total power consumption in a contention-based cluster-tree topology.

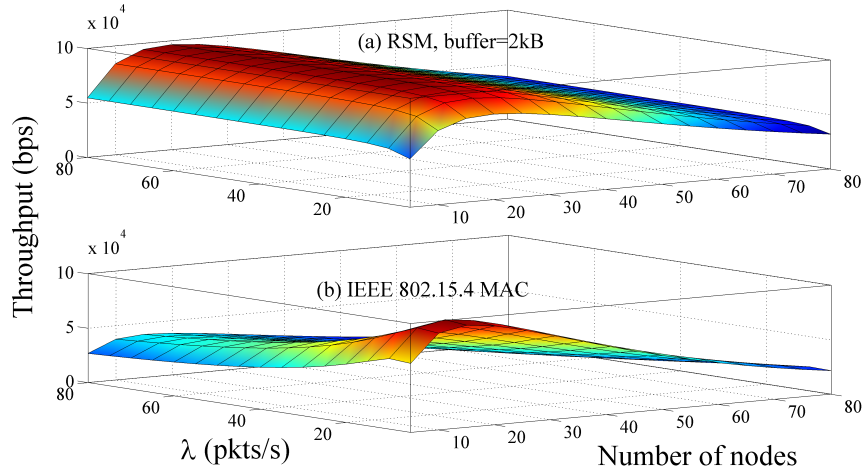


Figure 4.11: RSM throughput in a contention-based cluster-tree topology.

Scheduling-based Cluster-tree

For the scheduling-based cluster-tree topology, the tagged node is assumed to be located at the lowest level and that $h=3$ (refer to Figure 4.3). The number of nodes in the low level clusters, the intermediate and the sink clusters is assumed to be equal to 20 and 10 nodes respectively. The values derived in Table 4.1 and all of the assumptions made in Section 4.2 are followed.

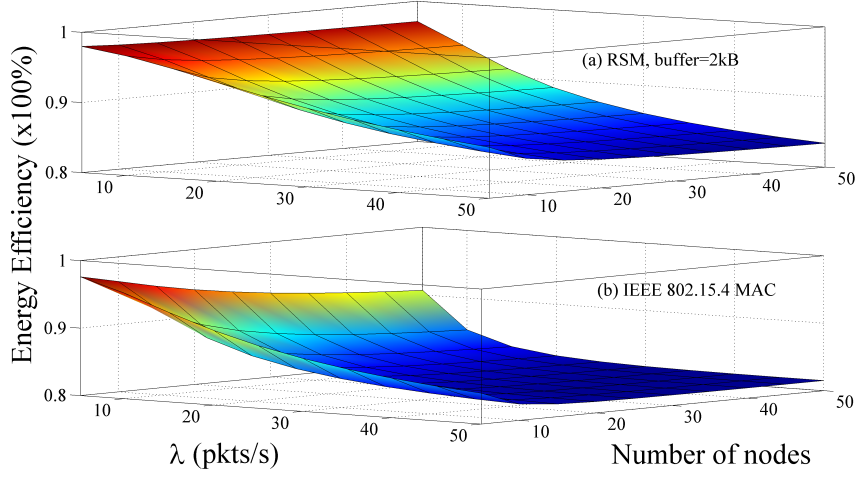


Figure 4.12: RSM energy efficiency in a contention-based cluster-tree topology.

Figure 4.13 shows the end-to-end delay of packet transmission in the tagged node against the packet arrival rate for different cluster-tree network scenarios. The first scenario Scenario(1) is when the tagged node is located in a low-level cluster, where the cluster is 2 hops away from the sink. Scenario(2) is similar to scenario 1, but the cluster is 3 hops away from the sink. In Scenario(1), it is seen that the end-to-end delay increases gradually similar to the result shown in Figure 4.8. However, when the packet arrival rate increases beyond 20 pkts/s, the transmitted packets miss the current SF and therefore have to wait for the next SF. Hence, an increase in the delay equal to the D_{sf} is seen as the packet arrival rate crosses certain limits. In the scenario where the tagged node is located in an intermediate cluster and its CH also receives packets from lower level clusters Scenario(3), it is seen that the end-to-end delay for the tagged node is initially lower than the than the end-to-end delay of a node in a low-level cluster. When the packet arrival rate increases beyond 20 pkts/s, the packets miss the current SF and have to wait for the next one. This happens because the CH of the intermediate cluster has also to forward packets form lower level clusters. Similar behaviour takes place when

the tagged node is located in a cluster 3 hops away from the sink Scenario(4).

Figure 4.14 shows the end-to-end delay of packet transmission from the tagged node against the packet arrival rate for different end nodes MAC buffer sizes for a tagged node located in the lower level cluster with 2 hops away from the sink. It is seen that when the packets are transmitted within the same SF the end-to-end delay is lower when the MAC buffer sizes of local nodes are higher. However, when the packet arrival rate increases, it is seen that increasing the MAC buffer size of a local node will increase the end-to-end delay. This happens because at certain packet arrival rates and higher MAC buffer sizes, the packets wait longer and hence miss the current SF. Therefore, a careful optimization between the packet arrival rate and the local nodes' MAC buffer sizes has to be put in place to minimize the end-to-end delay. Simulation results for a MAC buffer size of 2 kB agree with the theoretical results presented in Figure 4.14.

Figure 4.15 shows the end-to-end reliability of packet transmission from the tagged node to the sink versus the packet arrival rate for different local nodes' MAC buffer sizes. The tagged node is assumed to be in a low-level cluster and 2 hops away from the sink. It is assumed that there are no packets lost during the inter-CH communication due to the synchronization between CHs. It is seen that the reliability increases as the end nodes' MAC buffer increases for all packet arrival rates. The reliability levels are higher than the contention-based cluster-tree scenario.

Figure 4.16 shows the power consumed during packet transmission from the tagged node to the sink as a function of packet arrival rate for different end nodes' MAC buffer sizes. The power consumed during buffering of data packets is assumed to be negligible. It is seen that as the local nodes' buffer sizes increase the power consumption decreases for all packet arrival rates. The power consumption is lower than the contention-based cluster-tree scenario. This is because the CHs do not experience retransmissions and

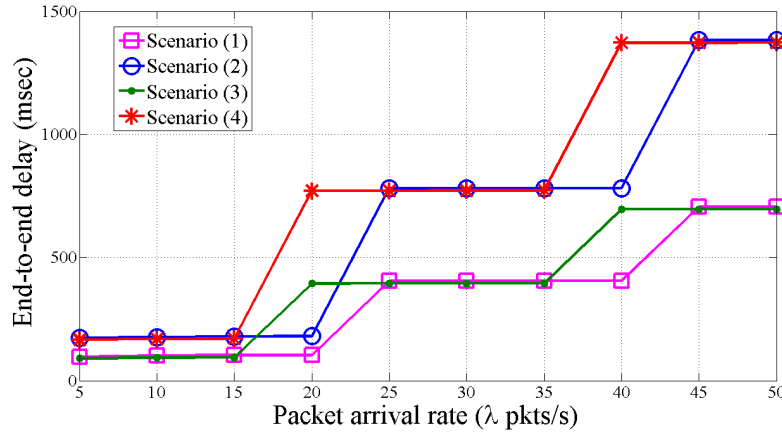


Figure 4.13: RSM end-to-end delay in a scheduling-based cluster-tree topology.

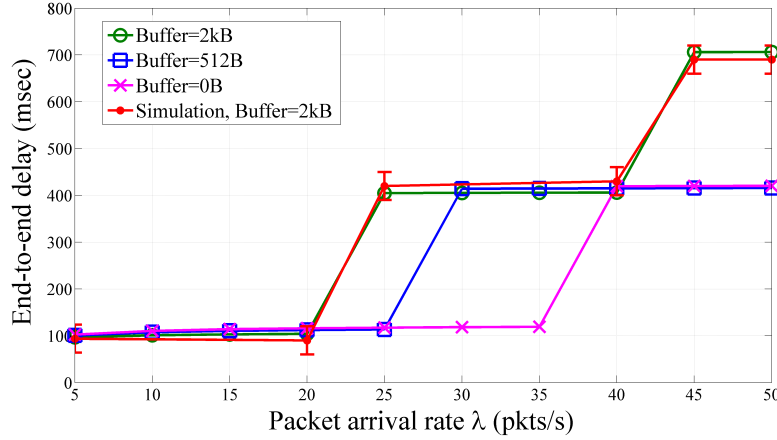


Figure 4.14: RSM end-to-end delay in a cluster-tree topology for different MAC buffer sizes.

BOs as they communicate with each other.

The number of nodes in a tagged cluster are changed and the effect of cluster size is observed when using scheduling-based cluster-tree topology on the performance of the network. Figure 4.17 shows the end-to-end delay from a tagged node to the sink node for various cluster sizes and when a tagged cluster is 1 and 2 hops away from the sink and the packet generation rate is 10 pkts/s. It is seen that as the cluster size increase the end-to-end delay increases when the tagged node is located 1 or 2 hops away from

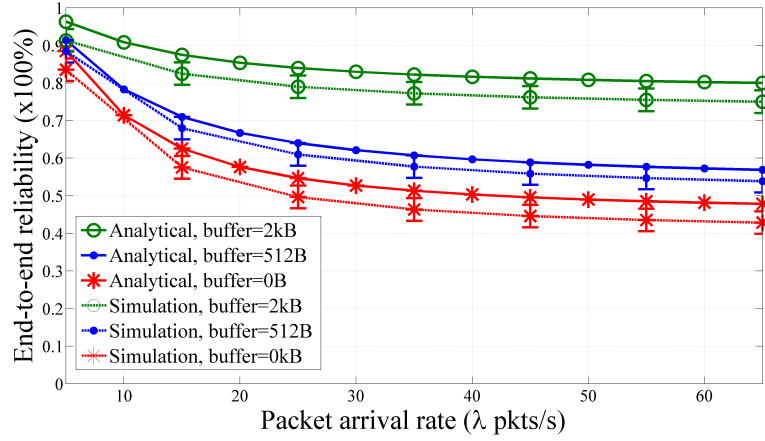


Figure 4.15: RSM end-to-end reliability in a scheduling-based cluster-tree topology.

the sink. It is seen that the end-to-end delay is lower when the MAC buffer is 2 kB for all number of nodes. This is due to the reduction in the number of collisions and thus the number of retransmissions is reduced as well, leading to lower delay. The simulation results agree with the analytical results.

Figure 4.18 shows the total power consumed in packet transmission from the tagged node to the sink for various cluster sizes and when the tagged node is 1 or 2 hops away from the sink and the packet generation rate is 10 pkts/s. It is seen that as the number of nodes increase the power consumed decreases, this is because the tagged node tends to transmit less often because it acquires the channel less times as the size of the cluster increases. It is also seen that the power consumed is reduced by about 50% when a MAC buffer is 2 kB compared to a 0 B MAC buffer. This is also due to the reduced contention which leads to less collision.

Figure 4.19 shows the end-to-end reliability of packet transmission from a tagged node to the sink node for various cluster sizes and the packet generation rate is 10 pkts/s. An accurate synchronization between CHs is assumed to be in place, hence there are no packets lost in transmission between cluster heads and thus the packet delivery ratio

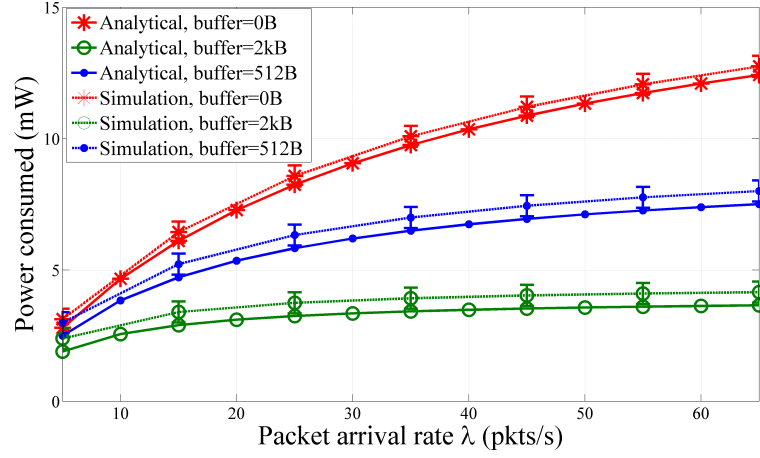


Figure 4.16: RSM power consumption in a scheduling-based cluster-tree topology.

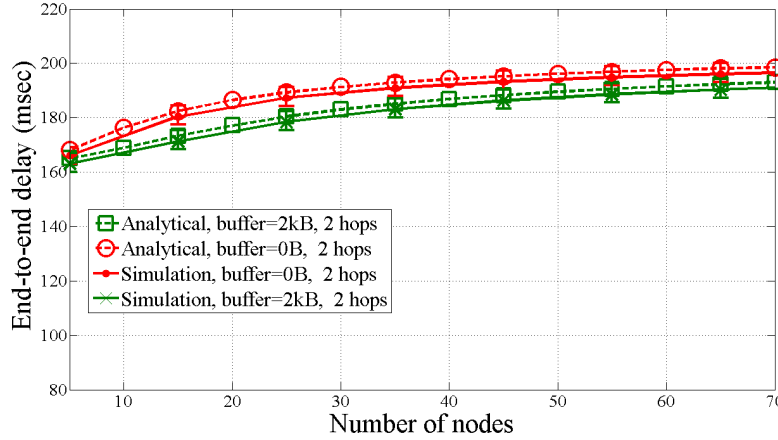


Figure 4.17: RSM end-to-end delay in a scheduling-based cluster-tree topology for different number of nodes.

between cluster heads is 100% for all network levels. It is seen that as the cluster size increases the end-to-end reliability decrease and that the reliability is higher when the MAC buffer size is 2 kB. These reliability values are the same if the tagged node is located at different hops away from the sink.

In the previous results packet arrival rates ranging from (5 to 50) pkts/s are used. These arrival rate are considered normal for application with high data rates such as PD monitoring [121, 122]. Figure 4.20 shows the end-to-end delay for low arrival rates

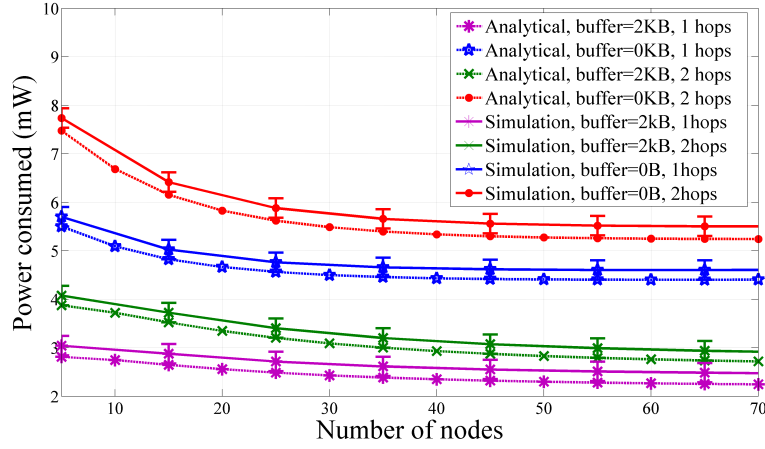


Figure 4.18: RSM Power consumption in a scheduling-based cluster-tree topology for different number of nodes.

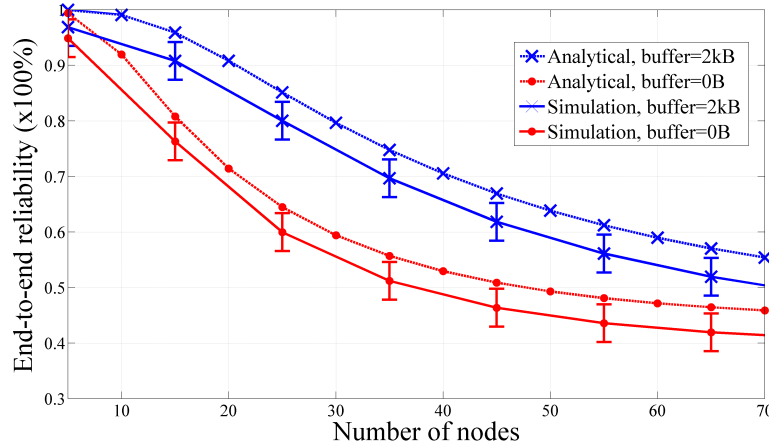


Figure 4.19: RSM end-to-end reliability in a scheduling-based cluster-tree topology for different number of nodes.

(i.e. from 0.001 to 10 pkts/s). Two scenarios are considered, namely Scenario(1) and (2). Scenario(1), is when the tagged node is in 2 hops away from the sink CH, in this scenario it is assumed that packet arrival rate for all the upper level CHs varies from (0.001 to 10 pkts/s). Scenario(2), is when the tagged node is 3 hops away from the sink CH and the packet arrival rate of all the upper level CHs varies from (0.001 to 1) pkts/s. It is shown that for Scenario(1), the end-to-end delay remains within acceptable ranges until the packet arrival rate is approximately more than 2 pkts/s and then it increases

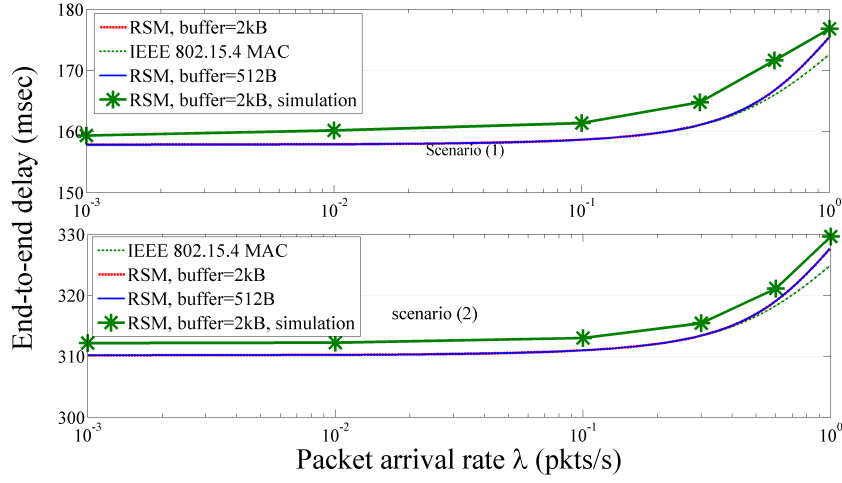


Figure 4.20: RSM end-to-end delay for low packet arrival rates.

for both the RSM model and the IEEE 802.15.4. In Scenario(2), the end-to-end delay remains within acceptable ranges until the packet arrival rate exceeds 0.2 pkts/s. The simulation results agree with the analytical model.

4.4 Conclusion

In this chapter, an analytical model was presented for the MAC layer of the IEEE 802.15.4 standard, the model can be used to provide QoS to certain smart grid applications such as condition monitoring. The model can provide QoS by reducing the variations of the WSN performance parameters as the traffic rates and the number of nodes varies. The model considered a star WSN topology and two cluster-tree based WSN topologies. Actual traffic generation rate were included rather than a predefined idle state length to study the overall performance in terms of the end-to-end delay, reliability and power consumption. The impact of modelling MAC-level finite buffers on the performance of these WSNs was also studied. The proposed model was validated and performance analysis us-

ing extensive simulations were carried out. The presented analytical results agreed with the simulation results for different number of nodes operating at different traffic generation rates. These results demonstrated the accuracy of the RSM model in different environments. It was shown through analytical and simulation studies that including the effect of a finite MAC buffer in the model has a significant impact on improving the network performance in terms of end-to-end delay, reliability and power consumption. The impact of implementing the proposed model on the performance of contention-based and scheduling-based cluster-tree topologies was shown. The contention-based cluster-tree topology can achieve lower end-to-end delays than scheduling-based cluster-tree topology at high packet generation rates. Scheduling-based cluster-tree topology (which is a more realistic scenario for distributed condition monitoring applications) can achieve higher reliability and lower power consumption for all traffic generation rates.

In the next chapter a QoS scheme to solve the excessive latency problem arising in scheduling-based cluster-tree topologies due to the SF scheduling and high packet arrival rates is presented.

Chapter 5

An Adaptive QoS Scheme for WSNs

5.1 Introduction

Monitoring and controlling systems with severe risks of damage due to the occurrence of certain events or faults have strict QoS requirements, including requirements on the functional behaviour, robustness, reliability, and timeliness [123, 27, 7, 9, 124]. Therefore, a real-time monitoring system should not only manage system resources and offer a well-defined set of services to application programs, but should also provide guarantees about the timeliness of such events, that is, its behaviour must be predictable. Thus, for example, the maximum latency to monitor and control a system should be known in advance. The maximum allowed latency depends on the specific application; typical values are tens of milliseconds for discrete manufacturing, seconds for process control, and minutes for asset monitoring [125, 96].

In chapter 4, a Realistic and Stable Markov-based model (RSM) is presented for single hop star topology as well as for cluster tree topologies WSNs. The proposed model takes into account the traffic generation probabilities and considers the impact of a finite MAC buffer on the end-to-end delay, reliability and power consumption. In this chapter, an

Adaptive RSM model (ARSM) is presented [126] to reduce the delay of high priority data in WSNs smart grid monitoring applications. The RSM model is extended to be suitable for high and low data rate condition monitoring applications. ARSM builds on the mathematical model of RSM. However, it presents major improvements to RSM by solving the issue of excessive latency by adaptively providing QoS guarantees to delay critical condition monitoring and control applications.

5.1.1 Related Work

The concept of using adaptive WSN protocols for delay sensitive applications has been extensively studied in the literature [29, 127, 80]. In addition to that, the use of an adaptive WSN protocols to control other WSN parameters has been discussed in [26, 34, 128]. Furthermore, different IEEE 802.15.4 modelling techniques (which can be utilized by these adaptive schemes) has been widely discussed in the literature [109, 111, 110, 107].

In [118], the authors have proposed a technique to schedule the SF of cluster-tree IEEE 802.15.4 networks over multiple channels to avoid beacon frame collisions as well as GTS collisions between multiple clusters. Their technique allows multiple clusters to schedule their SFs simultaneously on different radio channels. The ARSM scheme also uses SF scheduling to avoid beacon frame collisions. However, multichannel scheduling is not used, since that scheme requires significant changes to the hardware platform in addition to changes to the IEEE 802.15.4 protocol. Instead, the communication within a cluster is assumed to take place using CSMA/CA, and communication between CHs take place using mutual scheduling of interfering CHs which requires minimal changes to the hardware as well as the communication protocol. A QoS scheme based on a Markov chain-based model that can reduce the end-to-end delay of high priority traffic is added.

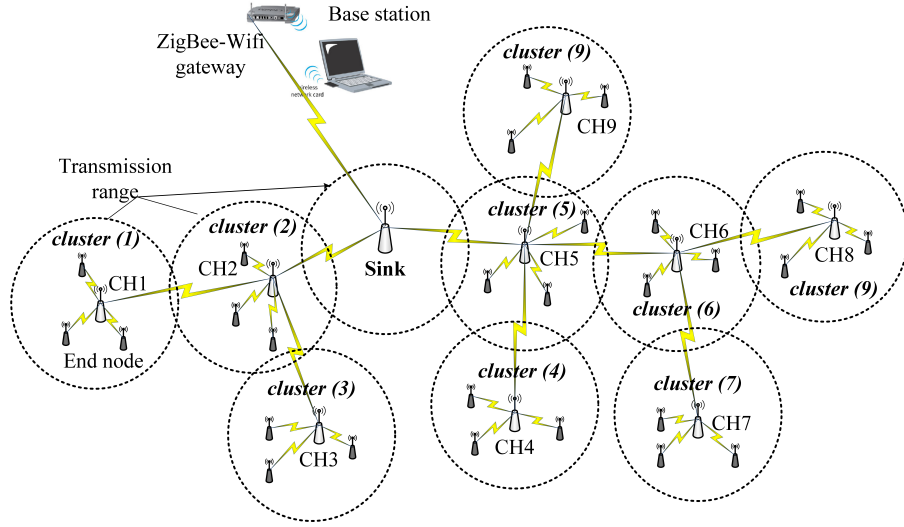


Figure 5.1: The proposed cluster-tree topology for the ARSM scheme.

5.2 System Model for Cluster-Tree Topology

5.2.1 Model Description

In a cluster-tree topology, CHs generate periodic beacon frames to synchronize with their end nodes and with higher or lower level CHs. Higher level CHs originate from the fact that in a cluster-tree network there can be several levels of parent-child relations among these CHs, up to the level that determines the tree depth. Figure 5.1 shows an example of a cluster-tree topology that is adopted to implement the ARSM scheme. In Figure 5.1 CH2 is the parent of CH1 and CH3, while being child of the PAN coordinator or the sink, which is also the root of the tree. In this scenario and in similar cluster-tree scenarios if the transmission of the beacon frames are not properly synchronized, (i.e. not properly scheduled), beacon frames could collide either with other beacon frames from different coordinators or with data frames from different clusters. Collision of beacon frames leads to loss of synchronization between communicating CHs, which results in the disconnection of the colliding CHs from the network.

5.2.2 Model Assumptions

In the ARSM scheme, each CH is assumed to communicate with its end nodes using the CSMA/CA mechanism. In condition monitoring applications such as WSN applications in industrial monitoring and power grid monitoring, this is a more practical and reliable situation, since generally end devices connected to a single CH are located close to each other within the same PAN. In addition to that, the number of end devices connected to their CH is expected to be in the order of tens of nodes, hence using time division approach [111] would be impractical. Each CH is assumed to forward the data from the end devices to upper level CHs until the parent CH is reached. In a typical WSN, most traffic is from the sensors to the sink. The traffic in the opposite direction is assumed to be mostly for control signalling and acknowledgement transmission. Therefore, its effect on the transmission delay is not significant and can be neglected. Hence, in this scheme the transmissions from the sensors to the sink is considered.

The traffic from the end nodes to their CH is denoted as a local traffic and the traffic between low level and high level CHs is denoted as the forwarded traffic. As shown in Figure 5.1, end nodes belonging to a certain cluster are placed in such a way that they do not suffer from co-channel interference from the transmissions in neighbouring clusters. To avoid beacon frame collisions between neighbouring CHs, the beacon frame collision avoidance approach described in [99] is used. In this approach the time is divided such that beacon frames and the SF duration of a given coordinator are scheduled in the inactive period of its neighbour coordinators. This approach is implemented by carefully selecting the duty cycle of each cluster-head in the network. This is done by selecting a specific BeO and SO.

The CHs in the network are divided into three type, namely, the sink, intermediate level CHs and low level CHs. Intermediate level CHs have CHs connected to them either

in the upper or lower levels. Low level CHs only forward the traffic upwards and do not receive any traffic from lower levels except from their end devices. In the ARSM scheme, the proposed SF structure described in Chapter 4 (Figure 4.4) contention access period which is based on the location of the CH and the expected traffic. The proposed SF structure shows the structure for the three types of CHs. The GTS of the CFP for all intermediate level CHs is divided into two equal spaced periods, one is GTS for transmitting to upper CHs (GTS_{TX}) and the other is for receiving from lower level CHs (GTS_{RX}). The GTS period of the low level CH is completely allotted to transmitting and the GTS of the CFP of the sink CH is completely allocated for receiving from intermediate CHs.

The inactive period of the SF is assumed to be equal to the active period for all the CHs in the network. The CAP of each SF is allocated for intra-cluster transmission (i.e. from end devices to their parent CH). CHs use the CFP of each SF to perform the scheduling. The CFP of all the intermediate level CHs (e.g. CH2, CH5 and CH6 in Figure 5.1) and the sink is assumed to be at least double of that of the low level CHs (e.g. CH1, CH3, CH4, CH7, CH8 and CH9). This assumption is made to allow the intermediate CH and sink to perform time division approach for beacon frame collision avoidance with as many CHs as possible. Another reason for allocating longer CAP to the low level CHs is that these clusters are assumed to have higher number of nodes compared to upper level clusters and thus having longer CAP will reduce the end-to-delay from the end devices to the parent CH.

Each CH is assumed to maintain a buffer (B_i) to store the received packets, which can be either from its own end devices or forwarded from the lower level CHs (if it is not a low level CH). These buffers are assumed to accommodate all of the incoming traffic. Furthermore, the following additional assumptions are followed:

- Packet arrival at MAC layer is the same for all end nodes in the network.
- The monitored events last at least for 500 ms.
- The traffic received by a CH in an upper level ($h + 1$) is equal to the aggregate of traffic from CHs at lower levels (h).
- All CHs have M/G/1/L queues; the difference between cluster heads is in the packet arrival rate (λ).
- Each cluster (i.e. a single hop star topology) is modelled with the same Markov chain model described in Chapter 4.

5.3 Performance Metrics

Three metrics are considered to study the performance of the ARSM scheme for the proposed WSN topology. These parameters are power consumption, reliability, and end-to-end delay.

Single Hop Topology

The performance metrics for the single hop star topology used to evaluate the local cluster parameters are presented below.

Power Consumption To calculate the power consumed in transmitting a packet from an end node to the local CH Equation (3.12) and the RSM model described in Chapter 4 is used.

Reliability To calculate the reliability of transmitting a packet from an end node to the local CH Equation (3.15) and the RSM model described in Chapter 4 are used.

End-to-End Delay To calculate the end-to-end delay in transmitting a packet from an end node to the local CH Equation (3.25) and the RSM model described in Chapter 4 are used.

5.3.1 Cluster Tree Topology

Power Consumption The average power consumed to transmit a packet from an end node to the sink in a cluster-tree topology is equal to the sum of the power consumed in transmitting the packet from the end node to its immediate CH (according to Equation (3.12)) and the power consumed in transmitting this packet to the CHs along the path to the sink CH. Since it is initially assumed that all the CHs use scheduling to transmit their packets then there is no power consumed in BO, channel sensing, and retransmissions. Therefore, the total power consumed in transmitting a packet from an end node to the sink along multiple hops is given by Equation (4.32). Furthermore, the power consumed in transmitting a packet is equal to the power consumed in receiving a packet.

Reliability In the cluster-tree topology it is assumed that there are no packets lost in the transmission between CHs due to the employed synchronization and beacon collision avoidance mechanisms. Hence, the reliability from the low level CHs to the sink is 100% (i.e. the total reliability of the cluster-tree network is equal to R in Equation (3.15)).

End-to-end delay

The total end-to-end delay to transmit a packet from an end node to the sink in the cluster-tree topology is equal to the sum of the end-to-end delays along the path from the end node to the sink. The total end-to-end delay (D_{SCT}) depends on the number of nodes and the packet arrival rate in each level h . It also depends on the location of the end node (i.e. its depth in the tree), the total number of CHs in the network and how

much traffic they are generating. The value of (D_{SCT}) is the combination of Equation (4.28) and Equation (4.31).

5.4 ARSM Scheme

When the implementation of the RSM model [106] is extended to the topology proposed in Figure 5.1, it is found out that at high λ , (i.e. higher than 20 pkts/s) data pack transmissions start to experience excessive delays (in the order of 400 ms and higher depending on the location of the end node in the network). This behaviour is presented in the results section in details. This delay is expected in all cluster-tree topologies where packets arrive to the MAC sub-layer at high rates. The reason behind this delay is that when data packets are forwarded from a lower level CH at a high data rate, upper level CHs cannot fit these packets in the current GTS of the SF duration. Therefore, they have to buffer these packets until the next GTS in the following SF. This delay problem deteriorates if end nodes continue to generate packets at high rates. This delay is a common problem in cluster-tree topologies where the GTS is used to avoid beacon frame collisions. Therefore, this issue must be addressed if the WSN is to be used to monitor delay critical environments with traffic generation rates where the monitored events are expected to have high occurrence frequency. To resolve this delay issue an appropriate QoS provisioning scheme should be used to reduce the end-to-end delay of high priority data. The ARSM scheme is presented which can be implemented in general cluster-tree topologies and can provide QoS guarantees in an adaptive manner especially in highly delay critical events monitoring applications.

The ARSM scheme works as follows; the application layer marks packets that require QoS provisioning with a flag indicating the criticality of such data. The node then uses the analytical model (described in Chapter 4) to estimate the reliability (R) and then

estimates the number of full SF δ this packet is expected to wait in the CH before it is serviced and forwarded to an upper level CH. The estimation of δ depends on several factors such as the number of nodes in each cluster, packet arrival rates, the depth of the CH in the tree, the packet size and other MAC parameters such as the *macMaxCSMABOs* and *macMaxFrameRetries*.

In the ARSM scheme, the tagged node (i.e a node generating high priority data) estimates δ using Equation (4.27) and if it finds the value of δ more than zero, which means that the packet is expected to wait for more than one D_{SF} , and hence the deadline is not going to be met. In this situation the tagged node application layer inserts a flag in its frame to request its CH to double its GTS period so that it can accommodate the increasing λ and to allow the high priority packets to be transmitted to the next CH in the current D_{SF} . Upon arrival of the data packets to the CH, the latter coordinates with its higher level CH to accommodate the request of its end node. After implementing this scheme, it is found out that other end nodes sharing the same cluster with the tagged node take advantage of this scheme even if they are transmitting less urgent data. This happens because all the nodes in the same PAN use CSMA/CA scheme to gain access to the channel and hence all the nodes are treated with high priority. Therefore, to solve this problem and increase the probability of the node generating high priority data in acquiring the medium and transmitting its data, the LDRX scheme (described in Chapter (3)) is implemented on top of the ARSM scheme. In the LDRX scheme the tagged node performs linear BO instead of exponential BO and also preforms CCA in $64 \mu s$ instead of $128 \mu s$. This linear BO period allows the tagged node to come out of its BO duration before other nodes and then it would have higher probability in sensing the medium with a reduced CCA duration. Figure 5.2 shows a flow chart describing the ARSM scheme. Algorithm 2 shows the details of the ARSM algorithm.

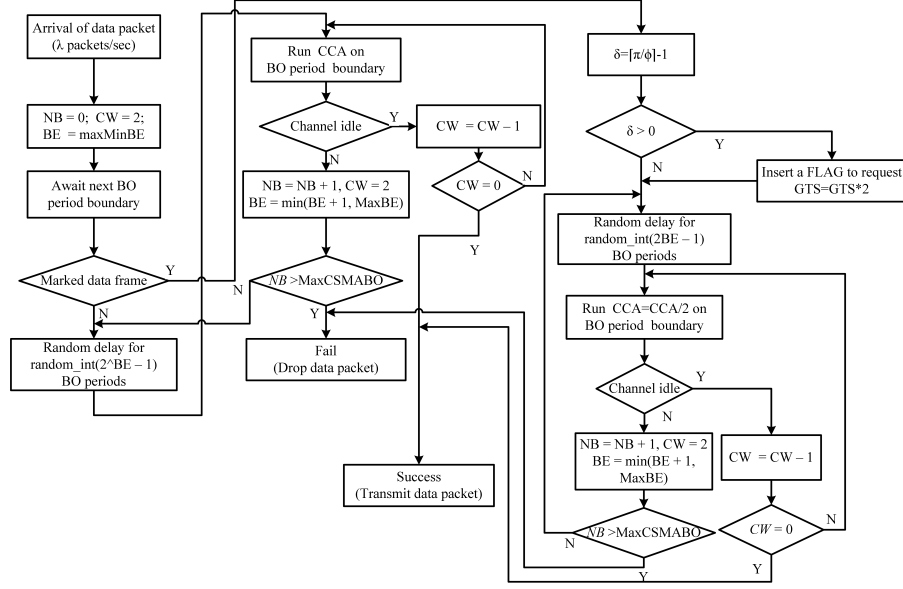


Figure 5.2: A flowchart describing the ARSM scheme.

5.5 Simulation and Analysis

QualNet [97] network simulator is used to simulate the network topology presented in Figure 5.1. Simulation results are compared with the analytical results of the ARSM scheme. The location of the tagged node is changed between cluster(7) and cluster(5). All the simulation parameters are set similar to the mathematical model environment. In both the simulation and the analytical model, Poisson traffic arrivals is used. In all of the clusters in the network the number of end nodes in a (20 m x 20 m) area is varied. All of the end nodes and CHs are operating in the 2.4 GHz band with a maximum bit rate of 250 kbps. Each simulation is run for 400 seconds and each simulation is repeated 10 times. All end nodes within an individual cluster transmit and sense the medium with sufficient power. The noise level is constant throughout the entire simulations. The acknowledgement mechanism is activated in both the simulation and the mathematical model. The power consumed during the buffering state as well as the BO state is assumed to be equal to the power consumed during the idle state. Simulation parameters are set

Algorithm 2 ARSM Algorithm

```

//Arrival of data packets to the MAC sub-layer//
 $NB \leftarrow 0$ ,  $CW \leftarrow 2$ ,  $BE \leftarrow macMinBE$ 
// Frame is marked from the Application layer//
if High priority flag = on then
    //Run the reliability estimation algorithm //
     $E[R]$ 
    //Estimate the number of full SF a packet can wait before being forwarded to the
    next CH//
     $\delta = \left\lceil \frac{\varphi_i}{\mu_i} \right\rceil$ 
end if
if  $\delta > 0$  then
    //insert a flag to request CH to double GTS//
     $GTS_{NEW} \leftarrow 2GTS$ 
    //Use linear random delay and reduced CCA duration//
     $Randomdelay \leftarrow random\_int(2BE - 1)$ 
     $CCA \leftarrow 64\mu s$  //on BO period boundary//
    (Execute IEEE 802.15.4 CSMA/CA Algorithm)
else
    //Use Exponential random delay and normal CCA duration Run the remaining of
    the CSMA/CA normally//
     $Randomdelay \leftarrow random\_int(2^{BE} - 1)$ 
     $CCA \leftarrow 128\mu s$ 
end if
    (Execute IEEE 802.15.4 CSMA/CA Algorithm)

```

similar to Table 3.1, the rest of the parameters are acquired from the IEEE 802.15.4 standard document [5] and the actual specification document of MicaZ platform. In the following analysis, the CH associated with the tagged node is referred to as the “tagged CH”.

Figure 5.3 shows the end-to-end delay of packet transmission from the tagged node to the sink versus λ for different MAC buffer sizes and for the ARSM and the RSM schemes, (the tagged node is located in cluster(5) (refer to Figure 5.1). All clusters in the network are assumed to have 20 end nodes. It is seen that for λ values between 5 pkts/s and 20 pkts/s, the ARSM scheme outperforms RSM scheme for all MAC buffer

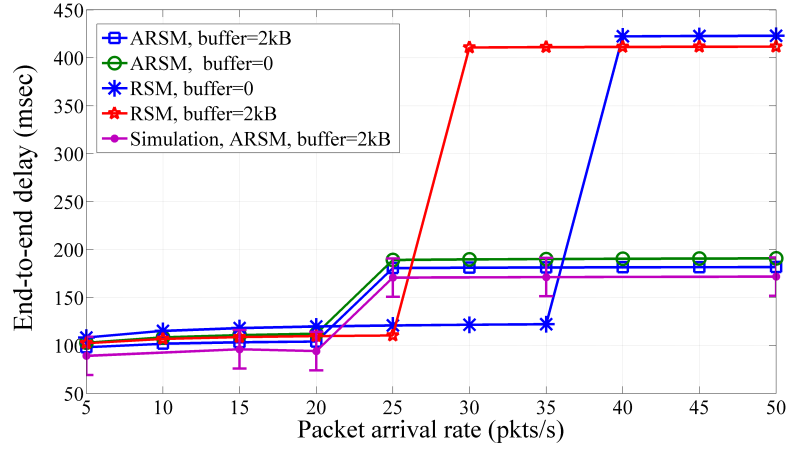


Figure 5.3: ARSM end-to-end delay for different MAC buffer values.

sizes. This delay reduction takes place because the ARSM scheme is using linear BO period and shorter CCA duration. When λ is higher than 25 pkts/s and the MAC buffer size is 2 kB the end-to-end delay drops from 420 ms to 170 ms is shown. This significant delay reduction is due to the extended GTS period, which is adaptively granted to the node by upper level CHs. It is also shown that when λ is between 25 pkts/s and 35 pkts/s the end-to-end delay when the MAC buffer is 0 B is lower than the MAC buffer is 2 kB. This behaviour is normal because when the MAC buffer size is 2 kB, the reliability is higher [106] and hence there will be more packets arriving to the tagged CH and hence miss the current super-frame. However, in ARSM it is shown that this behaviour disappears (i.e. the end-to-end delay always lower when the MAC buffer is 2 kB). It is shown that simulation results of ARSM agree with the analytical results of ARSM for all λ values. The end-to-end delay performance of the ARSM scheme is tested for different network scenarios. This is done by assuming that the tagged node is either located in cluster(5) or cluster(6) as shown in Figure 5.1. In addition to that, CH5 is assumed to receive high priority packets from either a single cluster head (e.g. CH4) or from two cluster heads (e.g. CH4 and CH6) at the same time. Another scenario is when

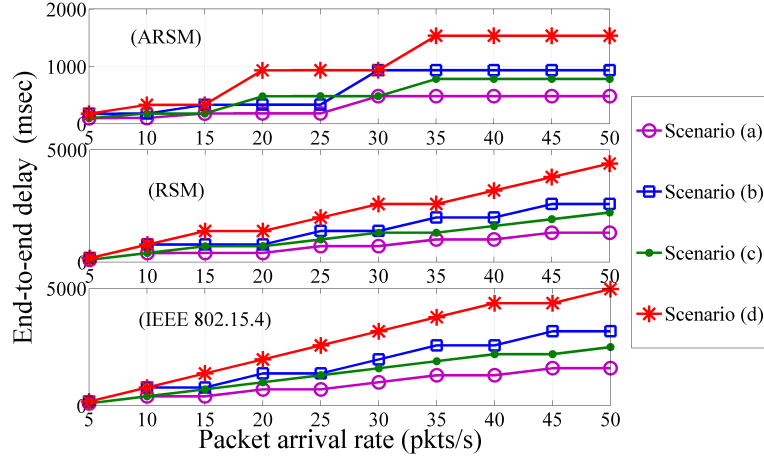


Figure 5.4: ARSM end-to-end delay for different network scenarios.

the tagged node is located in cluster(6) and cluster(6) receives high priority packets from either CH7 or from CH7 and CH8 at the same time. The following four scenarios are simulated: Scenario(a), when the tagged node is located in cluster(5) and CH5 receives high priority data from CH4 at the same rate; Scenario(b), when the tagged node is located in cluster(6) and CH6 receives high priority data form CH7 at the same rate; Scenario(c), when the tagged node is located in cluster(5) and CH5 receives high priority data from CH4 and CH6 at the same rate; Scenario(d), when the tagged node is located in cluster(6) and CH6 receives from high priority CH7 and CH8 at the same rate. Figure 5.4 shows the end-to-end delay of packet transmission from a tagged node versus λ for the different network scenarios. In this simulation the MAC buffer is assumed to be 2 kB for both the RSM and ARSM schemes. It is seen that the ARSM scheme outperforms the RSM scheme and the default IEEE 802.15.4 MAC setting by reducing the delay by approximately 50% for high priority traffic for all network scenarios and traffic rates. It is also seen that this delay reduction becomes highly significant as λ increases and as the tagged node is located further away from the sink (i.e. the depth of the tree increases).

Figure 5.5 shows the end-to-end reliability (i.e. the reliability of packet transmission

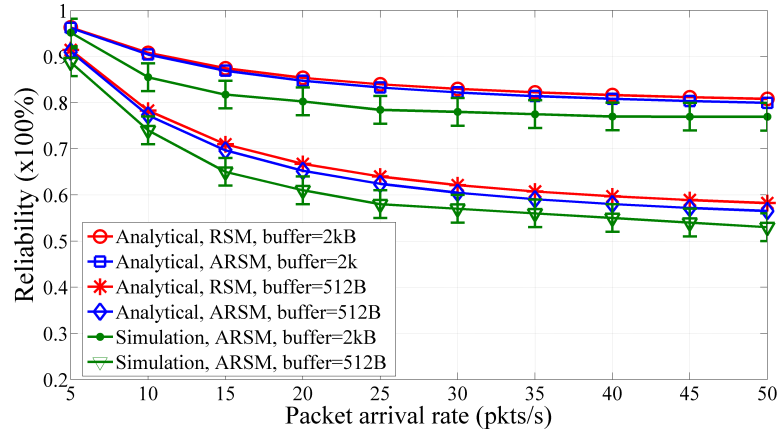


Figure 5.5: ARSM reliability for different MAC buffer sizes.

from the tagged node to the sink) versus λ for different MAC buffer sizes and when the tagged node is located in cluster(5). There are 20 end nodes in all of the clusters. From Figure 5.5, it is seen that there is no significant drop in the reliability when a node implements the ARSM scheme, and that this difference is negligible especially when the MAC buffer size is 2 kB. This indicates that the ARSM scheme is working effectively without affecting the reliability of packet delivery. It is shown that the simulation results of the ARSM scheme agree with the analytical results of ARSM for all λ values.

Figure 5.6 shows the total power consumed in transmitting a packet from the tagged node to the sink versus λ for different MAC buffer sizes when the ARSM and RSM schemes are used (assuming that the tagged node is located in cluster(5)). There are 20 end nodes in all of the clusters. It is seen that there is virtually no difference in the power consumption when a node implements the ARSM scheme (when the MAC buffer size is equal to 2 kB). It is shown that the ARSM scheme does not affect the total power consumption as it significantly reduces the end-to-end delay. Simulation results of the ARSM scheme agree with the analytical results for all λ values.

In Figure 5.7, the number of nodes in each cluster is increased (from 5 to 40) and

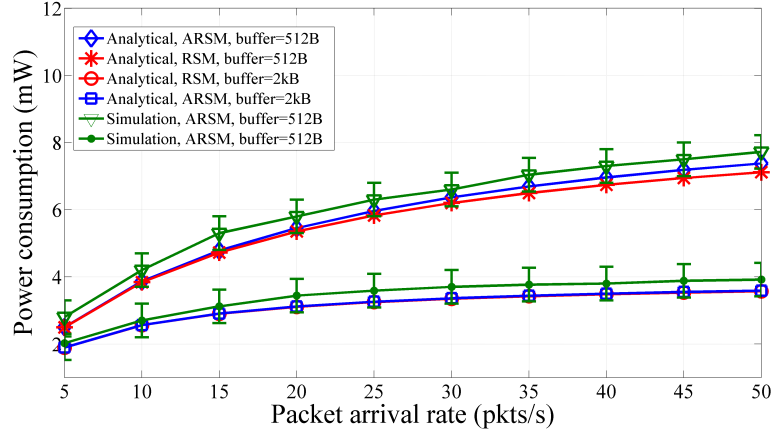


Figure 5.6: ARSM total power consumed for different MAC buffer values.

the end-to-end delay of packet transmission is observed. The tagged node is assumed to be located either two or three hops away from the sink. The value of λ is fixed at 30 pkt/s. It is seen that as the number of nodes increases the end-to-end delay also increase, this takes place because higher number of nodes lead to more contention and higher collisions, thus higher delay. The end-to-end delay drops drastically when a node implements the ARSM scheme compared to the RSM scheme (more than 50% reduction can be observed). The performance is tested when the tagged node is either two or three hops away from the sink. Simulation results of the ARSM scheme agree with the analytical results for all number of nodes and scenarios.

In the previous simulations nodes in the WSN are assumed to be experiencing high traffic generation rates (from 5 pkts/s to 50 pkts/s). These rates are normal in high data rate condition monitoring applications. The performance of the ARSM scheme in low to moderate traffic generation rates is also investigated. Figure 5.8 shows the end-to-end delay of packet transmission from the tagged node to the sink versus λ for low traffic generation rates and two different scenarios, namely Scenario(1), is when the tagged node is located in cluster(4) and Scenario(2), is when an additional tagged node is generating

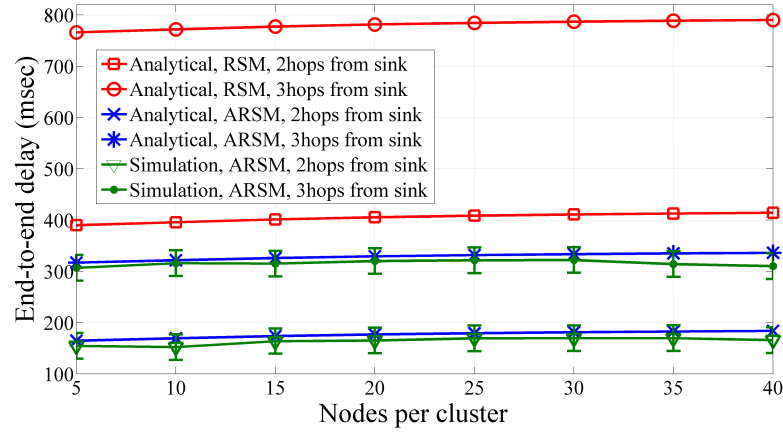


Figure 5.7: ARSM end-to-end delay for different number of nodes.

high priority traffic and is located in cluster(9). Each cluster is assumed to contain 20 nodes. It is seen that for low traffic arrival rates, the ARSM does not significantly reduce the end-to-end delay because all of the arriving packets are served during the same SF. However when λ is more than 6 pkts/s (in Scenario(1)), CH4 could not transmit all of the incoming packets during the current SF, hence, a sudden increase in the delay approximately equal to one SF duration is seen. At this point, the ARSM scheme kicks in automatically and drops the delay by approximately 40%. For Scenario(2), it is seen that the end-to-end delay is around 220 ms (for $\lambda > 6$ pkts/s) when the default IEEE 802.15.4 MAC is used, but this delay drops by approximately 40% when the ARSM is implemented.

Figure 5.9 shows the total power consumed in transmitting a data packet from the tagged node to the sink for low traffic generation rates. It is seen that there is no major difference in the power consumption when the node is implementing the ARSM scheme. These results also show that the ARSM scheme does not significantly affect the total power consumption as it reduces the end-to-end delay. Simulation results of ARSM agree with the analytical results for all λ values for the reliability and the power

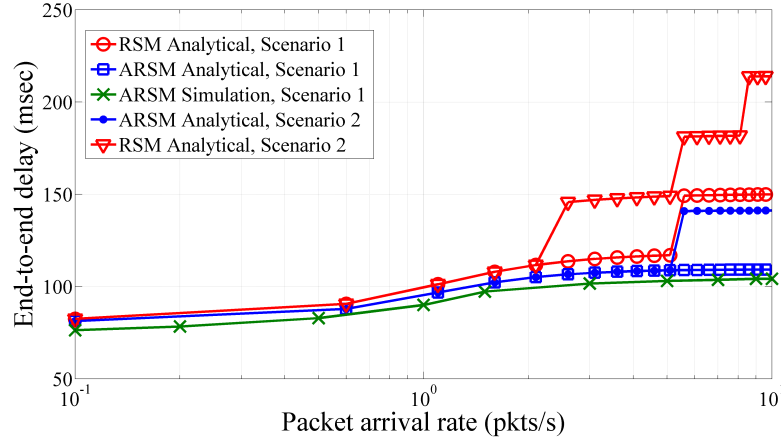


Figure 5.8: ARSM end-to-end delay for a three-hop WSN.

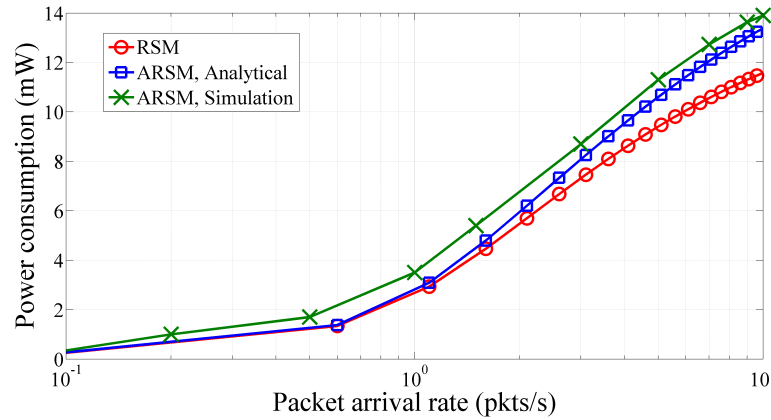


Figure 5.9: ARSM total power consumed for low traffic generation rates.

consumption.

Figure 5.10 shows the reliability of packet transmission from the tagged node to the sink versus λ for low traffic generation rates, the tagged node is located in cluster(5). There are 20 end nodes in each cluster. It is seen that as λ increases the reliability drops. From Figure 5.10, it is seen that there is no significant drop in the reliability when a node implements the ARSM scheme, and that this difference is negligible when taking into account the delay reduction at high λ .

Figure 5.11, shows the end-to-end delay of packet transmission from an end node to

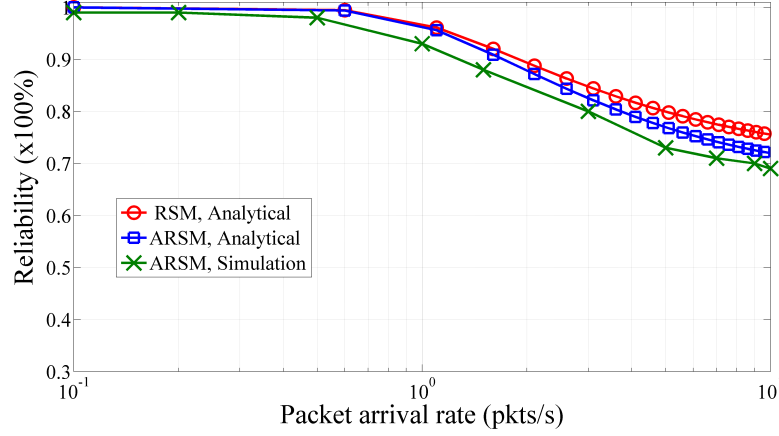


Figure 5.10: ARSM reliability for low traffic generation rates.

the sink as a function of the two MAC parameters ($macMaxCSMABOs$ and $macMaxFrameRetries$), the end node is assumed to be located in cluster(9). The number of nodes in each cluster is assumed to be 30 and λ is 30 pkts/s, in this scenario the MAC buffer is assumed to be equal to 2 kB. It is seen that as the $macMaxFrameRetries$ and $macMaxCSMABOs$ increase the end-to-end delay increases. This is due to the fact that as the frame retries increase more nodes try to access the channel and therefore, data transmission experience higher delays. Similarly, as the number of BOs increase, all the nodes sharing the same PAN spend more time backing off which leads to an increase in the delay. It is seen that when a node runs the ARSM scheme (Figure 5.11(b)) there a significant reduction (more than 40%) in the end-to-end delay compared to default IEEE 802.15.4 MAC (Figure 5.11(a)) for all MAC parameters values.

Figure 5.12 shows the end-to-end delay of packet transmission from an end node to the sink for different packet sizes and λ values for the default IEEE 802.15.4 MAC setting (Figure 5.12(a)) and the ARSM (Figure 5.12(b)) scheme. In this scenario, each cluster is assumed to contain 30 nodes and the tagged node is assumed to be located in cluster(9). It is seen that as the packet sizes increase the end-to-end delay slightly increases for low

λ values. There is a reduction in the delay in the two approaches when the packet size is higher than 60 B and λ is more than 40 pkts/s. This takes place because the network reaches optimum packet size where the contention within a single cluster is reduced which leads to less retransmission and hence lower end-to-end delay. Furthermore, for all packet sizes and λ values the ARSM scheme significantly outperforms the default IEEE 802.15.4 MAC. Figure 5.13 shows the channel utilization of both the default IEEE 802.15.4 MAC

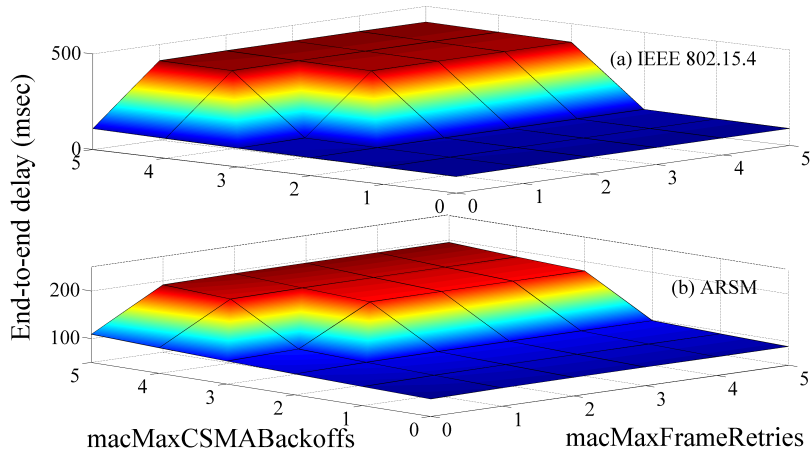


Figure 5.11: ARSM end-to-end delay for different MAC parameters.

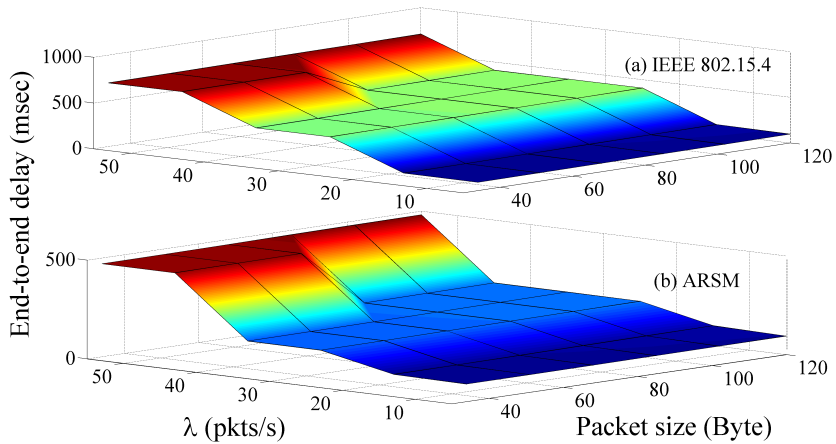


Figure 5.12: ARSM end-to-end delay for different packet sizes and λ values.

setting (Figure 5.13(a)) and the ARSM (Figure 5.13(b)) scheme versus the number of

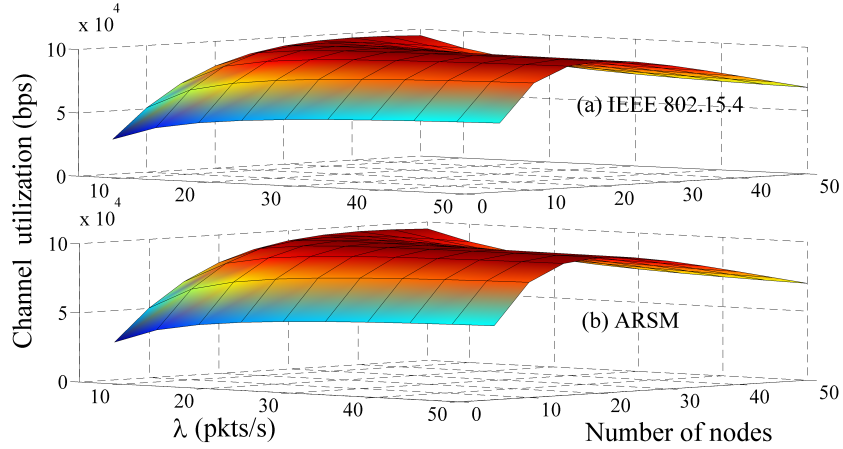


Figure 5.13: ARSM channel utilization for the ARSM and RSM schemes.

nodes in the cluster and λ . It is seen that there is no change in the channel utilization when a node implements the ARSM scheme.

5.6 Conclusion

In this chapter, an adaptive delay reduction scheme for cluster-tree WSNs was presented for delay critical high data rate condition monitoring and control applications. Analytical and simulation results showed that the ARSM scheme significantly reduces the end-to-end delay for high data rate event monitoring. The presented scheme solved the excessive latency by adaptively modifying the GTS based on requests made from the end devices after probabilistically estimating the WSN operating conditions. A delay reduction of more than 50% was achieved when the ARSM scheme was implemented, and at the same time, high reliability and low power consumption values were maintained.

The delay reduction achieved by implementing the ARSM scheme enhances the performance of the WSNs application in monitoring critical environments. The ARSM achieved this QoS differentiation with minimal modifications to the IEEE 802.15.4 MAC protocol.

In the next chapter an other adaptive QoS differentiation scheme based on an optimization model run in CH of a cluster-tree WSN is presented. The model combines the ARSM scheme with a distributed optimization algorithm.

Chapter 6

QoS-aware Inter-Cluster Head Scheduling in WSNs

6.1 Introduction

Most power grid monitoring applications are based on on-site diagnoses of suspected equipment using portable diagnoses instruments. The available on-line monitoring systems are based on systems with infrastructures [129] that are in most cases very expensive and require constant maintenance. Furthermore, some on-line monitoring systems are based on Radio Frequency (RF) transmission [130]. These RF-based systems can wirelessly provide measurement to a base station. However, these systems have limited coverage and cannot provide information on multiple networked systems, which is considered vital in studying the correlation between incidences in multiple devices. WSNs are expected to be excellent candidates to replace manual diagnoses and other infrastructure-based on-line monitoring systems.

The use of WSNs with multi-hop cluster-tree and mesh topologies, it is essential to overcome the coverage problem and to prevent any losses due to multipath reflections

or path losses resulting from the nature of the environment [131]. In WSNs with such topologies a CH or a relaying node is expected to forward packets from its own cluster as well as from other CHs or nodes connected to it. In monitoring applications where the packet arrival rate is expected to be very high, CHs located in the middle of the tree (intermediate level CHs) may be overwhelmed with incoming traffic. This increase in traffic arrival at an intermediate level CH combined with a low transmission bandwidth could lead to serious delays and packet drop rates which might eventually lead to the failure of the entire monitoring system. Therefore, to mitigate this delay problem an optimization problem to minimize the delay and transmit as much data as possible in addition to providing firm QoS guarantees to critical monitoring data (critical data is defined as a data that requires a near real time attention) is formulated.

In this chapter, two QoS schemes for WSNs based on distributed optimization model implemented in the CHs of a cluster-tree or relaying nodes in a mesh topology are presented. The presented QoS schemes can find an optimum delay for specific reliability values. In addition to that, the presented Adaptive Inter-CH Delay Control (AIDC) scheme for cluster-tree topology and QoS-aware GTS Allocation (QGA) scheme in mesh-based WSNs can reduce the end-to-end delay of delay of critical data in smart grid monitoring and control scenarios. Both the AIDC and QGA schemes build on the mathematical model presented in Chapter 4. However, they presents major improvements to that model by presenting an optimization model for a multi-hop cluster-tree and mesh topologies and by solving the issue of excessive latency by adaptively providing QoS guarantees to delay critical applications.

6.1.1 Related work

Channel access techniques in cluster-tree based WSNs have been discussed in numerous studies. These studies discuss the timing and scheduling of cluster-tree WSNs topologies [99, 118, 111]. Most of this work assume that all sensor nodes in the network use scheduling or timing between CHs and end devices, whereas in the AIDC scheme the combination of two channel access schemes is assumed to be used to achieve best performance for smart grid monitoring application.

Other studies discuss the optimization of some operating conditions in a cluster tree topology [132, 133]. Most of these papers discuss the optimization of routing [120], network life time [134] and optimum sensor positions in the network [133].

In [132], the authors have proposed a technique to schedule the SFs of cluster-tree IEEE 802.15.4 networks over multiple channels to avoid beacon frame collisions as well as GTSs collisions between multiple clusters. In the AIDC scheme, the communication between CHs is suggested to take place using mutual scheduling of interfering CHs which requires minimal changes to the hardware as well as the communication protocol.

In [135], the authors have introduced a cross-layer solution for packet size optimization in WSNs to capture the effects of multi-hop routing, the broadcast nature of the physical wireless channel, and the effects of error control techniques. They have showed that longer packets reduce the collision probability in WSNs. They have formalized an optimization solution using three different objective functions, Furthermore, they have also investigated the effects of end-to-end delay and reliability constraints required by a particular application. In this chapter, an entirely different approach is followed to derive the optimization model that minimize the end-to-end delay in a cluster-tree WSN. In addition to that, a technique is proposed to reduce the delay by allowing CHs to choose the optimum packet arrival rates.

6.2 Delay Optimization Model

In this section the delay optimization model for cluster-tree topology is explained, later in this chapter, assumptions for the mesh topology are presented.

In a beacon-enabled WSN, a CH can only receive packets during the active period of the SF duration, where the SF duration is mainly controlled by the SO [5]. In the AIDC scheme, CHs are assumed to use the CAP to receive data from their own cluster and the CFP to receive data from other CHs. Therefore if a CH increases the CAP it expects to receive more packets from end nodes connected to it and if it increases the CFP it expects to receive more packets from the lower level CHs.

The main objective of the optimization model is to allow an intermediate level CH to minimize the one hop inter-CH delay, D_{int} . This is done by allowing the CH to adjust the CAP and the CFP based on the packet arrival rate at the CH and priority of these packets. In other words, the amount of packets expected at a CH depends on the rate of successful packet transmission (reliability) and on the time slot allocation for the CAP and CFP. The focus of this chapter is on deriving an optimization model for an individual CH at a specific level, other CHs run the same optimization model. By combining these optimization models the overall end-to-end delay from the tagged node to the sink can be minimized. Since CHs use scheduling during the CFP of the SF, then the value of the inter-CH delay D_{int} (in time slots) can be given by the Equation (4.29).

The value of λ depends on the the bit rate of the on-board Analogue to Digital Converter (ADC). Therefore, the value of λ can be obtained by using the following relation;

$$\lambda = \frac{\gamma}{l} \quad (6.1)$$

The bit arrival for high data rate monitoring applications is assumed to be in the range

of kbps (based on the data available in [136]) and the packet size is assumed to be equal to 120 B. In the following analysis, the value of λ is varied to study its effects on the performance of the WSN. Furthermore, it is seen that the value of λ is a pivotal factor for the optimization problem. The number of the packets arriving at the CH (ϵ) depends on the tree depth and the number branches connected to the tagged CH.

The reliability R is related to the probability of successful packet transmission which is given by Equation (3.15).

It is seen that value of the R depends on the MAC parameters, the number of nodes as well as the packet arrival rates.

Based on the above assumptions and equations, the objective function is to minimize D_{int} from the local CH to the sink as a function of λ . The objective function and the constraints are described below:

$$\begin{aligned}
 & \underset{\lambda}{\text{minimize}} && D_{int}(\lambda) \\
 & \text{subject to} && \mu + \epsilon = \psi \\
 & && \kappa \geq \mu \geq 0 \\
 & && v \geq \epsilon \geq 0 \\
 & && \lambda_{min} \geq \lambda \geq \lambda_{max}
 \end{aligned}$$

General smart grid monitoring applications require certain reliability and latency values to be achieved. For example, monitoring high voltage transformers require that the reliability to be between (98% - 99%) [125], other applications can accept lower reliability values. The minimum reliability R_{min} is normally specified by the smart grid operator who is monitoring power grid asset. Equation (3.15) is used to solve the optimization problem derived above.

The value of μ is bounded by the maximum number of packets that can be transmitted

from an end node in a local cluster. If no collisions between nodes are assumed, then the maximum number of packets the CH can receive from its own cluster is bounded by (κ) . The value of κ is dependent on the length of the packet (l), the *BaseSlotDuration* and the SO. Since individual CHs communicate among themselves using scheduling during CFP using GTS of the SF duration [5], then the value of ϵ depends on the GTS period of the intermediate level CH and all the received packets should be accommodated in this period. The maximum value of ϵ is bounded by (v) . The value of v depends on the length of the packet l , the *BaseSlotDuration* and the SO. In a single D_{SF} the intermediate level CH should be forced not to receive more than the combined values of ϵ and μ .

6.3 The AIDC Scheme

In the AIDC scheme, all end nodes in each cluster estimate the expected reliability $E[R]$ of successful packet transmission to their CH using Equation (3.15). Sensor nodes then transmit the reliability estimation results and their packet arrival rates λ to the CH during the beacon exchange phase. If the CH is located in an intermediate level in the cluster tree then it receives ϵ from lower level CHs. The CH uses these values to run the optimization algorithm to find the optimum D_{int} and the corresponding values of the packet generation rate (λ_{opt}) and the optimum time slot allocation between the CAP and the CFP. The optimum value of the time slot allocation corresponds to the maximum number of packets a CH can receive during the entire active period. The CH broadcasts λ_{opt} and the optimum time slot allocation to all nodes in its cluster and to all corresponding CHs.

In the AIDC scheme, four different cases are considered depending on the source of high priority data. The first case is when the CH receives no high priority data (AIDC-1). The second case is when the CH receives high priority data from its own cluster

(AIDC-2). The third case is when the CH receives high priority data from low level CHs (AIDC-3) and finally the fourth case is when the CH receives high priority data from both the local cluster and from lower level cluster heads (AIDC-4). The AIDC scheme solves each of these cases independently.

In the first case, the CH runs the optimization algorithm and broadcast the results to all of the nodes. The nodes must adhere to λ_{opt} to achieve the minimum D_{int} . In this situations the nodes follow the default IEEE 802.15.4 MAC settings.

In the second case, when sensor nodes in the cluster receive λ_{opt} , they run the Weighted Moving Average (WMA) algorithm [137] to further reduce the fluctuations in the read data and then reduce the sampling rate by a factor of ω to achieve λ_{opt} .

$$\omega = \left\lceil \frac{\lambda}{\lambda_{opt}} \right\rceil \quad (6.2)$$

If a sensor node sharply lowers its sampling rate then it takes too long for a change to appear in the moving average and it may miss important events. Furthermore, when a node continues sampling at a high rate then it fails to satisfy λ_{opt} . To perform WMA, the node also collects confidence data based on the location of the measured sample. The following relation to compute the WMA is used:

$$\bar{a} = \frac{w_{t-k}a_{t-k} + \dots + w_t a_t}{w_{t-k} + \dots + w_t} \quad (6.3)$$

where, w_t is the weight of the read value a_t at time stamp t , w_t is assigned by the node to data point depending on its confidence value (if the confidence value is not available then it is assigned a value of 1). k is a given window size.

A sensor node uses k and ω to achieve λ_{opt} . If the value of $k = 0$ and $\omega = 1$, then basically there is no averaging done by the node and the packets are forwarded down

to the MAC sub-layer at rate of λ . Therefore, the node increase k and ω until λ_{opt} is reached. Alternatively, when a sensor node senses a high priority data it sets $k = 0$ and $\omega = 1$ so that it can sample at a maximum allowable sampling rate. This is because some applications require precise measurement, for example, in PD analysis; the operator is interested in all peak values as well as the rise and fall times of these peaks [136]. To overcome the increased latency due to increased λ , the AIDC scheme request double the GTS from their CHs [126]. Therefore, when a failure is detected, the application layer of the corresponding node inserts a high priority flag (ON) in its packets to alert its CH so that it can double its GTS duration to accommodate the increase of the incoming traffic and transmit these packets in the same SF duration. Furthermore, to increase the probability of the node generating the alarm in accessing the channel and transmitting prior to other nodes, the node starts performing LDRX [82].

In the third case, when a lower CH receives high priority data it inserts a flag in its packets so that the higher level CH can increase the duration of the CAP on the expense of reducing the duration of the CFP. In other words, the CH receiving high priority data tunes the CAP and CFP to achieve the optimum D_{int} and to accommodate all of the incoming traffic from lower level CHs. Therefore the term “*tuning factor* (θ)” is introduced which represents the ratio of the CFP to the total active period of the SF duration. For example, if θ increases, more packets will be received from lower level CHs and less from local cluster. Consequently, when θ equals 1 no traffic is received from local cluster during the CAP. Figure 6.1 shows the SF structure with the tuning factor used to optimize the D_{int} .

In the fourth case, when both lower level CHs and a node in local cluster generate high priority packet. The intermediate level CH combines the solutions of the second and third cases to accommodated the high priority traffic from both directions. However, to

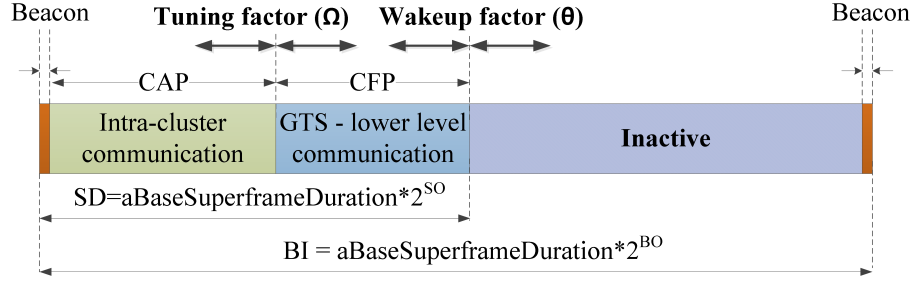


Figure 6.1: AIDC SF scheduling.

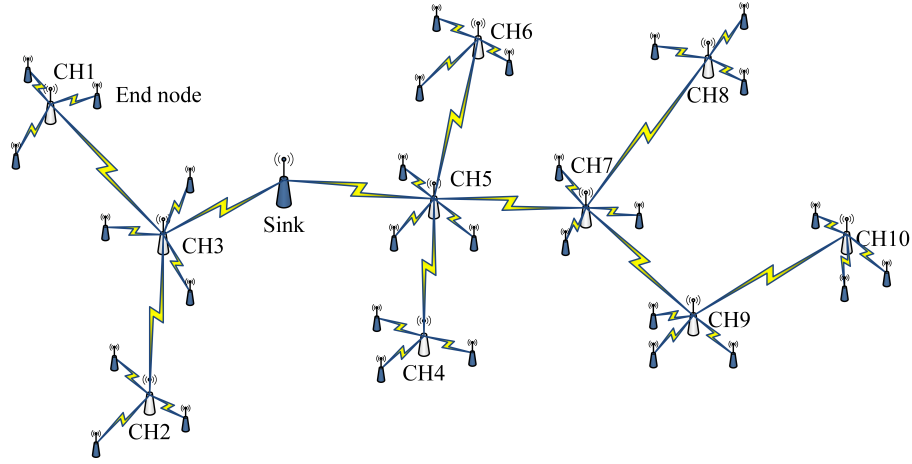


Figure 6.2: The proposed topology for the AIDC scheme.

accomplish this process successfully it utilizes the entire BI for the CAP and CFP using the “wakeup factor” (Ω) (i.e. there will be no inactive period for this CH).

6.3.1 Simulation and Analysis

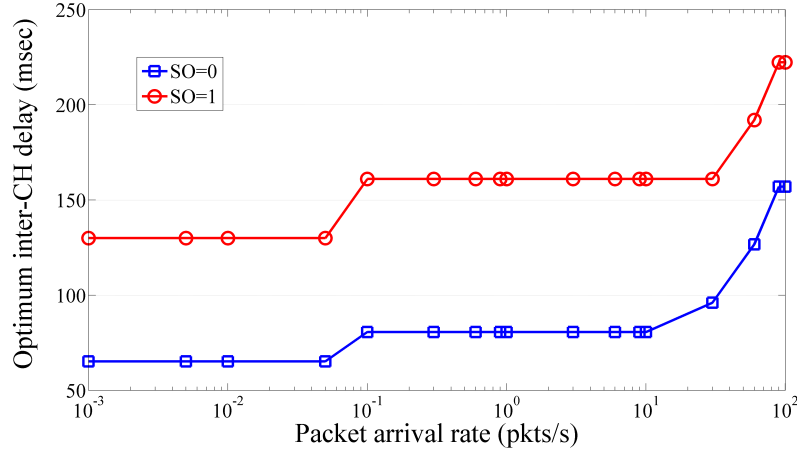
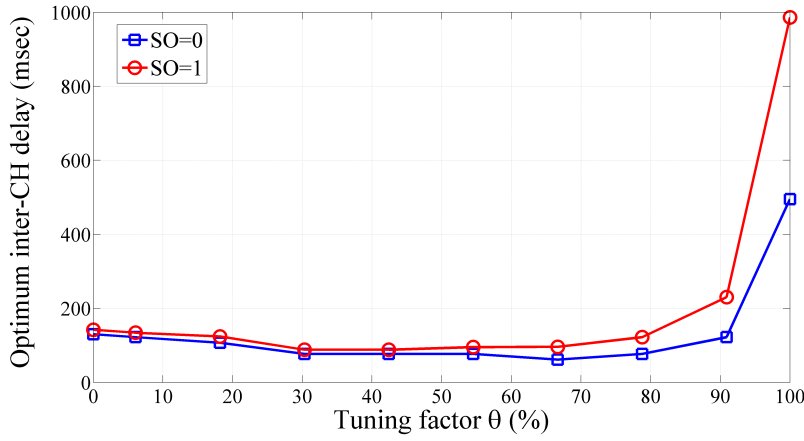
To support the analytical results of the AIDC scheme, the WSN topology presented Figure 6.2 is simulated using QualNet [97] network simulator. All of the simulation parameters are set similar to the parameters of the analytical model. All the nodes in the network are operating in the 2.4 GHz band with a maximum bit rate of 250 Kbps. Each simulation is run for 300 seconds and each simulation is repeated 10 times. All of the nodes in a single cluster are assumed to hear each other. The acknowledgement

mechanism is activated in the network in both the simulation and the analytical model. The power consumed during the buffering state as well as the BO state is assumed to be equal to the power consumed during the idle state. The power consumed in transmitting a packet is equal to the power consumed in receiving a packet. The rest of the parameters are set according to the IEEE 802.15.4 standard document [5] and the actual specification document of MicaZ platform.

The optimization problem is solved using LINGO optimization tool to find the minimum value of D_{int} for different packet arrival rates λ . Figure 6.3 shows the minimum values of D_{int} from a certain CH to the next CH at the i^{th} level for different values of λ and different SO. From Figure 6.1, if the SO is equal to 1 then the D_{SF} is higher than when SO is equal to 0 and hence the CH expects higher number of packets and the delay becomes higher for all λ values.

Figure 6.4 shows the optimum inter-CH delay as a function of the AIDC tuning factor. A high θ value represents a situation where more packets are allowed from lower level CHs (i.e. $CFP > CAP$). It is seen that low values of D_{int} can be obtained if the CH allows up to 70% of the packets to be received from lower level CHs. It is seen that if the CH allows close to 100% of the packets to be received during the CFP, D_{int} increases abruptly due to the congested CAP traffic. It is also shown that if the SO is equal to 1, then there is slight increase in the delay due the increased number of packets received during the longer SF. However, when the θ is close to 100% the delay rapidly increases because of the congested traffic from the CAP and the increased number of packets received from lower level CHs.

Figure 6.5 shows the minimum values of D_{int} from a certain CH to the next CH at the i^{th} level against λ . The results are shown for different R values to illustrate the effect of the desired reliability on the optimum value of the D_{int} . In Figure 6.5 if the

Figure 6.3: Optimum value of D_{int} .Figure 6.4: Optimum value of D_{int} for different θ .

desired reliability is 95% and λ is 30 pkts/s then the optimum D_{int} is approximately 128 ms. However, the optimum D_{int} drops to 110 ms if the desired probability drops to 75%. This happens because as the value of reliability is higher, there would be higher number of packets arriving to the CH, and hence the CH cannot serve all the incoming packets in the current SF. Therefore, an additional delay is seen which equivalent to one SF duration or higher depending on the location of the CH in the tree and the value of λ .

Figure 6.6 shows the end-to-end delay of packet transmission from a tagged node to

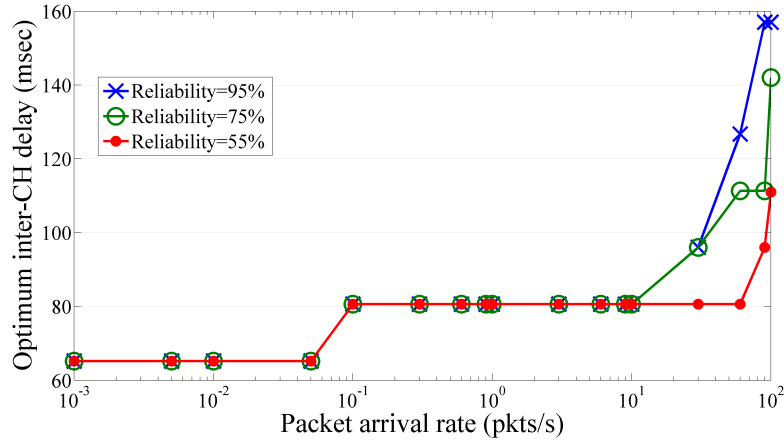


Figure 6.5: Optimum value of D_{int} for different θ .

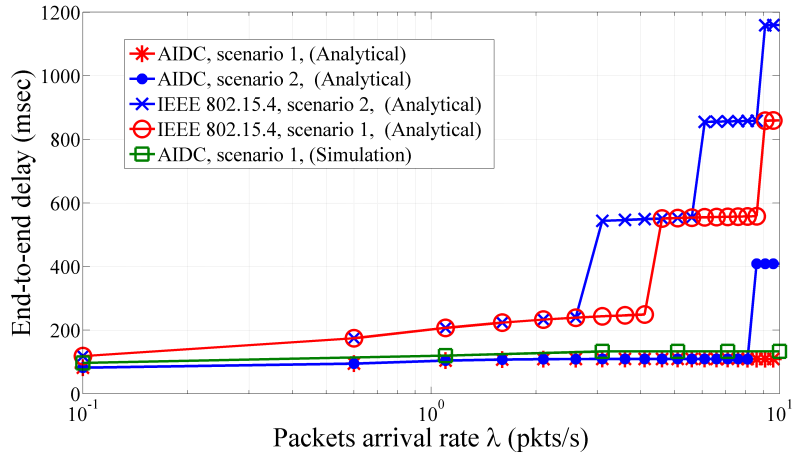


Figure 6.6: AIDC end-to-end delay for different scenarios.

the sink when a node is implementing the AIDC scheme and the default IEEE 802.15.4 MAC for two different network scenarios. Each cluster is assumed to contain 20 nodes. Scenario(1) is when the node generating high priority traffic is located in CH5. Scenario(2) is when the node generating high priority traffic is located in CH7. For both Scenario(1) and (2), it is seen that the AIDC scheme performs the optimization of the D_{int} and significantly reduces the delay especially at high traffic arrival rates. It is shown that the simulation results of Scenario(1) agree with analytical results. Figure 6.7 shows the energy efficiency of transmitting a packet from a node in CH5 to the sink. The

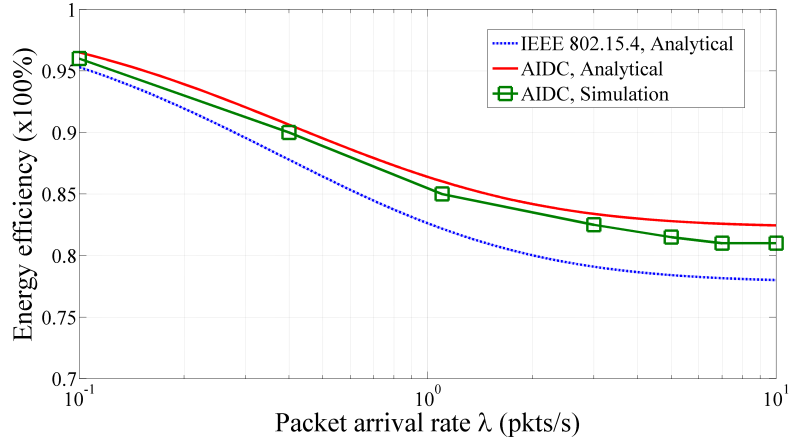


Figure 6.7: AIDC energy efficiency.

energy efficiency is defined as the ratio of the energy consumed in transmitting an actual packet through a cluster-tree network to the total energy consumed in the transmission, BO and retransmissions due to collisions. It is shown that there is slight improvement in the energy efficiency when a node implements the AIDC scheme and the default IEEE 802.15.4 setting. It is seen that even when the tagged node implements the delay reduction at high λ values the energy efficiency is maintained at acceptable values compared to the IEEE 802.15.4 protocol.

Figure 6.8 shows the end-to-end reliability of transmitting a packet from a node located in CH5 to the sink. It is seen that the reliability of a node implementing the AIDC scheme is maintained very close to the default IEEE 802.15.4 MAC setting. For high packet arrival rates there is a slight difference between the two schemes.

Figure 6.9 shows the end-to-end delay of packet transmission from a tagged node to the sink when a node is implementing the AIDC scheme, the default IEEE 802.15.4 MAC and the QoS scheme of [83]. The scheme described in [83] assumes that the node having high priority data performs single CCA with frame tailoring. The scheme of [83] as is referred to as (S-CCA) in the results. The described cases of the AIDC

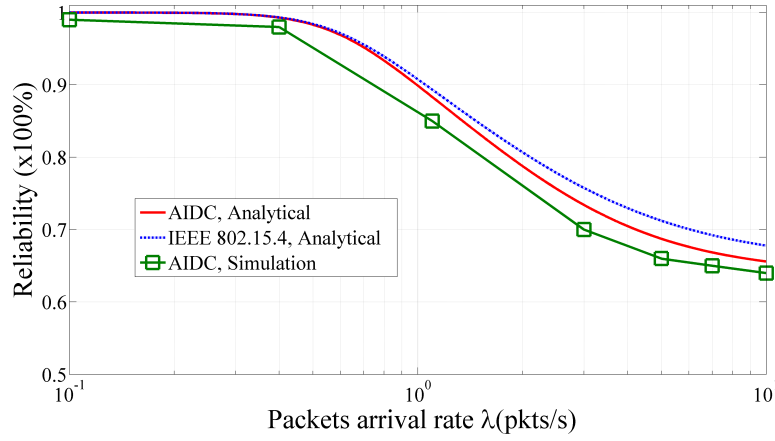


Figure 6.8: AIDC end-to-end reliability.

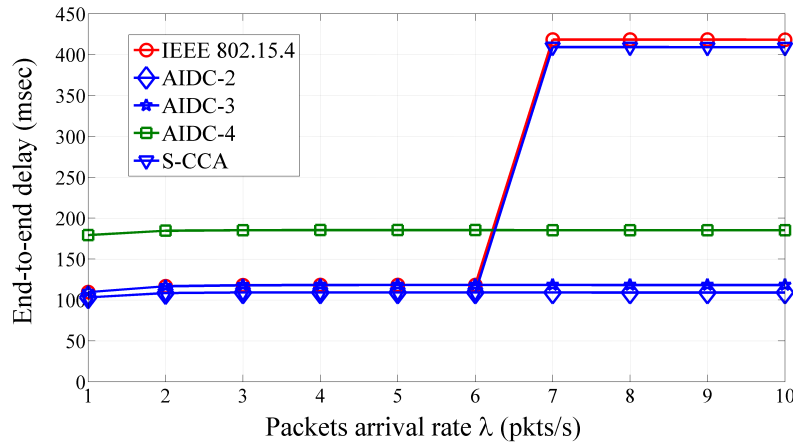


Figure 6.9: AIDC end-to-end delay for different cases.

scheme are run (i.e. AIDC-2, AIDC-3 and AIDC-4). AIDC-1, corresponds to the default IEEE 802.15.4 MAC. Each cluster is assumed to contain 30 nodes. The node generating high priority traffic is assumed to be located in CH1. Furthermore, CH2 and CH6 are assumed to generate high priority traffic in cases 3 and 4. It is seen that the AIDC scheme significantly reduces the delay especially at high traffic arrival rates. In addition to that AIDC-4 performs very well even when multiple clusters generate high priority traffic at the same time.

Figure 6.10 shows the end-to-end delay of packet transmission from a node in CH5

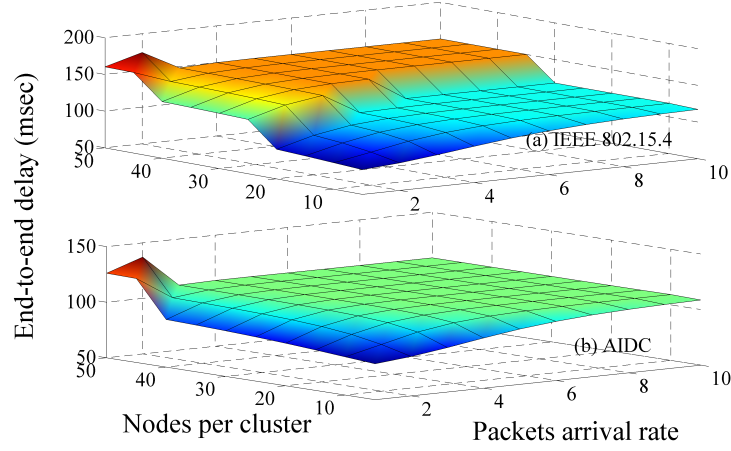


Figure 6.10: AIDC end-to-end delay for different cluster sizes.

to the sink as a function of the packet arrival rate and the number of nodes in CH5. It is seen that for high number of nodes and low λ (the left corner of the plot) the end-to-end delay is highest in both the AIDC and the default IEEE 802.15.4 MAC setting. This behaviour is expected in a cluster-tree network topology since low λ and high number of nodes means more nodes get a chance to transmit and hence more packets being accumulated at the CH leading to excessive delays. However, this delay drops as λ increases, since higher collisions take place within CH5. It is seen that the AIDC significantly reduces the end-to-end delay for all number of nodes and all λ values. In fact it is seen that AIDC has almost a flat performance (i.e. the end-to-end delay does not change much) compared to the default IEEE 802.15.4 MAC setting.

Figure 6.11 shows the channel utilization of the AIDC compared to the default IEEE 802.15.4 MAC protocol versus the packet arrival rates. It is seen that the channel utilization of the AIDC scheme is almost identical to the IEEE 802.15.4 MAC for low packet arrival rates ($\lambda \geq 10$ pkts/s).

Figure 6.12 shows the energy consumed per useful bit as a function of packet size for both the AIDC scheme and the default IEEE 802.15.4 MAC. It is seen that as the

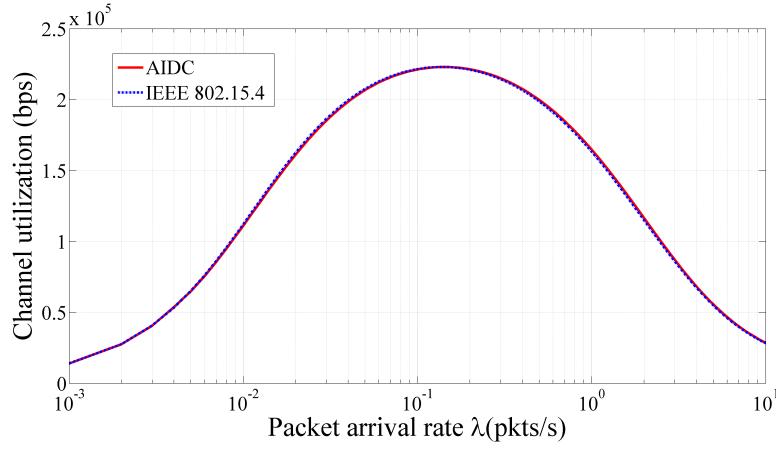


Figure 6.11: AIDC channel utilization.

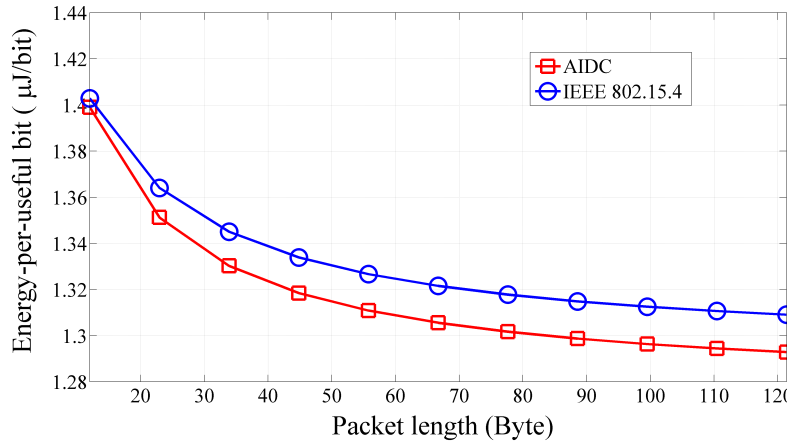


Figure 6.12: AIDC energy consumed per useful bit versus packet size.

packet size increases the energy per useful bit decreases. This is because the packet size is inversely proportional to the packets arrival rate. If the bit rate is constant, then increasing the packet size leads to reduction in λ , which leads to fewer collisions and therefore less energy consumed in transmitting a single bit. It is also seen that the AIDC outperforms the default IEEE 802.15.4 MAC for all packet sizes. To have a more clear perspective of the energy consumed per useful bit, The effects of the arrival rate of a certain phenomenon with the effects of packet size is considered.

Figure 6.13 shows the energy consumed per useful bit versus the packet size and

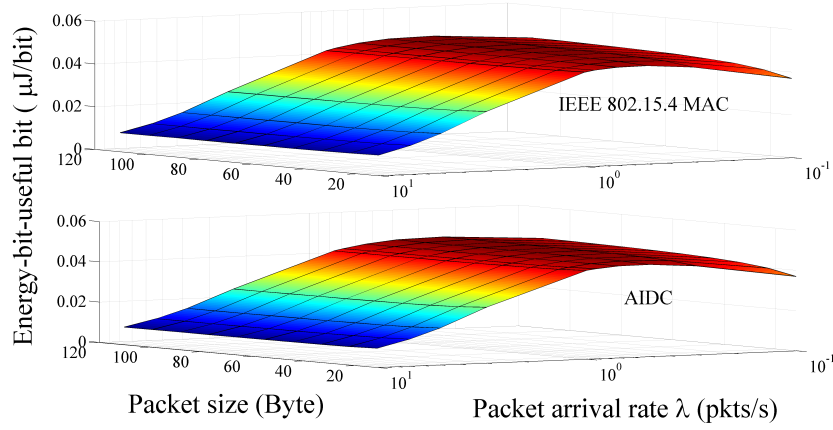


Figure 6.13: AIDC energy consumed per useful bit versus the packet size and λ .

the data arrival rate in kbps. It is seen that as the amount of arriving bits per second increases the energy consumed per useful bit slightly increase. However, when the bit rate continues to increase, nodes in the cluster experience extensive contention, which leads to less number of transmissions and hence less energy consumed.

6.4 QoS-Time Slot Allocation in Mesh-based WSNs

In this section, a QoS scheme for WSNs with multi-hop mesh topologies is presented. The QGA scheme can reduce the end-to-end delay of delay critical data in smart grid monitoring and control applications. QGA works by allowing intermediate level sensor nodes (relaying nodes) in a mesh-based network to run an optimization model that can select optimum time slot allocation to minimize the delay of critical data. In QGA, when a relaying sensor node receives a request for time slot allocation from a node with delay critical data, it allocates the entire CFP to that node and completely rejects access to nodes caring non-critical data. Hence, nodes transmitting less critical data request time slots from alternative relaying nodes or buffer their data until the delay critical

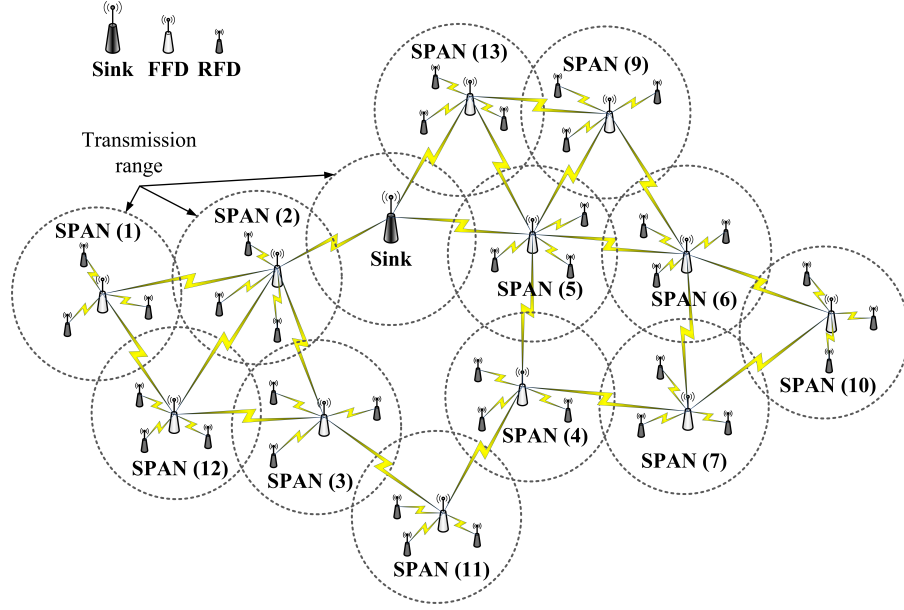


Figure 6.14: The proposed topology for QGA scheme.

traffic passes through this relaying node. The relaying node does that by adaptively and properly allocating time slots to important traffic while depriving less important traffic from time slots.

In the proposed mesh based WSN, sensor nodes are divided into two categories, namely, Reduced Function Devices (RFDs) and Full Function Devices (FFDs). A RFD can only communicate with an FFD (i.e its parent FFD) and can not perform routing. Therefore, its main role is to collect data and forward it to the FFD. A FFD can communicate with its own RFDs and can perform routing through neighbouring FFDs within its transmission range. A number of RFDs are grouped depending on their location and functionality into a single Sub-Personal Area Network (SPAN) as shown in Figure 6.14. In Figure 6.1, the SF duration is mainly controlled by the SO [5]. FFDs are assumed to use the CAP to communicate with their own RFDs and the CFP to communicate with neighbouring FFDs. This assumption is vital in WSN scenarios where the number of RFDs used to monitor an environment or an equipment is high, which makes using CFP

not a good choice because of the limited GTS. On the other hand, using CAP for FFD communication is not a good choice either, this is because the FFDs are located far apart which makes them unable to hear each other and hence a collision problem arises due to hidden terminal.

The optimization model presented in Section 6.2 allows an intermediate-level FFDs (i-FFDs) to minimize one hop inter-FFD delay, D_{FFD} . This is done by allowing an i-FFD to adjust the CAP and the CFP based on the packet arrival rate and priority of these packets. In other words, the amount of packets expected at an i-FFD depends on the rate of successful packet transmission (the reliability) from its own RFDs and neighbouring FFDs and also on the time slot allocation for the CAP and CFP. By combining D_{FFD} and the delay from a RFD to its FFD, the overall end-to-end delay from a RFD to the sink can be minimized.

Since FFDs use scheduling during the CFP of the SF, then the value of the D_{FFD} (in time slots) can given by Equation (4.29).

6.4.1 The QGA Scheme

In the QGA scheme, the WSN with multihop mesh topology described in Figure 6.14 is followed. In smart grid monitoring scenarios a FFD is considered to receive high priority data from RFDs in its SPAN or from one or more neighbouring FFD. In the QGA the following assumptions are followed:

- Packets arrive at the MAC sub-layer with an arrival rate of λ pkts/s.
- RFDs use CSMA/CA during the CAP to communicate with their parent FFDs.
- FFDs use scheduling during the CFP to communicate with neighbouring FFDs.

- FFDs use directed diffusion routing described in [138] to route the packets through multihop route to the sink node.
- Each FFD is at least connected to two other FFDs (i.e. there is always a secondary path to route the packets to the sink).
- FFDs perform the optimization scheme described above [139] to minimize D_{FFD}

In the QGA scheme, four cases are considered. These four cases are explained below:

Case 1 (QGA-2) is when neither a RFD nor a FFD generate high priority traffic. In QGA-1, the i-FFD divides the SF duration equally between the CAP and CFP as shown in Figure 6.1.

Case 2 (QGA-2) is when one or more of the RFD generate high priority traffic. In QGA-2, the node implements the ARSM scheme described in Chapter 5 [126]. In this scheme a RFD requests double the GTS from its FFD to allow all of the incoming packets to be transmitted in the current SF.

Case 3 (QGA-3) is when a neighbouring FFD generates high priority traffic. In this case the i-FFD uses the θ to control the allocation of the the time slots between the CAP and CFP. In QGA, the FFD uses θ which is defined as follows; $\theta = \frac{CAP}{CFP}$. when $\theta = 1$, RFDs and neighbouring FFDs have the same time slot allocation. On the other hand, when $\theta < 1$, the neighbouring FFDs get more time to transmit their packets. Therefore, in QGA-3, the forwarding i-FFD reduces θ to 0.25 and does not grant any GTS to other FFDs that are not generating high priority traffic. In this situation the “blocked FFD” has to seek an alternative time slot to transmit its packets since it was not granted any access from one FFD.

Case 4 (QGA-4) is when the forwarding i-FFD receives high priority data from more than one direction. In QGA-4, the FFD uses the wakeup factor (Ω) to control its SF duration refer to Figure 6.1. The value of Ω is equal to the ratio of the SF to the BI. $\Omega = \frac{SD}{BI}$, when $\Omega = 1$ the active duration is equal to the inactive duration. In QGA-4, a FFD increase the value of Ω to two and uses θ to control CFP and CAP based on the source of the high priority traffic.

6.4.2 Simulation and Analysis

To evaluate the performance of the QGA scheme, the WSN topology presented in Figure 6.14 is simulated with various network and traffic conditions. All RFDs in a single SPAN are assumed to be able to hear each other. The acknowledgement mechanism is assumed to be used in the network. The power consumed during the buffering state as well as the BO state is assumed to be equal to the power consumed during the idle state. The power consumed in transmitting a packet is assumed to equal the power consumed in receiving a packet. The *macMaxFrameRetries* is set to 3, *macMaxCSMABo*s is set to 4 and the *macMinBE* is set to 3. The MAC buffer size is set to 512 B [106]. The packet size is 120 B and to test the performance of QGA, the number of nodes and λ is varied in each of the SPANs shown in Figure 6.14. The rest of the parameters are set according to the IEEE 802.15.4 standard document [5].

Figure 6.15 shows the full SF duration a transmitted packet is expected to wait in an i-FFD before it is transmitted to the next FFD as a function of number of time slots allocated to that packet by the i-FDD for three different scenarios. Scenarios(1), (2) and (3) are when there are 5, 3 and 1 SPANs generating high priority traffic and are transmitting to the same i-FDD respectively. It is seen that as the number of time slots allocated increase, the the expected number of full SFs a packet should wait in an i-FFD

decrease. This is expected behaviour as the i-FDD is allowing more time for incoming packets either from neighbouring or from local SPANs.

Figure 6.16 shows the end-to-end delay of packet transmission from a RFD to the sink when a node is implementing the QGA scheme and the IEEE 802.15.4 MAC protocol. Two different scenarios are simulated, namely, scenario(1) and scenario(2). Scenario(1) is when the RFD is located in SPAN(6) and the FFD of SPAN(6) is receiving high priority traffic from SPANs(7) and (10) at the same time. Scenario(2) is when the RFD is located in SPAN(2) and the FFD of SPAN(2) is receiving high priority traffic from SPAN(1). It is seen that in both scenarios the end-to-end delay drops sharply when the QGA scheme is implemented. This is because all the FFD along the path from the source of high priority traffic to the sink block other incoming traffic by not allotting GTSs in the SF duration. Non-high priority traffic is transmitted through other FFDs which do not encounter high priority data. However, if other FDDs also encounter high priority traffic the non-high priority traffic is buffered in the i-FFD until it is served in the next round of communication.

Figure 6.17 shows the total power consumed in transmitting a packet from a RFD generating high priority traffic and the sink for QGA and the IEEE 802.15.4 MAC protocol. The RFD is assumed to be located in SPAN(2). It is seen that the power consumption is slightly higher when the QGA scheme is implemented, this is expected behaviour as the node generating high priority traffic is transmitting more often than when it is using the default IEEE 802.15.4 MAC protocol.

Figure 6.18 shows the end-to-end reliability of transmitting a packet from a RFD located generating high priority traffic and the sink for QGA and the IEEE 802.15.4 MAC protocol. The RFD is assumed to be located in SPAN (2). It is seen that the reliability drops slightly the QGA is implemented. This is because RFD implements

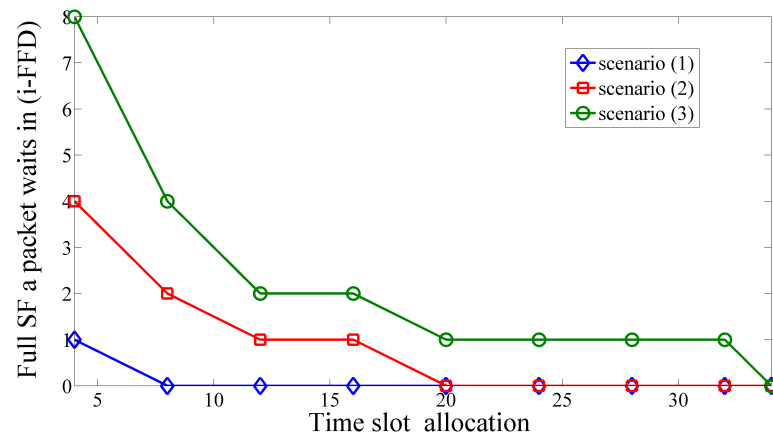


Figure 6.15: QGA SF waiting duration.

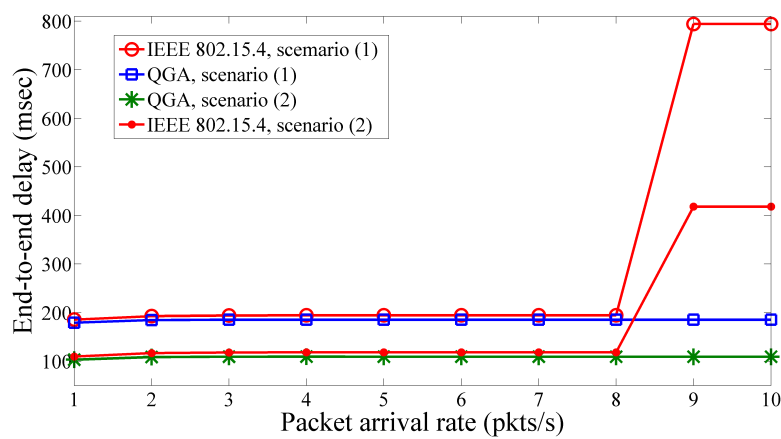


Figure 6.16: QGA end-to-end delay of packet transmission.

linear BO to reduce the end-to-end delay and that causes a slight increase in collision among other nodes sharing the same SPAN.

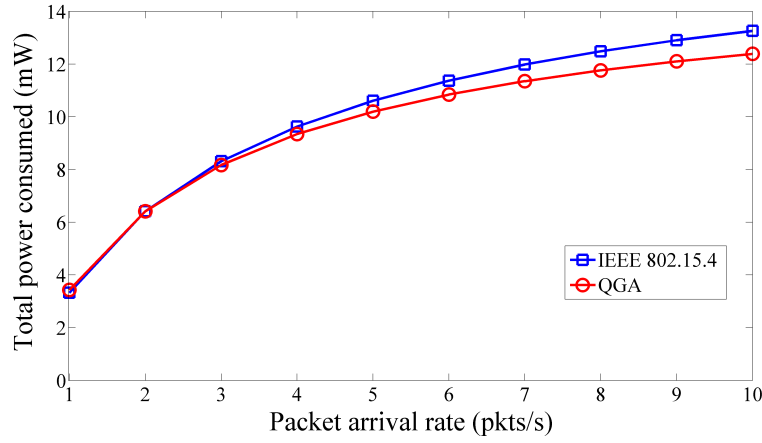


Figure 6.17: Total power consumed.

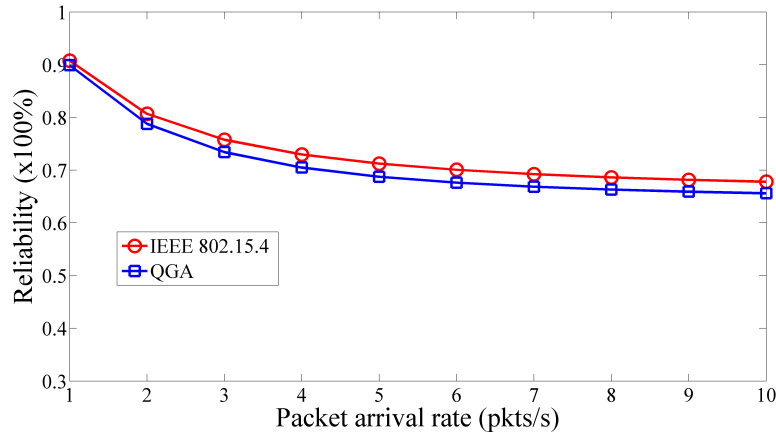


Figure 6.18: QGA reliability.

6.5 Conclusion

Monitoring high data rate signals (such as PD activities) in the smart grid calls for modifications in the operation of the IEEE 802.15.4-based WSNs to achieve accurate and reliable monitoring.

In this chapter, an optimization model was presented for cluster-tree and mesh based WSNs that can allow each CH to globally optimize the inter-CH delay while maintain-

ing acceptable reliability values. A scheme based on the optimization model was also presented to provide QoS differentiation and significantly reduce the end-to-end delay of high priority data. The presented scheme could adaptively change the MAC parameters to achieve the delay reduction and can invert back to normal IEEE 802.15.4 MAC setting when there is no high priority data. Simulation and analytical results showed that the AIDC scheme could reduce the end-to-end delay by more than 50% while maintaining acceptable reliability and energy efficiency values.

A scheme based on an optimization model to provide QoS differentiation and significantly reduce the end-to-end delay of high priority data in mesh-based WSNs was presented. The presented scheme could adaptively change the MAC parameters to achieve the delay reduction and can invert back to normal IEEE 802.15.4 MAC setting when there is no high priority data. Delay reduction was achieved by adaptively allocating larger time slots to high priority traffic while rejecting access to traffic with no priority. Low priority traffic is either granted time slots in intermediate nodes with no critical data or it is buffered until the high priority instance passes. Simulation results showed that the QGA scheme could sharply reduce the end-to-end delay while maintaining acceptable reliability and energy consumption values.

Chapter 7

Conclusions and Future Research

7.1 Conclusions

In this thesis, the issue of providing Quality of Service (QoS) differentiation to Wireless Sensor Networks (WSNs) that are used for delay critical monitoring application was extensively studied. Different smart grid scenarios were used as examples of a delay critical application. Providing QoS to the resource limited WSNs is a challenging topic and is gaining increasing focus by the research community. QoS for WSNs is diverse and varies depending on the application and on the network layer where the QoS approach is to be implemented. Some studies have considered implementing QoS in the network layer as an optimum solution, others consider implementing it in other layers such as the application or the MAC. In this work, the main focus was to implement QoS solutions in the MAC layer and use a cross layer approach which combines more than one network layer to achieve the requirement.

Initially, three novel priority and delay-aware medium access techniques that utilize cross layer approaches were proposed and extensively investigated. These techniques respond to the delay requirements of smart grid applications by predicting the end-to-

end delay and creating cross layer measures.

The first scheme, namely Delay-Responsive Cross layer (DRX), first estimates the end-to-end delay using an existing analytical model and if the estimated delay cannot meet the delay requirements of this application, then DRX reduces the Clear Channel Assessment (CCA) duration, in order to allow the high priority packet to access the medium before other contending packets. The second scheme, namely Fair and Delay-aware Cross layer (FDRX), incorporates fairness into delay-sensitive data transmission by yielding other nodes periodically to allow other nodes in the network to transmit their data periodically. The third scheme, namely, Delay-Responsive, Cross layer scheme with Linear back-off (LDRX), was tailored for a WSN with cluster-tree topologies. The LDRX scheme, allows sensor nodes with high priority data to utilize linear BackOff (BO) instead of exponential BO. Results showed that the DRX, FDRX and LDRX schemes adaptively reduces the end-to-end delay of high priority data packets while maintaining constant reliability and power consumption compared to the default IEEE 802.15.4 MAC protocol.

A new analytical model, namely, Realistic and Stable Markov-based (RSM), was presented for the MAC sub-layer of the IEEE 802.15.4 standard that can be used by QoS provisioning schemes instead of the existing analytical models which were previously used. The model considered WSNs with star and cluster-tree topologies. Actual traffic generation rates were included rather than a predefined idle state length to study the overall performance in terms of the end-to-end delay, reliability and power consumption. The impact of modelling MAC-level finite buffers on the performance of these WSNs was also included in this model. The proposed model was validated through extensive simulations. Results showed that introducing a finite MAC buffer into the model improves the network performance in terms of end-to-end delay, reliability and power consumption.

A novel adaptive delay reduction scheme for cluster-tree WSNs, namely, Adaptive Realistic and Stable Markov-based (ARSM) scheme, was presented for delay critical high data rate condition monitoring and control applications. Results showed that the ARSM scheme significantly reduces the end-to-end delay for high data rate event monitoring. The ARSM scheme solved the excessive latency by adaptively modifying the Guaranteed Time Slot (GTS) based on requests made from sensor nodes after probabilistically estimating the WSN operating conditions using the RSM model. A delay reduction of more than 50% was achieved when the ARSM scheme was implemented, and at the same time, high reliability and low power consumption values were maintained.

An optimization model based on the RSM model was presented for cluster-tree and mesh WSN topologies. The optimization model allowed each Cluster Head (CH) to globally optimize the inter-CH delay while maintaining acceptable reliability values. Two novel QoS provisioning schemes were proposed based on the optimization model. The two schemes, namely, Adaptive Inter-CH Delay Control (AIDC) and QoS-aware GTS Allocation (QGS) could significantly reduce the end-to-end delay of high priority data by adaptively changing the MAC parameters to achieve the delay reduction and can invert back to normal IEEE 802.15.4 MAC setting when there is no high priority data. Simulation and analytical results showed that the AIDC and the QGS schemes could reduce the end-to-end delay by more than 50% while maintaining acceptable reliability and energy efficiency values. The QGS scheme achieved delay reduction in mesh topologies by adaptively allocating larger time slots to high priority traffic while rejecting access to traffic with no priority.

The delay reduction achieved by DRX, FDRX, LDRX, ARSM, AIDC and QGA schemes enhance the smart grid operation in situations where sudden changes in loads or the generation cycle take place. All of the presented schemes showed that they could

achieve the intended goal of delay reduction without impacting the entire performance of the WSNs. Each of these proposed schemes presented an improvement to the QoS approaches existing in the literature and showed an evolution to the presented schemes in this thesis.

7.2 Future Research

QoS provisioning in WSNs is currently getting more research attention and is being widely investigated. Based on the investigations and findings done in this thesis, there are several areas that can be considered for further future research, these areas can be summarised as follows:

- The concept of implementing cross layer approaches between the network and the MAC layers was not investigated in this thesis. The effect implementing a QoS routing protocol with the adaptive cross layer QoS schemes presented in this thesis can be investigated and studied in WSNs with mesh topologies.
- In most smart grid environments, the IEEE 802.15.4 based WSNs might be deployed in locations where there are other wireless devices that use the same frequency spectrum such as the IEEE 802.11 network standard. It would be interesting to study the coexistence of the two standards in such environments and the effect of this coexistence on the proposed QoS schemes proposed in this thesis.
- One of the main concepts in a smart grid monitoring context is to test the communication protocols in a smart grid test beds. The proposed schemes can be tested in test beds and the obtained results can be compared with the simulation and the analytical results.

- In the proposed RSM model, the traffic from the sink to the end nodes is assumed to be for Acknowledgement (ACK) and control purposes, hence it was not considered in the model. In some smart grid applications, sensor nodes might be deployed in environment where an action is required by a sensor. Therefore, it would be interesting to investigate the performance of the proposed analytical model with two directional traffic flows. The effect of the buffer size can be investigated in the presence of traffic flows from the sink to the end nodes.
- The proposed delay optimization model was implemented in every CH or FFD device in the network. The effectiveness of implementing this optimization model in the sink node can be further studied using the same scenarios that were considered with the distributed model.
- The issue of security in smart grid monitoring is one of the main QoS requirements in WSNs that are used for such applications. Security was not considered in this thesis. The effect of implementing a certain security protocol on the performance of the proposed QoS schemes can be investigated and the effect of implementing a security protocol on the end-to-end delay can be studied.

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Appendix A

Confidence Intervals

A Confidence Interval (CI) is used to quantify the uncertainty in any collected sample of data. It is defined as the estimated range of values within which a generated data lies with a specified probability. Simulated results such as end-to-end delay, reliability and power consumption are measured by taking the mean of a successive of n runs, each of long enough time and with different simulation seed to ensure that there no correlation in the presented results. All simulation runs are have the same environment (identical), however they are independent from each other.

As an example, the result for the reliability R is considered, where the n independent results are represented by $R_1, R_2, \dots, R_n$. where R_i represents the reliability of packet transmission obtained from simulation run i .

The mean of all the reliability simulation measurements is therefore given by:

$$\bar{R} = \frac{1}{n} \sum_{i=1}^n R_i \quad (\text{A.1})$$

However, the mean of the independent simulation runs $\bar{R}$ provides a single numerical value for the estimate of the expected value of $E[R] = \mu_S$. In order to know how good

is the estimate provided by $\bar{R}$ for the simulation results, it is necessary to compute the variance (σ_S^2). The variance is given by the following equation:

$$\sigma_S^2 = \frac{1}{n-1} \sum_{i=1}^n (R_i - \bar{R})^2 \quad (\text{A.2})$$

Small σ_S^2 indicates that the results are tightly clustered around $\bar{R}$ and we can be confident the $\bar{R}$ is close to the $E[R]$. On the other hand, σ_S^2 is large, the results are widely dispersed about $\bar{R}$ and we can not be confident that $\bar{R}$ is close to $E[R]$. Instead of seeking a single value to estimate the $E[R]$, we can specify an interval of values that is highly likely to contain the true value of the parameter.

A probability of $1 - \alpha_S$ is defined, an interval $[L(R), U(R)]$ is found such the probability is given by the following relation:

$$P [L(R) \leq \mu_S \leq U(R)] = 0.95 \quad (\text{A.3})$$

This interval contains the true value of the parameter with probability 0.95. Such an interval is a 95% CI.

Using Standard deviation and t-distribution table (since the number of measurements used are less than 30), the lower and upper limits of the CI is calculated using the following relation:

$$L[R] = \bar{R} - \frac{t_{[\frac{0.05}{2}, d_f]} \times \sigma_S}{\sqrt{n}} \quad (\text{A.4})$$

and

$$U[R] = \bar{R} + \frac{t_{[\frac{0.05}{2}, d_f]} \times \sigma_S}{\sqrt{n}} \quad (\text{A.5})$$

where n is the number of measurements, d_f is the degree of freedom and is equal to $n - 1$, σ_S is the standard deviation of the measurements.

In all of the simulations presented in this thesis the CI is calculated based on 10 different runs with each run being 300 second. From the t-distribution the value of $t_{[\frac{0.95}{2}, 9]}$ is found to be equal to 2.262, this value is used in Equations (A.4) and (A.5) to find CI in the presented results. It is found that more than 95% of the results were within the calculated value of CI in all of the simulations.

Appendix B

A Brief Overview of the IEEE 802.15.4 Standard

The IEEE 802.15.4 standard defines the MAC and physical layers including the CSMA/CA process [5]. CSMA/CA is used with a slotted binary exponential BO scheme to reduce collisions. Two channel access techniques are defined in the IEEE 802.15.4 standard; these are the beacon-enabled mode, which employs a slotted CSMA/CA and exponential BO, and a basic unslotted CSMA/CA without beacons.

The MAC sub-layer uses four variables to regulate channel access, these variables are the Number of BOs (NBO), CW, BE and RT. Prior to a particular transmission in the slotted CSMA/CA, the MAC layer initializes the four variables as follows: $NBO = 0$, $CW = 2$, $BE = minBE$ and $RT = 0$. In the next step, the MAC sub-layer delays for a random number of back-off period ranging from 0 to (2^{BE-1}) . When the BO period becomes zero, the node can perform the first CCA for a certain amount of time. If two successive CCAs are idle, then the node is allowed to start packet transmission. On the other hand, if either of the CCA fails due to a busy channel, the MAC layer will increase the value of both NBO and BE by one. This process is repeated until

the maximum value of either the BOs ($MACmaxBackoffs$) or the maximum value of back-off exponent ($MACmaxBE$) is reached, and at this point the packet is dropped and channel access failure is declared. On the other hand, if the channel access is successful, the node initiates the transmission of the packet. If the ACK mechanism is activated, the node waits for an ACK which indicates successful packet transmission. If the transmitting node does not receive the ACK within a specified duration, the RT is increased by one up to a value equal to $MaxFrameRetries$. If RT is less than $MaxFrameRetries$, the MAC layer initializes two variables $CW = 0$, $BE = MinBE$ and repeats the above process. Otherwise, the packet is discarded due to the retry limit. The default MAC parameters of the IEEE 802.15.4 standard are $MinBE = 3$; $MaxBE = 5$; $MaxBackoffs = 4$; $MaxFrameRetries = 3$. Other values such as IFS and the ACK wait duration are specified in [5]. Figure B.1 shows a flow chart of the slotted CSMA/CA mechanism.

CFP is used to support QoS requirements which is basically, the coordinator may dedicate a number time slots of the SF active period for these requirements. These time slots, which constitute the CFP, are called the GTS. The GTSs start immediately following the CAP. The maximum number of GTSs a coordinator can assign is seven, and a single GTS may span more than one time slot. GTSs are assigned to nodes based on their request. Once assigned to a node, the GTS is dedicated to that node and no other node can contend for the medium or transmit a packet during that GTS. Nodes activity during its GTS should be completed before the start of the next GTS or the end of the CFP. In this thesis, we omit the CFP and consider the active period of the SF to include only the CAP.

Three bands for operation are defined in the IEEE 802.15.4 standard: 868 MHz, 902 MHz and 2.4 GHz. A data rate of 250 kbps can be provided by the 2.4 GHz band by

application and the environment. Each CCA method differs in its ability to sense signal existence and in its power consumption. Hence, the choice of the CCA method and parameters has a considerable impact on the performance of MAC sub-layer metrics such as, delay and energy efficiency. These metrics are conflicting and require critical optimization of CCA parameters to achieve a practical adjustment.

CCA with energy detection technique is based on measuring the signal energy around the carrier frequency and detecting the presence of signal in the communication channel. Energy detection method is simple in design and it is energy efficient since it does not need to operate continuously and can be turned on when the MAC sub-layer requests the PHY for a CCA. This permits the radio to sleep for prolonged periods and hence save energy. The main disadvantage of energy detection method is that this method tends to be less reliable in systems where the SNR is low.

In the carrier sensing method, the node must accomplish time synchronisation with the ongoing transmission. Achieving time synchronisation in packet based wireless systems is done by transmitting a preamble in front of each packet. This preamble consists of repetitions of a sequence of predefined symbols. The receiver performs a correlation of the known sequence with the received signal with varying time offsets. The correlation becomes high due to the repetition of the known symbols which corresponds to time synchronisation. This high correlation is indicative of signal presence and provides an estimate of time offset, where this method is also known as preamble detection. Due to the use of signal spreading and the use of known symbols in the preamble, carrier sensing method has much higher SNR than the energy detection method, and hence operates with higher reliability. The biggest disadvantage of carrier sensing is that it is required to be constantly running. This is because when the physical layer is requested to do a CCA within 8 symbol durations, it may not be able to perform preamble detection because the

channel could contain data packets with elapsed preamble when CCA is request. This makes the carrier sensing method a power hungry scheme.

The third method combines the advantages of the carrier sensing and energy detection schemes which enables carrier detection anywhere within the packet duration. This technique provides reliable detection with less energy consumption compared to the carrier sensing technique. The details of this technique can be found in [5].