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BAHÇEŞEHİR UNIVERSITY

QUALITY OF SERVICE AWARE COMMUNICATION FRAMEWORK FOR WIRELESS SENSOR NETWORK BASED SMART GRID APPLICATIONS

Ph.D. Thesis

MELİKE YİĞİT KAPDAN

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ABSTRACT

QUALITY OF SERVICE AWARE COMMUNICATION FRAMEWORK FOR WIRELESS SENSOR NETWORK BASED SMART GRID APPLICATIONS

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The smart grid is a modernized electric power grid that utilizes advanced electrical power components, information and communication technologies to collect and process the power grid's operational information. Smart grids provide bi-directional communications and use advanced control capabilities to generate, distribute and consume the electricity more efficiently, unlike the existing power grid. Reliable and timely data transmission from suppliers to consumers is critical in smartgrid applications. To this end, wireless sensor networks (WSNs) are one of the most promising communication solutions that can meet the delay and reliability requirements of smart grid applications. However, recent field tests show that the smart grid infrastructure has harsh and complex environmental conditions, noise, interference, and multi-path fading problems during low-power wireless communications. Therefore, providing the quality of service (QoS) requirements of smart grid applications with WSNs is difficult because of the power constraints of sensor nodes and unreliable wireless links.

This thesis specifically focuses on the robust and timely delivery of data over lossy and error prone WSN in smart grid environment. In order to satisfy the QoS requirements of the smart grid application, a range of new protocols considering the characteristics of the application data is proposed. The impact of wireless environment on smart grid communication performance is analyzed in order to propose more accurate solutions. Due to transmission distortions induced by some specific smart grid system challenges including interoperability, security, optimization and control of the grid, network traffic loads and exchanged of different data types, smart grid communication performance may not be acceptable for providing QoS requirements of smart grid applications. Hence, the impact of multi-channel communication and the selection of efficient routing trees, including routing trees constructed considering the link qualities, Capacitated Minimum Spanning Trees (CMSTs), capacitated minimum spanning tree considering link qualities and Minimum Hop Spanning Trees (MHSTs), on the performance of wireless sensor networks in different smart grid spectrum environments are comprehensively analyzed. In order to provide application-specific smart grid QoS requirements, link-quality-aware routing algorithm (Link-Quality-Aware Capacitated Minimum Hop Spanning Tree (LQ-CMST)) is proposed as well as the priority and channel-aware multi-channel (PCA-MC) scheduling algorithm. Furthermore, the effect of different modulation and encoding schemes on the performance of the proposed algorithms has also been evaluated under harsh smart grid channel conditions. Additionally, in order to design an entire system in QoS-aware smart grid communication, two new medium access control (MAC) protocols, which are QoS-aware omnidirectional antenna-based MAC (QODA-MAC) and QoS-aware four-sectored antenna-based MAC protocol (QFSA-MAC), are designed to increase channel utilization with efficient service differentiation considering traffic flows with different requirements as well as providing reliable and fast delivery of data. Furthermore, proposed LQ-CMST routing protocol with multi-channel scheduling is integrated with Hamming error correction code, Reed Solomon code and Bose-Chaudhuri-Hochquenghem (BCH) code to achieve the QoS requirements such as reliability and high data rate along error prone wireless channels. A comprehensive analysis of these error correction codes with Frequecny Shift Keying (FSK), Differential Shift Keying (DPSK), Binary Phase Shift Keying (BPSK), and Offset Quadrate Phase Shift Keying (OQPSK) modulation schemes is also done in smart grid environment. Moreover, an efficient adaptive error control algorithm is proposed and integrated with LQ-CMST routing protocol and multi-channel scheduling algorithm.

The performance results expose that LQ-CMST routing algorithm together with QFSA-MAC algorithm is greatly capable of providing QoS requirements of smart grid applications. Hence these techniques are comprehensively analyzed in terms of delay and throughput which are important performance metrics for providing QoS requirements of smart grid applications. Additionally, in order to specify the physical layer parameters of the proposed algorithms, their performance are extensively analyzed by using different modulation and encoding schemes. Moreover, in order to verify the usability of the proposed adaptvie error control algorithm with the proposed algorithms to satisfy application requirements, its delay and throughput performance is evaluated with using different modulation schemes. As a result, it is found that adaptive error control algorithm is suitable for meeting the reliability requirements of smart grid applications.

A novel QoS-aware communication framework is proposed to meet application-specific QoS requirements for WSN-based smart grid applications. Proposed framework aims to provide delay, reliability and throughput requirements of smart grid applications. The innovation of the proposed scheme lies in the combined use of LQ-CMST routing algorithm with QFSA-MAC algorithm and in the combination of LQ-CMST and adaptive error control algorithm. Consequently, an efficient QoS-aware communication framework is provided for WSN-based smart grid applications.

Keywords: Smart Grid, Wireless Sensor Networks, Multi-Channel Communication, Routing Algorithms, Adaptive Error Control

ÖZET

KABLOSUZ SENSÖR AĞ BAZLI AKILLI ŞEBEKE UYGULAMALARI İÇİN HİZMET KATLİTESİ DUYARLI SİSTEM

Melike Yiğit Kapdan

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Akıllı şebeke, güç şebekesinin operasyonel bilgilerini toplamak ve işlemek için gelişmiş elektrik güç bileşenleri, bilgi ve iletişim teknolojilerini kullanan modern bir elektrik şebekesidir. Akıllı şebekeler, çift yönlü iletişim sağlar ve mevcut güç şebekesinin aksine, elektriği daha verimli bir şekilde üretmek, dağıtmak ve tüketmek için gelişmiş kontrol yetenekleri kullanır. Akıllı şebeke uygulamalarında tedarikçilerden tüketicilere güvenilir ve zamanında veri iletimi kritik öneme sahiptir. Bu amaçla, kablosuz sensör ağları (WSN'ler) akıllı şebeke uygulamalarının gecikme ve güvenilirlik gereksinimlerini karşılayabilecek en umut verici iletişim çözümlerinden biridir. Ancak, son saha testleri, akıllı şebeke altyapısının düşük güçlü kablosuz iletişimde zorlu ve karmaşık çevresel koşullara, gürültüye, parazite ve çok-yollu sönümlenme sorunlarına sahip olduğunu göstermektedir. Bu nedenle, akıllı şebeke uygulamalarının servis kalitesi (QoS) gereksinimlerini WSN'lerle sağlamak, sensör düğümlerinin ve güvenilmez kablosuz bağlantıların güç kısıtlamaları nedeniyle zordur.

Bu tez, özellikle akıllı şebeke ortamında, kayıplı ve hataya açık WSN üzerindeki verilerin sağlam ve zamanında teslim edilmesine odaklanmaktadır. Akıllı şebeke uygulamasının QoS gerekliliklerini karşılamak için, uygulama verilerinin özelliklerini göz önünde bulundurarak bir dizi yeni protokol önerilmiştir. Kablosuz ortamın akıllı şebeke iletişim performansı üzerindeki etkisi, daha doğru çözümler önerilmesi amacıyla analiz edilmiştir. Birlikte çalışabilirlik, güvenlik, optimizasyon ve şebekenin kontrolü, ağ trafiği yükleri ve farklı veri tiplerinin değişimi gibi belirli akıllı şebeke sistemi zorluklarının yol açtığı iletim bozulmalarına bağlı olarak akıllı şebeke iletişim performansı, akıllı şebeke uygulamalarının QoS gereksinimlerini sağlamak için yeterli olmayabilir. Bu nedenle, çok kanallı iletişimin ve verimli yönlendirme ağaçlarının seçiminin (bağlantı kalitesi düşünülerek kurulmuş yönlendirme ağaçları, kapasiteli asgari tarama ağaçları (CMSTs), bağlantı kalitesi düşünülerek kurulmuş kapasiteli asgari tarama ağaçları ve asgari tarama ağaçları (MHSTs) dahil) farklı akıllı şebeke spektrum ortamlarında bulunan kablosuz sensör ağları üzerindeki etkisi kapsamlı olarak analiz edilmiştir. Akıllı şebeke uygulamasına özel QoS gereksinimlerini sağlamak için, öncelik ve kanal duyarlı çoklu kanallı (PCA-MC) zamanlama algoritmasının yanı sıra bağlantı kalitesi duyarlı (link kalitesi duyarlı kapasiteli asgari tarama ağacı (LQ-CMST)) yönlendirme protokolünü önerilmiştir. Ayrıca, farklı modülasyon ve kodlama şemalarının, önerilen algoritmaların performansı üzerindeki etkisi sert akıllı şebeke kanal koşulları altında da değerlendirilmiştir. Ek olarak, QoS duyarlı akıllı şebeke iletişiminde bütün bir sistem tasarlamak için, farklı gereksinimlere sahip trafik akışlarını göz önüne alıp verimli hizmet farklılaştırması yaparak kanal kullanımını artıran ve bunun yanı sıra güvenilir ve hızlı veri sunumu sağlayan iki yeni ortam erişim kontrol (MAC) protokolü, QoS duyarlı çok yönlü anten tabanlı MAC (QODA-MAC) ve QoS duyarlı dört sektör anten tabanlı (QFSA-MAC), tasarlanmıştır. Ayrıca, çok kanallı sıralama ile önerilen LQ-CMST yönlendirme protokolü, hata eğilimli kablosuz kanallar boyunca güvenilirlik ve yüksek veri hızı gibi QoS gereksinimlerini sağlamak için Hamming hata düzeltme kodu, Reed Solomon kodu ve Bose-Chaudri-Hochquenghem (BCH) kodu ile entegre edilmiştir. Bu hata düzeltme kodlarının performansı frekans kaydırmalı anahtarlama (FSK), diferansiyel faz kayması anahtarlama (DPSK), ikili faz kaydırmalı anahtarlama (BPSK) ve offset kuadratör faz kaydırmalı anahtarlama (OQPSK) modülasyon teknikleriyle de kapsamlı şekilde akıllı şebeke ortamında incelenmiştir. Ayrıca, verimli bir adaptif hata kontrol algoritması önerilmiş ve bu algoritma çok kanallı sıralama algoritması ve LQ-CMST yönlendirme protokolü ile entegre edilmiştir.

Performans sonuçları, LQ-CMST yönlendirme algoritması ile birlikte QFSA-MAC algoritmasının akıllı şebeke uygulamalarının QoS gereksinimlerini büyük ölçüde sağlayabileceğini ortaya koymaktadır. Bu nedenle, bu teknikler, akıllı şebeke uygulamalarının QoS gereksinimlerini sağlamak için önemli performans ölçümleri olan gecikme ve verim açısından kapsamlı bir şekilde analiz edilmiştir. Ek olarak, önerilen algoritmaların fiziksel katman parametrelerinin belirlenmesi için, performansları farklı modülasyon ve kodlama şemaları kullanılarak kapsamlı şekilde analiz edilmiştir. Ayrıca, uygulama gereksinimlerinin karşılanması için önerilen adaptif hata kontrol algoritmasının kullanılabilirliğini doğrulamak amacıyla algoritmanın gecikme ve üretim performansı farklı modülasyon şemaları kullanılarak değerlendirilmiştir. Sonuç olarak, adaptif hata kontrol algoritmasının akıllı şebeke uygulamalarının güvenilirlik gereksinimlerini karşılamak için uygun olduğu bulunmuştur.

WSN tabanlı akıllı şebeke uygulamaları için uygulamaya özel QoS gereksinimlerini karşılamak için QoS duyarlı yeni bir iletişim sistemi önerilmiştir. Önerilen sistem, akıllı şebeke uygulamalarının gecikme, güvenilirlik ve verimlilik gereksinimlerini sağlamayı amaçlamaktadır. Önerilen şemanın yeniliği, QFSA-MAC algoritması ile LQ-CMST yönlendirme algoritmasının birlikte kullanımı ve adaptif hata kontrol algoritması ile LQ-CMST yönlendirme algoritmasının kombine olarak kullanılmasına dayanmaktadır. Sonuç olarak, WSN tabanlı akıllı şebeke uygulamaları için verimli bir QoS duyarlı iletişim sistemi sağlanmıştır.

Anahtar Kelimeler: Akıllı şebeke, kablosuz sensör ağları, çoklu kanal iletişimi, yönlendirme algoritmaları

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LIST OF ABBREVIATIONS

ACKs	:	Acknowledgments
AEC	:	Adaptive Error Control
AFEC	:	Adaptive Forward Error Correction
AMFEC	:	Adaptive MAC-Level FEC
ARQ	:	Automatic Repeat Request
ASIC	:	Application Specific Integrated Circuit
AWGN	:	Additive White Gaussian Noise
BCH	:	Bose-Chaudhuri-Hochquenghem
BE	:	Best Effort
BER	:	Bit Error Rate
BERs	:	Bir Error Rates
BPSK	:	Binary Phase Shift Keying
CDF	:	Cumulative Distribution Function
CI	:	Confidence Interval
CMST	:	Capacitated Minimum Hop Spanning Tree
CMSTs	:	Capacitated Minimum Hop Spanning Trees
CSMA/CA	:	Carrier Sense Multiple Access with Collision Avoidance
CSS	:	Combine-skip-substitute
CTS	:	Clear to Send
DARA	:	Distributed Aggregate Routing Algorithm
DPSK	:	Differential Phase Shift Keying
DRX	:	Delay-responsive Cross-layer
ECC	:	Error Correction Code
ECCs	:	Error Correction Codes
FDRX	:	Fair and Delay-aware Cross-layer
FEC	:	Forward Error Correction
FPGA	:	Field Programmable Gate Array
FSK	:	Frequency Shift Keying
HARQ	:	Hybrid Automatic Repeat Request
iHEM	:	In-home Energy Management

LOS	:	Line-of-Sight
LQ-CMST	:	Link-Quality-Aware Capacitated Minimum Hop Spanning Tree
MAC	:	Medium Access Control
MHST	:	Minimum Hop Spanning Tree
MHSTs	:	Minimum Hop Spanning Trees
MMSPEED	:	Multi- SPEED
MPR	:	Main Power Control Room
M-QAM	:	M-quadrate Amplitude Modulation
MR-CSS	:	Multirate - Combine-skip-substitute
MRL-CC	:	Multi-agent Reinforcement Learning
NCFSK	:	Non-Coherent Frequency Shift Keying
NJN	:	Nearest-job-next
NRT	:	Non-real-time
OMCR	:	Optimized Multi-Constrained Routing
OQAP	:	Quality of Service Aware Placement
OQPSK	:	Offset Quadrature Phase-Shift Keying
OREM	:	Optimization-based Residential Energy Management
PCA-MC	:	Priority and Channel-Aware Multi-Channel
PER	:	Packet Error Rate
PHEV	:	Plug-in Hybrid Electric Vehicle
PRR	:	Packet-Reception-Rate
PSNR	:	Peak-Signal-to-Noise-Ratio
QFSA-MAC	:	Quality of Service Aware Four-Sectored Antenna-Based Medium Access Control
QODA-MAC	:	Quality of Service Aware Omnidirectional Antenna-Based Medium Access Control
QoS	:	Quality of Service
RBCA	:	Receiver-Based Channel Assignment
RLTD	:	Real Time Routing Protocol with Load Distribution
RF	:	Radio Frequency
RNs	:	Relay Nodes
RRR	:	Randomized Re-Routing

RS	:	Reed Solomon
RSSI	:	Radio Received Signal Strength Indicator
RT	:	Real-time
RTLD	:	Real Time Routing Protocol with Load Distribution
RTS	:	Request to Send
SAMAC	:	Sectored Antenna-based Medium Access Control
SINR	:	Signal to Interference Noise Ratio
SNR	:	Signal to Noise Ratio
Subs	:	Substation
T&D	:	Transmission and Distribution
TDMA	:	Time Division Multiple Access
TMCP	:	Tree-based Multi–Channel Protocol
TSCH	:	Time Slotted Channel Hopping
UTV	:	Underground Network Transformer Vaults
WSN	:	Wireless Sensor Network
WSNs	:	Wireless Sensor Networks

SYMBOLS

Ambient noise level	:	$\mathcal{N}$
Minimum bit error rate	:	BER_{MIN}
Maximum bit error rate	:	BER_{MAX}
Code word length	:	n
Complementary error function	:	erfc
Distance	:	d
Edge cost	:	c
Frame length	:	f_L
Galois finite field	:	GF
Gate	:	g_i
Graph	:	G
Interarrival time of BE packets	:	BE_IAT
Interarrival time of NRT packets	:	NRT_IAT
Interarrival time of RT packets	:	RT_IAT
Noise bandwidth	:	BN
Noise floor	:	P_η
Output power	:	P_t
Path loss exponent	:	η
Preamble length	:	PL
Probability of bit error	:	P_b
Propagation attenuation	:	g_{ij}

Reference distance	:	d_0
Set of edges	:	E
Set of nodes	:	V
Shadowing deviation	:	X_σ
Signal energy to noise power density ratio	:	E_b/N_0
Signal to noise ratio	:	Ψ
Signal to noise ratio	:	γ (d)
Signal-to-interference- plus-noise ratio	:	$SINR_{ij}$
Standard deviation	:	σ
Standard Gaussian Error Function	:	Q(x)
Syndrome matrix	:	S
Terrain dimension of X	:	D_X
Terrain dimension of Y	:	D_Y
Threshold	:	β
Tradeoff function	:	t (ai)
Transmit power	:	P_T
Transmitted signal	:	P_i
Vertice	:	a

1. INTRODUCTION

1.1 SMART GRID COMMUNICATION NETWORK

Given the growing energy demand and increasing age of power grid, electric utilities face the challenge of ensuring reliable power delivery to the customers at competitive prices. Power grid failures because of the complex electric distribution systems cause congestion in the power network. All these component failures, accidents, and network congestions cause power outages leading to major blackouts all around the world (Yigit and et al. (2014)). To address these issues, a new concept of next generation electric power system, the smart grid, has been proposed. The smart grid is a modern electric power system that integrates many devices with energy management techniques and a state-of-the-art communication infrastructure on the traditional power grid (Yigit and et al. (2017)). The smart grid provides significant energy savings, decrease operational costs, and increase safety and power quality. To this end, the cost and design of the communication network in smart grid applications becomes important to the performance of the overall electric power system (Gungor and et al. (2013)).

The recent developments in embedded systems and Wireless Sensor Networks (WSNs) have enabled reliable and cost effective power grid management systems, which have the capability of monitoring and controlling the real-time operating conditions and performance of the grid (Bicen and et al. (2012), Gungor and et al. (2011), Gungor and et al. (2010)). In these systems, the low-cost nature of WSNs brings many benefits over traditional electric monitoring systems, including greater accuracy, improved fault tolerance, extraction of localized events (Yigit and et al. (2014)). In this respect, wireless sensor networks provide low-cost and low-power wireless communications for diverse sets of smart grid applications, including automatic wireless metering, conductor temperature, dynamic thermal rating, line fault and power theft detection, distribution automation, outage detection, underground cable system monitoring, real time pricing. However, the realization of these currently designed and envisioned WSN-based smart grid applications and to meet the general application demands in terms of delay, reliability, energy efficiency and throughput directly depends on reliable communication capabilities of the deployed sensor network in harsh smart grid environments.

Design of a WSN for a specific smart grid application in smart grid environments is influenced by several facotrs such as low link-quality; network topology; interference; contention; and hardware constraints. Link-quality of wireless links varies greatly with time and location because of fading, multi-path and noies in different smart grid environments, including outdoor substation, main power control room and underground network transformer vaults (Gungor and et al. (2010)). On top of these factors, RF (Radio Frequency) interference due to parallel transmissions and contention on the wireless medium limit the capacity of WSNs specifically in smart grid environments (Yigit and et al. (2014)). There also exist additional factors, that affect the efficiency of WSN-based smart grid communication network such as application-specific QoS (Quality of Service) requirements, WSN-coding techniques, service prioritization and scheduling. These factors should be also considered while designing communication protocols and algoritms for efficient communications in WSN-based smart grid communication network. They are explained in detail as follows:

a. **Application-Specific QoS Requirements:** WSN-based smart grid applications are exposed to packet losses during transmission because of wireless nature. This leads to QoS degradation for consumers using these applications. Furthermore, some of the smart grid applications require on time transmission of the data in case of emergency situation. Therefore, the developed protocols should be designed to meet these QoS requirements of each smart grid application.

b. **Error Detection and Correction:** The effect of data loss is minimized by using error correction codes in WSNs. However, efficiency of error dectection and correction techniques changes according to communication environment. Therefore, in order to increase the quality during communication, the error detection and correction techniques should be analyzed and designed in harsh smart grid communication environments for WSN-based smart grid applications.

c. **Service Prioritization:** Various types of traffic, such as best effort (BE), non-real-time (NRT), and real-time (RT), are delivered by WSN-based smart grid applications. Improper management of these traffic type leads to more quality degradation at the consumers who use these smart grid applications. In order to manage these traffic types during transmission, prioritization and service differentiation based on the requirements of various traffic types with different requirements should be performed.

d. **Scheduling:** Link-quality of wireless links in different smart grid environments decreases due to multi-path, fading and noise. Furthermore, capacity of WSNs is also limited by the radio frequency (RF) interference due to parallel transmission. Hence, the scheduling algorithms should be analyzed and designed for the WSN-based smart grid applications so as to improve network performance in these environments.

1.2 PROBLEM STATEMENT

In this thesis, WSN is used in different smart grid spectrum environments such as outdoor substation for satisfying QoS requirements including delay bound, throughput, and power efficiency of smart grid applications. Field tests show that meeting these requirements for smart grid applications is difficult since the link-quality of wireless links in smart grid environments varies both in space and time due to many factors which are multi-path, fading, RF interference, node contentions, and noise. This leads to both time and location dependent capacity limitations of wireless links in smart grid environments.

To improve the network capacity in smart grid environments, multi-channel communication and the use of proper routing topologies emerge as efficient solutions to achieve interference-free and, simultaneous transmissions over multiple channels. Capacitated Minimum Hop Spanning Trees (CMSTs) and Minimum Hop Spanning Trees (MHSTs) are different routing tree algorithms which are designed for WSNs to reduce the schedule length with multi-channel scheduling (Incel and et al. (2012)). However, their performance was not evaluated in smart grid environments with varying link qualities. Constructing routing topologies considering the link qualities can certainly contribute to avoid bad-quality links and improve the network performance. Therefore, multi-channel scheduling integrated with the routing trees constructed considering the link qualities may also play an important role to increase the energy efficiency and throughput and also to decrease the delay. In order to show their benefits in WSNs operated in smart grid applications, multi-channel scheduling with use of the routing tree algorithms considering the link qualities should be addressed by comparing their performances with that of routing trees which are not considered the link quality.

There exist QoS-aware communication protocols proposed for WSNs. However, none of these protocols does not meet the application-specific smart grid requirements. Most protocols either ignore data prioritization or make communication without considering the channel conditions under different network traffic loads. Furthermore, none of them analyzes the modulation and encoding schemes on delay performance of smart grid applications. Therefore, the QoS requirements of WSN-based smart grid applications cannot be met completely. For this reason, priority and channel-aware scheduling algorithms are vital for QoS based smart grid applications. In addition, analyzing the effect of modulation and encoding schemes on the delay performance of smart grid applications under harsh smart grid channel conditions is crucial to increase the overall network performance.

An efficient MAC (Medium Access Control) protocol is a prominent issue in order to provide the QoS requirements of smart grid applications. Because there exist many design challenges while designing an efficient MAC protocol. One of these challenges is that high latency can occur during data collection process due to variable channel capacity of WSNs. In WSNs, the interference level perceived at the receiver determines the capacity of each wireless link. Hence, the capacity of each link is environment-dependent, providing QoS provisioning a compelling issue. Second, sensor nodes are resource-constraint, and therefore, they have limited processing capability, memory, and data rate. These make it difficult to develop QoS-aware scheduling for smart grid applications. Finally, each smart grid application has specific QoS requirements because some of them are delay-sensitive or need high bandwidth. Therefore, designing an efficient MAC protocol that meets requirements of each application by addressing prioritization, delay and reliability-aware data transmission for smart grid communication network is required.

Error detection and correction is an important issue in the design and the maintenance of a smart grid communication network to provide reliable communication between receiver and sender. Various error control coding techniques, such as Automatic Repeat Request (ARQ), Forward Error Correction (FEC), and Hybrid FEC/ARQ, are employed to reduce bit error rates for WSNs. In ARQ technique, when the receiver detects an error in data, it sends feedback to the transmitter for retransmission of the data and therefore, it may be inefficient to meet the delay requirements of applications. There is no correction at receiver side. However, FEC adds redundant bits to the data to create a codeword and so the receiver can detect and correct the errors by using these redundant bits. In FEC technique, no feedback sends from receiver to transmitter and therefore, half-duplex communication is sufficient for FEC technique. Therefore, FEC scheme is an effective mechanism since it does not to require retransmission to correct the data. Hybrid FEC/ARQ combines both ARQ and FEC techniques and requires full duplex communication between the transmitter and receiver. Hybrid FEC/ARQ also requires to retransmission of the data and therefore, it is not suitable to provide QoS requirements of applications. The performance of these techniques are also compared and evaluated to find the most suitable technique for WSNs. Furthermore, there are also some studies which evaluate the performance of error correction methods with some different physical layer parameters, such as different modulation techniques, various packet sizes, and several output power levels. However, there is not a study that compares and evaluates the most efficient error coding technique with different physical layer parameters for WSNs in smart grid environment. Compared to ARQ and Hybrid FEC/ARQ schemes, FEC codes, such as Hamming, Reed Solomon (RS), and Bose-Chaudhuri-Hochquenghem (BCH) codes have advantage of not introducing retransmission delay. In order to represent advantages of these codes for WSNs in smart grid environments, it should be evaluated by comparing its performance with the performance of without FEC with using different physical layer parameters. Furthermore, based on this evaluation, a new adaptive error control technique should be proposed in order to meet the reliability requirements of smart grid applications.

1.3 CONTRIBUTIONS

This thesis focuses on the efficient and QoS-aware data transmission in various harsh smart grid environments. Particular attention is given to design and development of a QoS-aware cross-layer model that is composed of the solutions, improving the network performance by satisfying the QoS requirements such as delay bound and throughput of smart grid applications.

a. **Contribution 1: Multi-channel scheduling and tree-based routing**

   Link quality of wireless links in different smart grid environments, including 500 kV outdoor Substation (Subs), Main Power Room (MPR) and Underground Network Transformer Vaults (UTV), varies because of various factors such as multi-path, fading, node contentions, Radio Frequency (RF) interference, and noise. In order to improve the network capacity in these environments, multi-channel communication and the use of proper routing technologies emerge as efficient solutions to achieve interference-free, simultaneous transmissions over multiple channels. In this respect, we explore the impact of multi-channel communication and the selection of efficient routing topologies on the performance of WSNs in different smart grid spectrum environments. We evaluate the network performance using a receiver-based channel selection method and using different routing trees, including routing trees constructed considering the link qualities (CMSTs), capacitated minimum hop spanning tree considering link qualities and MHSTs. Capacitated Minimum Hop Spanning Tree (CMST) were shown to minimize latency with perfect link qualities in (Incel and et al. (2012)), however, their performance was not evaluated for WSNs operating in smart grid environments with varying link qualities. Hence, it is imperative to evaluate the impact of different routing topologies on the network performance in such environments. Constructing the routing topologies considering the link qualities can certainly contribute to avoid bad-quality links and improve network performance.

   As the second approach, we investigate the performance with routing topologies constructed according to the Packet-Reception-Rate (PRR) metric. Besides, we combine the CMST and PRR-based routing topologies and investigate the possible capacity improvements. Furthermore, we consider the impact of retransmissions on the network performance in terms of both latency and capacity, considering the lost packets due to unreliable links in smart grid environments.

We focus on the performance measures in terms of delay and throughput that can benefit from the simultaneous parallel transmissions and show that the use of multiple channels together with routing trees. These trees consider the network capacity and link quality such as capacitated minimum spanning tree considering link qualities substantially improve the network performance in harsh smart grid environments compared to single-channel communication and minimum-hop routing trees. This work appears in the following paper:

Yigit, M., Durmaz Incel, O., and Gungor, V.C., 2014. On the interdependency between multi-channel scheduling and tree-based routing for wsns in smart grid environments. *Computer Networks*. 65, pp. 1–20.

b. Contribution 2: Channel-aware routing and priority-aware multi-channel scheduling

Providing QoS requirements of smart grid applications with WSNs is difficult because of the power constraints of sensor nodes and harsh smart grid channel conditions. To address these communication challenges, two novel algorithms, which are Link-Quality-Aware Capacitated Minimum Hop Spanning Tree (LQ-CMST) routing algorithm as well as the Priority and Channel-Aware Multi-Channel (PCA-MC) scheduling algorithm, have been proposed for smart grid applications. Furthermore, the effect of different modulation and encoding schemes on the performance of the proposed algorithms has been evaluated under harsh smart grid channel conditions.

The performance evaluations are done according to smart grid application scenarios by employing multi-channel scheduling. In the first scenario, traffic flows are classified based on their priority; in the second scenario, all traffic has been treated in a best effort manner and all packets are transmitted without any prioritization; in the third scenario, performance evaluations have been conducted under low and high traffic loads. Delay is used as a metric to evaluate all these performance results.

Comparative performance evaluations through extensive simulations show that the proposed algorithms significantly reduce communication delay and the choice of encoding and modulation schemes is critical to meet the requirements of envisioned smart grid applications. This contribution appears in the following paper:

Yigit, M., Gungor, V.C., Fadel, E., Nassef, L., Akkari, N., and Akyildiz, I.F., 2016. Channel-aware routing and priority-aware multi-channel scheduling for wsn-based smart grid applications. *Journal of Networks and Computer Applications*. 71, pp. 50–58.

c. Contribution 3: QoS-aware MAC protocols utilizing sectored antenna

Various types of traffic, such as BE, NRT, and RT, are delivered by WSN-based smart grid applications. Management of these traffic types can be performed by making prioritization and service differentiation based on the requirements of various traffic types with different requirements. MAC layer mechanisms can support the QoS requirements of these applications because they manage the sharing of medium and have the capability to affect the performance of the smart grid communication networks. Therefore, we present two protocols that aim to address prioritization, delay, and reliability-aware data transmission for smart grid communication networks. The proposed protocols make service differentiation (prioritization) between the traffic classes based on their requirements in order to achieve better performance. Our first approach, the QoS-aware Omnidirectional Antenna-based MAC (QODA-MAC) protocol, uses omnidirectional antennas for neighbor discovery. The QODA-MAC retrieves neighbor information and makes scheduling according to the traffic types including BE, NRT, and RT. The second approach, named QoS-aware Four-Sectored Antenna-Based MAC (QFSA-MAC) protocol, utilizes directional antennas, as opposed to QODA-MAC, to discover the neighbors by concentrating the transmission power towards a certain direction. In QFSA-MAC, the use of the directional antenna enhances the spatial reuse of the wireless channel that provides simultaneous communication between the nodes without interference. In this way, it can connect the nodes far away from each other and decreases the number of hops from source node to sink node when compared with omnidirectional antennas. Similar to QODA-MAC, QFSA-MAC makes the scheduling by making service differentiation and uses the same routing protocol for forwarding packets towards the sink node.

Both QODA-MAC and QFSA-MAC have two modes of operation, prioritized and unprioritized modes that provide switching from one mode operation to another according to the application requirements. Although many studies have been proposed to meet the QoS requirements of smart grid applications (Al-Anbagi and et al. (2014), Sun and et al. (2010), Singh and Tepe (2009)), QODA-MAC and QFSA-MAC are the first QoS-aware MAC protocols that consider service differentiation of different traffic classes by considering the impact of antenna for smart grid communication networks.

Performance of QODAMAC and QFSA-MAC is evaluated with comprehensive simulations for various traffic classes such as BE traffic, NRT traffic and RT traffic and their performance are compared with each other for smart grid communication networks. Simulation results show that the QFSA-MAC protocol yields adequately service differentiation and meets the QoS requirements of smart grid applications. It provides better performance from the point of delay, throughput and energy compared with QODA-MAC protocol for both the prioritized and unprioritized modes of operation. The contribution of this work appears in the following paper:

Yigit, M., Durmaz Incel, O., Baktir, S., and Gungor, V.C., 2016. Qos-aware mac protocols utilizing sectored antenna for wireless sensor networks-based smart grid applications. *International Journal of Communication Systems*. **30** (7), pp. 31-68.

d. Contribution 4: Comprehensive analysis of hamming code

Providing reliable communication links between the electric power utilities and consumers is an important issue of smart grid. Robust communication can be achieved if the data is transmitted with no error. However, achieving error-free transmission in WSN-based smart grid communication systems is difficult since communication channel suffers from many factors such as noise, path loss, fading, shadowing, reflection and diffraction. Using a proper error control technique is the most crucial issue to minimize the Bit Error Rate (BER) with lower delay in smart grid applications. Hence, comprehensive analysis of the Hamming code combined with the modulations including Binary Phase Shift Keying (BPSK), Differential Phase Shift Keying (DPSK), Frequency Shift Keying (FSK), and Offset Quadrature Phase-Shift Keying (OQPSK) is done in WSN-based smart grid communication networks. Particularly, we adopt the Hamming code for WSNs in smart grid environments to minimize the BER and to maximize the throughput.

LQ-CMST (Yigit and et al. (2016)) algorithm as well as the multi-channel scheduling algorithm are used for data transmission. In this way, impact of LQ-CMST and multi-channel scheduling on the performance of Hamming code are also analyzed for WSNs in smart grid environments.

Comparative performance evaluations of the Hamming code and without FEC algorithm have been performed according to different modulation schemes in 500kV substation smart grid environment. Bit error rate, throughput, and delay are used as performance metrics in simulations. Simulation results show that the Hamming code with OQPSK modulation is the most efficient in smart grid communication network because of its low BER and delay and high throughput performance. Hence, Hamming code with OQPSK modulation has been comprehensively investigated in terms of output power and packet size which leads to a deeper understanding of the impact of physical layer parameters on BER, throughput, and delay performance of smart grid communication. This work appears in the following paper:

Yigit, M., Güngör, V.C., and Bölük, P., 2017. Performance analysis of hamming code for WSN-based smart grid applications. 2018. *Turkish Journal of Electrical Engineering & Computer Sciences.* **26** (1), pp.125-137.

e. Contribution 4: A new efficient error control algorithm

Error detection and correction is an important issue in the design and maintenance of a smart grid communication network to provide reliable communication between sender and receiver. Various error-control coding techniques are employed to reduce Bit Error Rates (BERs) in WSNs. The performance of these techniques is also compared and evaluated to find the most suitable technique for WSNs. However, performance comparison of error detection and correction codes by combining various modulation techniques for WSN-based smart grid communication networks is not available in the literature. Furthermore, there is not an efficient error control protocol to meet the reliability requirements of smart grid applications. Hence, comparative performance analysis of RS and BCH codes with the modulations including FSK, DPSK, and OQPSK is done in WSN-based smart grid communication network and a new Adaptive Error Control (AEC) algorithm is proposed based on this comparison result.

LQ-CMST (Yigit and et al. (2016)) algorithm as well as the multi-channel scheduling algorithm are used for data transmission. In this way, impact of LQ-CMST and multi-channel scheduling on the performance of RS, BCH codes, and AEC are also analyzed for WSNs in smart grid environments.

Comparative performance evaluations of the RS code and BCH code have been performed according to different modulation schemes in 500kV substation smart grid environment. BER, throughput, and delay are used as performance metrics in simulations. Simulation results show that the RS code with OQPSK modulation is the most efficient in smart grid communication network because of its low BER and delay and high throughput performance. Therefore, RS codes with OQPSK modulation are used by the proposed AEC protocol. Different RS codes such as RS(39,35), RS(45,35), RS(51,35), RS(57,35), and RS(63,35) are used to change these codes according to channel conditions adaptively. Firstly, AEC assigns the RS codes to the nodes according to the transmission distance between the sender node and its parent, and performs the first transmission according to this assignment. Secondly, a switching criterion is defined according to the number of ACKs (Acknowledgments) of P previously transmitted packets that were received inside a window. The PER (Packet Error Rate) of these packets is measured and compared with the predefined threshold to determine whether to switch to a weaker or stronger RS code. A suitable RS code is chosen based on a look-up table that stores the BER levels of RS codes and the appropriate RS codes that can solve these BER levels. The aim of AEC is to maintain the reliability required by the smart grid application, while balancing the tradeoff between network overhead and reliability.

Performance of AEC is analyzed and compared with static RS and without-FEC mechanisms. The simulation results show that the proposed solution can decrease delay by transmitting less redundant bits and obtaining higher throughput than the static RS scheme. This work appears in the following papers:

Yigit, M, Sarisaray Boluk, P., and Gungor, V. C., 2018. Adaptive error control for wireless sensor network-based smart grid applications, *Second International Balkan Conference on Communications and Networking*. pp. 1-6.

Yigit, M., Sarisaray Boluk, P., and Gungor, V. C., 2018. A new efficient error control algorithm for wireless sensor networks in smart grid, *Computer Standards & Interfaces.* (submitted)

1.4 ORGANIZATION OF THE THESIS

This thesis starts by explaining the advanced in areas of multi-channel scheduling algorithms, QoS-aware routing protocols, QoS-aware MAC protocols, QoS-aware directional antenna based mac protocols, and error control techniques for WSNs in Chapter 2. The rest of the thesis is organized as follows:

a. **Chapter 3:** In this part of the thesis, the effect of multi-channel scheduling on the data transmission in smart grid environments is exhaustively investigated by using several routing protocols. This chapter corresponds to **Contribution 1**.

b. **Chapter 4:** In this chapter, link-quality-aware routing algorithm as well as the priority and channel-aware multi-channel scheduling algorithm are proposed for smart grid applications. This chapter corresponds to **Contribution 2**.

c. **Chapter 5:** In this chapter, a QoS-aware omnidirectional antenna-based medium access control and QoS-aware four-sectored antenna-based MAC protocol are proposed for providing the QoS requirements of smart grid applications. This chapter corresponds to **Contribution 3**.

d. **Chapter 6:** In this part of the thesis, the performance of Hamming code with various modulation techniques, such as FSK, DPSK, OQPSK and BPSK, is measured in terms of throughput, BER, and delay in a 500kV LOS substation smart grid environment. This chapter corresponds to **Contribution 4**.

e. **Chapter 7:** In this part of the thesis, the performance of RS and BCH codes with various modulation techniques, such as FSK, DPSK, and OQPSK, is measured in terms of throughput, BER, and delay in a 500kV LOS substation smart grid environment. Furthermore, a new efficient adaptive error control algorithm is proposed for smart grid applications. This chapter corresponds to **Contribution 5.**

f. Finally, thesis is concluded in Chapter 8 by discussing future works.

2. BACKGROUND

The link-quality of wireless links in different smart grid environments, such as outdoor substation, main power control room, and underground network transformer vaults, changes greatly with location and time because of multi-path, fading and noise. On top of these factors, contention on the wireless medium and RF interference due to parallel transmissions limit the capacity of WSNs specifically in smart grid environments. Hence, routing protocols, QoS-aware communication protocols and error detection and correction methods are needed to improve network performance in smart grid spectrum environments.

This thesis focuses on the efficient and QoS-aware data transmission for WSNs to be deployed various harsh smart grid environments by using multi-channel scheduling combined with tree-based routing protocols, channel-aware and priority-aware multi-channel scheduling algorithms, QoS based MAC protocols combined with service differentiation and directional antenna, and error correction methods. As a result, providing a QoS-aware cross-layer model to improve the network performance for satisfying the QoS requirements of smart grid applications. This chapter presents the previous works on the multi-channel protocols together with routing protocols, QoS-aware routing protocols, QoS-aware MAC protocols combined with omnidirectional or directional antenna for WSNs in smart grid environments and error detection and correction methods for WSNs.

The organization of the chapter is as follows: Section 2.1 presents an overview of related work on WSN multi-channel scheduling. QoS-aware routing protocols are explained in Section 2.2 along with their cons in terms of meeting the QoS requirements of smart grid applications. Sections 2.3 and 2.4 respectively present QoS-aware MAC protocols with service differentiation and QoS-aware directional antenna-based medium access control protocols. In Section 2.5, error control techniques in WSNs are presented. In Section 2.6, adaptive error control techniques are described.

2.1 RELATED WORK ON WSN MULTI-CHANNEL SCHEDULING

Multi-channel communication has been shown to be an efficient method to improve the network performance in terms of delay and capacity since it enables simultaneous transmissions over multiple channels which cannot be performed on a single-channel due to interference and collisions (Incel 2011). Channel assignment can be performed at the link level, node level or cluster level and assignments can be static, semi-dynamic and dynamic. In static assignment, radios are assigned channels for permanent use (Wu and et al. (2008)) whereas in semi-dynamic assignment (Incel and et al. (2011), Salajegheh and et al. (2007), Zhou and et al. (2006)) the radios are assigned static channels, either for receiving or transmitting, but it is possible to change the channel for communicating with the radios that operate on different channels. Dynamic assignment approaches (Borms and et al. (2010), Kim and et al. (2008)), on the other hand, consider that nodes can dynamically switch their interfaces from one channel to another between successive data transmissions.

Multi-channel protocols for WSNs also differ according to the medium access scheme that they utilize. Some of the protocols utilize contention-based medium access (Kim and et al. (2008), Zhou and et al. (2006)), where some others utilize contention-free Time Division Multiple Access (TDMA) approaches (Incel and et al. (2011), Borms and et al. (2010), Salajegheh and et al. (2007)).

(Palattella and et al. (2013)) uses the Time Slotted Channel Hopping (TSCH) mechanism for multi-channel communication and focus on the impact of routing trees on the performance. TSCH, which is included in IEEE802.15.4e standard, provides energy efficient and reliable communication with minimizing collision and frequency diversity (Palattella and et al. (2013)). Energy efficiency and reliability are obtained by using TSCH with the synchronization of nodes via slot frame structure and with channel hopping, respectively. After the synchronization, a schedule is established to define the slots and channel offsets of each nodes for making transmission (Palattella and et al. (2013)).

An alternative solution to improve the network capacity is to utilize transmission power control. Instead of transmitting signals with maximum power, transmissions with just enough power has been shown to improve the network capacity (Moscibroda 2007). Although these studies on utilizing multi-channel communication and transmission power control provide valuable foundations in the design of WSNs, most of these algorithms have focused on minimizing schedule length and latency assuming excellent link qualities and none of them has focused on the performance of WSNs in different smart grid environments (Moscibroda 2007).

Network performance has been investigated in terms of capacity and delay by (Florens and et al. (2004), Florens and McEliece (2003)). Besides the elimination of interference utilizing multi-channel communication, it is clear that the network capacity is also limited by the topology of the network. For instance, network capacity certainly differs if we have a star topology with single-hop or line topology with multiple hops to the sink node. Therefore, (Florens and et al. (2004), Florens and McEliece (2003)) focus on the scheduling problem in WSNs by utilizing different network topologies that are line, multi-line and tree networks, and show that the capacity of the network substantially differs according to the underlying topology.

Network capacity using tree-based data collection (convergecasting) has been also studied in previous work (Incel and et al. (2012), Malhotra and et al. (2011), Chen and et al. (2010), Ghosh and et al. (2009), Gandham and et al. (2008)). In (Incel and et al. (2012)), it was shown that once the impact of interference on the network capacity is eliminated with multiple channels, the network capacity is limited with the topology of the network. Furthermore, it was shown that CMSTs result in the best performance in terms of fast data collection in WSNs.

2.2 QoS-AWARE ROUTING PROTOCOLS

Routing protocols provides to deliver data from nodes to sink node. However, the main QoS requirements including timeliness, energy efficiency and reliability are not considered together by the all proposed routing protocols. In this thesis, the network layer is considered to provide delay requirements of WSN-based smart grid applications.

Within this context, some of the studies (Villaverde and et al. (2012), Liang and et al. (2010), Li and Zhang (2010), Lee and Younis (2009), Ahmed and Fisal (2008), Razzaque and et al. (2008), Akkaya and Younis (2005), He and et al. (2003)) about routing layer design are analyzed in this chapter. Real Time Routing Protocol with Load Distribution (RTLD) has been designed in (Ahmed and Fisal (2008)) for sending packets according to their delay requirements. RLTD increases throughput and decreases power consumption while making transmission in a timely manner. Real time routing is achieved by RLTD by combining the geocast forwarding considering link qualities, highest velocity and remaining energy. This approach decreases the routing holes problem by using remaining power. Although RLTD considers both link qualities and power constraints of sensor nodes, it does not consider the effects of multi-channel scheduling for meeting delay requirements of WSN-based smart grid applications.

Akkaya and Younis (2005) presents an energy and QoS-aware routing protocol for sensor networks. The proposed protocol employs the class based queuing model to support both real-time and best effort traffic and defines the routes according to distance, energy reserve and error rate. Furthermore, it adjusts the data rate for real-time and non-real-time at the sensor nodes by using two different mechanisms in order to maximize the throughput for non-real-time data. In this way, the proposed protocol meets the delay and throughput requirements of both real-time and non-real-time traffic.

A stateless, localized routing algorithm, SPEED has been presented by the authors in (He and et al. (2003)) for providing real-time communication. This is achieved with additional modules that provide to reduce congestion by balancing network traffic. SPEED algorithm has been extended with the study of Multi-Path and Multi- SPEED Routing Protocol (MMSPEED) explained in (Felemban and et al. (2006)) for increasing reliability of SPEED algorithm. Scalability, adaptability and end-to-end reliability requirements are provided by MMSPEED in a localized way by multi-path forwarding. In addition, a Randomized Re-Routing (RRR) protocol has been presented by the study in (Gelenbe and Ngai (2008)). Unusual events are detected by this protocol and packets are sent through the sink by providing QoS requirements. In this way, critical data is transmitted over the network in reliable manner.

OQAP (Optimized QoS-Aware Placement) of relay nodes algorithm has been proposed by Lee and Younis (2009). A centralized greedy heuristics is used and cell based least cost paths are found to minimize the number of relay nodes (RNs) while providing connected topology and meeting the QoS requirements. Then the authors measure the performance of proposed approach through simulations. Although the authors demonstrated OQAP efficiency, they didn't consider all the QoS requirements and complex topologies where more than one cells are involved by a segment. Multi-agent Reinforcement Learning (MRL-CC) based cooperative communication protocol has been presented by Liang and et al. (2010). Using cooperative communications for meeting QoS requirements of resource constrained WSN-based applications has been analyzed by the authors.

A multi-sink and multi-path protocol, Distributed Aggregate Routing (DARA), has been proposed in (Razzaque and et al. (2008)). DARA provides making real-time transmission by constructing shortest routes for delay critical packets. On the other hand, non-time critical packets are delivered by DARA via longer paths while preserving shortest paths for time critical packets. The most proper relaying nodes are found by DARA for all types of packet, RT and NRT. DARA guarantees reliability with packet duplication. Only the source nodes duplicates the packets and when needed copied packets are sent to intermediate nodes towards sink nodes. In addition, the protocol implements power controlled transmission and reduces number of retransmission to achieve energy efficiency. Even though DARA provides reliability, energy efficiency and delay requirements, real-channel conditions that are important for applying it in the real applications are not considered by DARA while constructing routing paths.

Optimized Multi-Constrained Routing (OMCR) has been proposed in (Li and Zhang (2010)) to derive the QoS requirement. They studied the dynamics of power load and analyzed impacts of different QoS metrics including delay and outage on the revenue of home appliances. Their motivations is to secure the QoS and meet the real-time requirement according to the derived QoS requirement. All the QoS-aware routing algorithms mentioned above are compared in Table 2.1.

Table 2.1: Comparison of existing QoS-aware routing algorithms for WSNs

Protocol	Delay	Throughput	Reliability
RTLD (Ahmed and Fisal (2008))	No	Yes	Yes
Energy-aware QoS routing algorithm (Akkaya and Younis (2005))	Yes	Yes	Yes
SPEED (He and et al. (2013))	Yes	No	No
MMSPEED (Felemban and et al. (2006))	Yes	Yes	Yes
RRR (Gelenbe and Ngai (2008))	Yes	Yes	Yes
OQAP (Lee and Younis (2009))	No	No	No
MRL-CC (Liang and et al. (2010))	No	No	No
DARA (Razzaque and et al. (2008))	Yes	No	Yes
OMCR (Li and Zhang (2010))	Yes	No	No

2.3 QoS-AWARE MAC PROTOCOLS WITH SERVICE DIFFERENTIATION

The choice of MAC protocol used plays a crucial role in the resulting delay and communication efficiency. Although there are protocols to meet the QoS requirements of general WSNs (Yigitel and et al. (2011)), there are only a few MAC protocols that consider QoS and service differentiation for smart grid. MAC protocols are generally categorized into three classes as contention-based, schedule-based and hybrid schemes (Akyildiz and et al. (2007)). In contention-based MAC protocols, also known as random access protocols, nodes try to access the channel, which can cause higher delays because of the collisions. To reduce these delays, the Real Time MAC (RT-MAC) protocol was proposed in (Singh and Tepe (2009)). Although RT-MAC avoids the false blocking problem, which occurs while Request to Send/Clear to Send (RTS/CTS) are exchanged, to increase the spatial channel reuse, RT-MAC cannot solve the interference problem of the multi-stream communications. Additional wake-ups are used by the MaxMAC protocol to reduce latency and to increase packet delivery ratio according to the traffic rate (Hurni and Braun (2010)), but additional wake-ups increase the power consumption for sensor nodes. QoS-MAC protocol for IEEE 802.15.4 was proposed in (Sun and et al. (2010)). The QoS-MAC is based on the IEEE 802.15.4 unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme that exploits service differentiation according to traffic types that have different priorities. Delay-Responsive

Cross-layer (DRX) and Fair and Delay-aware Cross-layer (FDRX) are other MAC protocols presented in (Al-Anbagi and et al. (2014)) for smart grid applications. They use application layer data prioritization and MAC layer parameters for estimating delay requirements of smart grid applications. If the delay requirements of an application are lower than the estimated delay, they give higher priority to the node to access the channel. The difference between DRX and FDRX is that FDRX provides fairness by periodically giving channel access to the nodes having lower priority. Although these contention-based protocols reduce delays, they cannot prevent the effect of collisions.

Many QoS-aware schedule-based MAC protocols were also proposed in (Deng and et al. (2015), He and et al. (2014), He and et al. (2013a), He and et al. (2013b), Erol-Kantarci and Mouftah (2011), Kim and et al. (2011), Kamruzzaman (2010), Siddique and Yang and Ulukus (2010), Bononi and et al. (2009), Yang and Ulukus (2009)). WRT-Ring is another schedule-based distributed RT MAC protocol, which works in the slotted virtual ring network (Bononi and et al. (2009)). WRT-Ring provides real-time communication according to the control signal, which rounds into the virtual ring. However, addressing the urgent alarm in WRT-Ring is difficult because the control signal is distributed while traveling. TDMA is one of the important schedule-based MAC protocols. In (Kim and et al. (2011)), a tree-based TDMA protocol was proposed for home area networks in the smart grid. Even though TDMA protocols are adequate when there is no collision in the medium, they are inefficient to meet different traffic loads. Rate allocation-based protocols proposed in (Yang and Ulukus (2010), Yang and Ulukus (2009)) are another schedule-based MAC protocol. These algorithms assign different rates to the users on demand according to their delay requirements. However, they suffer from abundant information exchange that causes extra overhead for providing QoS. Some studies are performed to increase the data collection performance for WSNs with mobile elements. In (He and et al. (2013a), He and et al. (2013b)), a Combine-Skip-Substitute (CSS) and Multirate CSS (MR-CSS) schemes are proposed. The main purpose of these schemes is that reducing the data collection latency of WSNs with mobile elements. CSS combines the data collection sites and then skip and substitute some sites for reducing the tour length of mobile elements. The other approach, MR-CSS, is designed for providing multirate communication model to mobile elements. MR-CSS allows the mobile elements to collect data from longer distances with a lower rate. The performance of these schemas is evaluated with extensive simulations to show their efficiency and effectiveness. In (He and et al. (2014)), an M/G/1/c-NJN queuing system is modeled with using Nearest-Job-Next (NJN) discipline to schedule the data collection requests that come to mobile elements in WSNs. Different combination of data collection requests can come to mobile element. Therefore, NJN is extended to NJN-with-combination, M/G/1/c-NJNC, to measure the gain when possible request combinations arrive at the mobile element. The performance of these models is evaluated through both theoretical analysis and simulations. Furthermore, the proposed models are compared with first-come-first-serve discipline. The simulation results show that the proposed models outperform the first-come-first-serve. In (Erol-Kantarci and Mouftah (2011)), the performance of an in-home energy management (iHEM) application is evaluated with an Optimization-based Residential Energy Management (OREM) scheme. The main purpose of this assessment is minimizing the energy outgoings of the consumers. In order to achieve this purpose, OREM schedules the appliances to hours, which are less expensive, according to the time-of-use tariff. Furthermore, the iHEM performance is also evaluated under the existence of local energy management capability, on the use of priority-based appliance scheduling and RT pricing. Simulations are performed to show the performance of iHEM application with OREM. Results show that energy consumption cost and carbon emissions iHEM application. In addition, iHEM application with the OREM scheme also decreases delay and increases delivery ratio with the priority-based scheduling.

Hybrid MAC protocols combine multiple schemes to overcome drawbacks of using a single scheme. IEEE 802.15.4 uses a hybrid scheme that is formed by combining of CSMA/CA and TDMA (Ullo and et al. (2010)). However, this scheme is not efficient for time-critical smart grid applications because of the limited number of available slots and congestion of the CSMA contention period under high traffic loads. EQ-MAC provides QoS for delay-sensitive smart grid applications by integrating a hybrid medium access scheme with service differentiation (Yahya and Ben-Othman (2010)). Contention-based medium access is used by EQ-MAC for sending messages, and therefore, EQ-MAC suffers from congestion and is inefficient for delay-sensitive smart grid applications.

Although there are many QoS-aware MAC protocols based on service differentiation and include sensor nodes equipped with different antenna types, there have been no studies that explored the performance of their protocols by designing different antenna models. Furthermore, no cross-layer QoS-aware sectored antenna-based MAC protocol has been proposed for smart grid applications in the literature. Within this context, in this thesis, two novel cross-layer QoS-aware and priority-based MAC protocols, QFSA-MAC and QODA-MAC, are explored for smart grid communication networks. Aim of QFSA-MAC and QODA-MAC is maximizing the network utilization and reducing the collision on different traffic loads for meeting the requirements of smart grid application.

2.4 QoS-AWARE DIRECTIONAL ANTENNA BASED MAC PROTOCOLS

Many wireless sensor network MAC protocols, including S-MAC (Ye and et al. (2002)), T-MAC (Van Dam and Langendoen (2003)) and Z-MAC (Rhee and et al. (2008)), use an omnidirectional physical layer, and therefore, they have limited channel capacity due to restricted state of the omnidirectional antenna. The use of directional antennas with wireless ad hoc networks (Ramanathan and et al. (2005), Korakis and et al. (2003), Ko and et al. (2000)) and mesh networks (Zhang and Jia (2009), Kumar and et al. (2006)) has been well explored in the literature; however, none of those approaches are suitable for smart grid communication networks because of their higher energy consumption. Currently, there is no study in the literature that uses directional antennas for smart grid communication networks. In this chapter, the studies on MAC protocols that use directional antennas designed for general WSNs are reviewed.

Authors in (Cho and et al. (2006)) propose a scheme where the sink node is equipped with a directional antenna that broadcasts its schedule to its relaying sensor nodes in the network. Their proposed approach increases the network lifetime when the directional antenna is used only at the sink node. Manes and et al. (2008) also show that a MAC protocol using directional antennas reduces power consumption more than a MAC protocol that uses omnidirectional antennas. Additionally, in (Dunlop and Cortes (2007)), it is shown that the network lifetime increases with the use of directional antennas by reducing the duty cycle.

Authors in (Dimitriou and Kalis (2004)) propose an approach for using directional antenna for WSNs. In this approach, a directional antenna mounted on the sink node is used to transmit beacon to all the nodes. When the nodes receive the signal, they choose the best beam to transmit the data packets towards the sink node. However, this protocol is not suitable for sensor networks because it can limit the spatial span of the sensor nodes. Zhang and Datta (2005) proposed another approach where each node computes a time schedule to organize directional communications with its neighbors. Each node exchanges its time schedule with its neighbors after they exchange neighboring information. If the time schedule of the node does not change after a few exchanges, the node can send the data packets through the sink node. However, nodes wait until their time schedule has been stabilized, which takes too much time and is not applicable for delay-sensitive applications. Sectored antenna-based MAC (SAMAC) protocol (Felemban and et al. (2010)) is an MAC protocol that uses directional antenna for sensor networks. It is a protocol equipped with sectored antennas. The authors also claim that SAMAC improves the throughput and end-to-end delay features of sensor networks by using the spatial reuse capability of directional antennas. Although SAMAC is advantageous for efficiency and predictable delay in sensor networks, service differentiation for delay-critical applications is not considered in this protocol. Moreover, the performance of SAMAC is not analyzed under different traffic loads such as high and low loads. All the described QoS-aware omnidirectional and directional antenna-based MAC protocols are also compared in Table 2.2.

Table 2.2: Comparison of existing QoS-awareWSN-based MAC protocols

Protocol	**Purpose**	**Type**	**Latency**	**Data delivery**	**Energy awareness**	**Complexity**	**QoS awareness**
RT-MAC (Singh and Tepe (2009))	Provide RT data streaming for WSNs.	CSMA	Yes	No	Yes	High	Low
MaxMAC (Hurni and Braun (2010))	Guarantee high throughput and low latency for WSNs.	CSMA	Yes	Yes	No	High	Low
QoS-MAC (Sun and et al. (2010))	QoS support for IEEE802.15.4 and IEE802.15.1	CSMA/CA	Yes	No	No	Low	High
DRX and FDRX (Al-Anbagi and et al. (2014))	Support delay and service requirements of smart grid.	CSMA/CA	Yes	Yes	No	Low	High

PCF-based medium access (Siddique and Kamruzzaman (2010))	Reduces latency for WLANs under high traffic loads.	TDMA	Yes	Yes	No	High	Low
WRT-Ring (Bononi and et al. (2009))	Guarantee timeliness for WSNs. & CDMA/TDMA	CDMA/TDMA	Yes	No	No	High	Low
Tree-based TDMA-MAC (Kim and et al. (2011))	A MAC for smart grid Home Area Network (HAN) network.	TDMA	Yes	Yes	Yes	Low	High
Rate allocation algorithms (Yang and Ulukus (2010))	Minimize the average delay of the system.	TDMA	Yes	No	No	High	Low
EQ-MAC (Yahya and Ben- Othman (2010))	Provide QoS for single-hop sensor networks.	TDMA/CSMA	Yes	No	Yes	High	High
CSS and MR-CSS (He and et al. (2013a), He and et al. (2013b))	Decreasing the data collection latency of mobile elements.	Scheduling	Yes	Yes	No	Low	No
NJN and NJNC (He and et al. (2014))	Increasing the data collection performance of mobile elements.	Scheduling	Yes	No	No	High	Low
iHEM with OREM scheme (Erol-Kantarci and Mouftah (2011))	Minimizing the energy bills of the consumers	Scheduling	Yes	Yes	Yes	High	High
DaaS (Cho and et al. (2006))	Increases the network lifetime in WSNs.	SMAC	No	No	Yes	High	Low
D-STAR (Manes and et al. (2008))	Provide energy efficiency for WSNs.	STAR MAC	Yes	No	Yes	High	Low
(Dimitriou and Kalis (2004))	Improve the throughput and energy consumption.	S-MAC	No	Yes	Yes	High	Low

(Zhang and Datta (2005))	An energy efficient MAC protocol for WSNs.	Scheduling	No	No	Yes	High	Low
SAMAC (Felemban and et al. (2010))	Guarantee energy efficiency and timeliness for WSNs.	CSMA/TDMA	Yes	Yes	Yes	High	High

2.5 ERROR CONTROL TECHNIQUES

Various error control techniques such as FEC are used to achieve reliable and secure data transmission over a channel. In these techniques, data is encoded by using various algorithms before transmission and then encoded data is decoded by the receiver to get the original data. Efficiency of these error control techniques change according to communication channel. Therefore, the performance of these techniques differs from each other through the same channel.

In the literature, many studies have been done to compare the error control techniques in WSNs (Okeke and Eng (2015), Akande and et al. (2014), Korrapati and et al. (2013), Islam 2010, Vuran and Akyildiz (2009), Balakrishnan and et al. (2007)). In (Akande and et al. (2014)), the performance of RS and BCH codes are compared over Correlated Rayleigh Fading Channel. The M-QAM (M-Quadrate Amplitude Modulation) is used in the order 16, 32 and 64. BER is used as a performance metric in simulations to show the performance of RS and BCH. Results show that the uncoded signal performs better if the modulation order is high. However, if RS and BCH codes are used, BER decreases for all modulation order. Furthermore, it is also presented that BCH 64-QAM achieves the lowest BER over correlated Rayleigh fading channel. In (Balakrishnan and et al. (2007)), binary-BCH codes, RS codes and the convolutional code with Viterbi algorithm are analyzed and compared in terms of their power consumption and BER performance on FPGA and ASIC platforms. According to their performance comparison of three error control codes on different platforms, binary-BCH codes performs better than the RS and convolutional codes with Viterbi algorithm if it is used with ASIC implementation. An efficient error correction code in terms of BER and power consumption performance is chosen for WSN in (Islam 2010). In this respect, BER performance of different Error

Correction Codes (ECCs) such as RS, Hamming, Golay, Convolutional (Hard) and Convolutional (Soft) codes are measured and compared with each other. Results show that RS and convolutional codes show better BER performance than the other ECCs. However, RS is more suitable than convolutional codes for WSNs due to high power consumption of convolutional codes. For this reason, the BER performance of different RS codes is also shown and RS(31,21) is chosen as the most suitable ECC (Error Correction Code) for WSN. In (Vuran and Akyildiz (2009)), error control schemes in WSNs are analyzed with using a cross-layer methodology which investigate the cross-layer effects of all layers such as medium access layer, routing layer and physical layer. FEC, ARQ, and Hybrid ARQ (HARQ) schemes are analyzed and compared in terms of the energy and latency performance. As a result of cross-layer analysis of error control techniques, error resiliency is improved by the FEC algorithm since FEC sends redundant bits over the wireless channel. In addition, it is also shown that end-to-end latency performance of WSNs increases along with targeted PER and energy efficiency when the FEC and the hybrid ARQ schemes are used. In (Korrapati and et al. (2009)), the performance of RS using BPSK modulation is evaluated in an Additive White Gaussian Noise (AWGN) Channel. BER is measured while signal energy to noise power density ratio is increasing. Results show that BER performance increases when code word length remains constant for the same code rate. Furthermore, results also show that the performance of RS code, which has more parity check bits to correct burst errors, has a higher BER value when energy to noise power density ratio is low. In (Okeke and Eng (2015)), RS and Hamming code are compared. As a result of comparative analysis, it was found that the performance of RS code is higher for data communication than Hamming code because RS provides a high coding rate with low coding complexity. The results of analysis also show that Hamming code is efficient for transmitting small data sizes since it is simple and can correct one error per message.

Performance comparison of error correcting codes for WSNs is widely done by many authors (Alrajeh and et al. (2015), Leeson and Patel (2015), Okeke and Eng (2015), Akande and et al. (2014), Korrapati and et al. (2013), Islam 2010, Balakrishnan and et al. (2007), Vuran and Akyildiz (2007)), however performance comparison of error detection and correction code by combining various modulation techniques for WSNs operating in smart grid environments is not available in the literature. Therefore, in this thesis, performance comparison of some of the Hamming code combined with the modulations including BPSK, DPSK, FSK, and OQPSK is analyzed and compared with without FEC algorithm in WSN-based smart grid communication networks.

2.6 ADAPTIVE ERROR CONTROL TECHNIQUES

Many studies have been done on adaptive FEC in WSNs (Pham and et al. (2017), Yu and et al. (2012)). In (Pham and et al. (2017)), an adaptive FEC coding algorithm at the MAC layer is proposed in WSNs. Energy consumption, energy efficiency, PER, recovery overhead, and the quality of the image, defined as the Peak-Signal-to-Noise-Ratio (PSNR) value of the image, are the performance metrics of this study in the case of image transmission. This algorithm is based on two look-up tables: namely, a distance look-up table and a BER look-up table. In these look-up tables, the best FEC codes are stored according to different distances and BERs because BER always changes due to changing channel conditions. The proposed algorithm provides a fast solution by selecting the optimum FEC value from the look-up tables. Furthermore, the performance of this algorithm is compared with an Adaptive MAC-Level FEC (AMFEC) mechanism (Tsai and et al. (2011)) and the method of Ghaida et al. (2012). PSNR values of these three methods are compared as the BER of channel changes to evaluate the quality of image transmission. The results show that the proposed algorithm of (Pham and et al. (2017)) achieves better performance than the other compared algorithms. This algorithm is effective since it uses look-up tables for quick selection of FEC codes. However, in this algorithm multi-channel scheduling is not considered to be effective for image transmission since it improves the network performance by achieving simultaneous transmission. In (Yu and et al. (2012)), an Adaptive Forward Error Correction (AFEC) algorithm is proposed for best effort WSNs. A finite state Markov model is used to describe the switching mechanism between the FEC codes. Switching from one state to another in this Markov model is done based on channel conditions that are measured through PER in the last 20 transmissions. If the average PER is higher than the predefined threshold, the current FEC code of the node is changed with a stronger FEC code. The proposed AFEC algorithm is compared with static FEC and an uncoded system. The results reveal that as the switching threshold increases, the throughput performance of AFEC increases as well as PER. This is a consequence of the fact that higher values of the switching threshold imply a less conservative reaction to channel changes, where weaker codes are used most often. The proposed AFEC schema is suitable for best effort WSNs and is not evaluated for smart grid applications. What is more, multi-channel scheduling is also not considered in the proposed schema.

3. MULTI-CHANNEL SCHEDULING and ROUTING FOR SMART GRID

3.1 INTRODUCTION

Given the increasing age of power grid and growing energy demand, electric utilities face the challenge of ensuring reliable power delivery to the customers at competitive prices. Power grid failures due to the complex electric distribution systems cause congestion in the power network. All these network congestions, component failures, accidents, and natural catastrophes cause power outages leading to major blackouts all around the world. To address these issues, a new concept of next generation electric power system, the smart grid, has been proposed. The smart grid is a modernized electric power grid aiming to improve productivity, reliability, and safety of the existing grid with the use of advanced communications and sensing technologies (Kilic and Gungor (2013), Shah and et al. (2013), Erol-Kantarci and Mouftah (2011), Gungor and et al. (2010)). It is expected that the smart grid will provide significant energy savings, decrease operational costs, and increase safety and power quality. To this end, the cost and design of the communication network in smart grid applications becomes crucial to the performance of the overall electric power system (Gungor and et al. (2013)).

The recent developments in embedded systems and WSNs have enabled reliable and cost-effective power grid management systems, which have the capability of monitoring and controlling the real-time operating conditions and performance of the grid (Bicen and et al. (2012), Gungor and et al. (2012), Gungor and et al. (2011), Gungor and et al. (2010)). In these systems, the collaborative and low-cost nature of WSNs brings several benefits over traditional electric monitoring systems, including greater accuracy, improved fault tolerance, extraction of localized events. In this respect, wireless sensor networks enable low-cost and low-power wireless communications for diverse sets of smart grid applications, including automatic wireless metering, line fault and power theft detection, conductor temperature and dynamic thermal rating, distribution automation, outage detection, underground cable system monitoring, real time pricing, tower and poles monitoring, etc. All of these applications are presented Table 3.1. However, the realization of these currently designed and envisioned WSN-based smart grid applications and to meet the general application demands in terms of delay, reliability and throughput directly depends on reliable communication capabilities of the deployed sensor network in harsh power grid environments.

Table 3.1: Summary of WSN-based smart grid applications

Applications	**Subsystem**
Advanced Metering Infrastructure	Demand-side
Real Time Pricing	Demand-side
Building and Industrial Automation	Demand-side
Conductor Temperature and Dynamic Thermal Rating	Utility-side
Line Fault and Outage Detection	Utility-side
Wind Farm Monitoring	Generation-side
Solar Farm Monitoring	Generation-side

Field tests in (Gungor and et al. (2010)) show that the link-quality of wireless links in different smart grid environments, such as outdoor substation, main power control room, and underground network transformer vaults, changes greatly with location and time because of multi-path, fading and noise. On top of these factors, contention on the wireless medium and RF interference due to parallel transmissions limit the capacity of WSNs specifically in smart grid environments. To improve network performance in these environments, multi-channel communication can be utilized to overcome the impact of interference and achieve simultaneous transmissions over multiple channels. With the parallel transmissions, network performance can be improved both in terms of delay and capacity, such as throughput. However, the design and implementation of sensor nodes is constrained by energy, memory, and processing capabilities, which require simple but effective multi-channel scheduling algorithms for WSNs to be deployed in smart grid spectrum environments.

Until now, several multi-channel algorithms have been proposed to improve the performance (Incel and et al. (2011), Kim and et al. (2008), Wu and et al. (2008), Salajegheh and et al. (2007), Zhou and et al. (2006)) of WSNs. However, it is not explored how the existing multi-channel scheduling algorithms for WSNs will perform under varying and harsh conditions of smart power grid. This motivates to explore the performance and the impact of multi-channel communication in WSNs for smart grid applications. Besides the impact of interference which can be eliminated with multi-channel communication, previous work shows that the capacity of WSNs is also limited by the topology of the network (Incel and et al. (2012)). Hence, it is imperative to evaluate the impact of different routing topologies on the network performance in such environments.

To address these needs, in this chapter, the network performance of WSNs for efficient data collection, i.e. convergecasting, in different smart-grid environments with harsh operating conditions is investigated. In particular, the network performance is investigated in terms of delay and network capacity, considering multi-channel communication to alleviate the effects of interference, using suitable network tree topologies and retransmission of lost packets in case of lost packet over unreliable links. The performance of a state of the art multi-channel MAC protocol (Incel and et al. (2012)), named Receiver-Based Channel Assignment (RBCA), together with different routing topologies in different smart grid spectrum environments, e.g., 500 kV outdoor Subs, MPR and UTV is investigated. Importantly, all these performance evaluations are based on real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in different smart grid environments (Gungor and et al. (2010)). As the multi-channel scheduling algorithm, the RBCA algorithm is utilized. The reason behind this selection is that, the performance of RBCA was evaluated for WSNs with perfect link qualities and it was shown that it can efficiently improve the network performance in terms of latency compared with other multi-channel MAC protocols, such as Tree-based Multi–Channel Protocol (TMCP) (Wu and et al. (2008)). Besides, RBCA is easy to implement and its source code is available for other researchers.

To evaluate the impact of the routing topology on the network performance, different routing topologies, namely, routing trees constructed considering the link qualities, CMSTs, capacitated minimum spanning trees considering link qualities and minimum hop spanning trees are considered. CMST topologies were shown to minimize latency with perfect link qualities in (Incel and et al. (2012)), however, their performance was not evaluated for WSNs operating in smart grid environments with varying link qualities. Constructing routing topologies considering the link qualities can certainly contribute to avoid bad-quality links and improve network performance. Hence, as the second approach, the performance with routing topologies constructed according to the PRR metric is investigated. Besides, the CMST and PRR-based routing topologies are combined and are investigated the possible capacity improvements. Finally, the impact of retransmissions on the network performance both in terms of latency and capacity, considering the lost packets due to unreliable links in smart grid environments is considered.

Overall, the contribution of this study is to investigate the performance of multi-channel WSNs for smart grid and to quantify how multi-channel communication combined with different routing trees will perform under harsh conditions of smart power grid and meet the general application requirements, such as delay, throughput and reliability. All the simulation results in this chapter provide precious understanding about multi-channel scheduling and topology construction for WSNs in harsh smart grid environments.

The rest of the chapter is organized as follows: Section 3.2 describes the network model and background. Section 3.3 presents the impact of routing topologies on data collection performance. In Section 3.4, performance results are given. Simulation results are summarized in Section 3.5 Finally, chapter is concluded in Section 3.6.

3.2 NETWORK MODEL and BACKGOUND

In this section, the design constraints of our problem together with the background information and assumptions are explained.

WSN is modeled as a graph $G = (V, E)$ where V is the set of nodes, and $E = \{(i, j) \mid i, j; \in V\}$ is the set of edges representing the wireless links. We assume that all the nodes have a single half-duplex transmitter, such that they cannot receive and transmit at the same time and cannot receive from multiple transmitters at the same time.

3.2.1 Modeling Interference

There are two commonly-used interference models in the literature. One of them is the protocol model and second is the physical interference model (Gupta and Kumar (2000)). In the protocol model, packets are received by the receiver if other senders do not transmit a packet at the same time. In this way, graph coloring-based scheduling algorithms can be used. However, interference has cumulative effects in a wireless network and according to (Brar and et al. (2006), Grönkvist and Hansson (2001)); this cumulative effect cannot be solved by the protocol model. Otherwise, physical model can solve these cumulative effects by using SINR (Signal to Interference Noise Ratio). In the physical model, the successful reception of a packet from node i to node j is affected by the ratio between the received signal strength at j and the cumulative interference caused by all other concurrently transmitting nodes and the ambient noise level. Hence, a packet is received successfully at *j* if the signal-to-interference- plus-noise ratio, $SINR_{ij}$, is greater than a certain threshold *b*. $SINR_{ij}$ is shown in Equation 3.1.

$$\boldsymbol{SINR_{ij}} = \frac{\boldsymbol{P_i \cdot g_{ij}}}{\boldsymbol{\sum_{k \neq i} P_k \cdot g_{kj} + \mathcal{N}}} \qquad \textbf{(3.1)}$$

In Equation 3.1, P_i is the transmitted signal power at node *i*; $\mathcal{N}$ is the ambient noise level, and g_{ij} is the propagation attenuation (link gain) between *i* and *j*. In this study we use the physical interference model for creating a realistic wireless communication environment.

3.2.2 Modeling Link Quality for Smart Grid Environments

Log normal shadowing model is used for modeling the wireless links. This model is used for different experimental studies and it has been shown that it provides more accurate multi-path channel models for wireless environments with obstructions. The parameter selection is based on the field studies presented in (Gungor and et al. (2010)) for link qualities and channel characteristics of different smart grid environments. These field tests have been performed in different harsh electric-power-system environments, such as 500kV Substation, industrial power control room and Underground Transformer Vault, using IEEE 802.15.4 compliant wireless sensor nodes measuring noise, channel characteristics, attenuation and link quality in these environments. In this respect, channel parameters used in our experiments are shown in Table 3.2.

Table 3.2: Path loss and shadowing deviation in electric power environments

Propagation environment	Path loss (η)	Shadowing deviation (X_{σ})
500 kV Substation	2.42	3.12
Underground Transformer Vault	1.45	2.45
Main Power Room	1.64	3.29

In log normal shadowing path loss model, the signal to noise ratio γ(d) at a distance d from the transmitter is shown in Equation 3.2 where P_T is the transmit power in dBm, $P_L(d_0)$ is the path loss at a reference distance d_0, n is the path loss exponent, X_{σ} is a zero mean Gaussian random variable with standard deviation (σ).

$$\boldsymbol{\gamma(d) = P_T - P_L(d_0) - 10_n log_{\eta} log_{10} \frac{d}{d_0} - X_{\sigma}} \qquad \textbf{(3.2)}$$

3.2.3 Data Collection Model

We assume all the sensor nodes except the sink node generate packets and transmit them over a routing tree to the sink node, i.e. we focus on convergecasting data towards a sink node. Since the nodes are equipped with half-duplex transceivers our first constraint in the data collection is that if a node is transmitting it cannot be scheduled to receive or transmit to another node. Similarly, it cannot receive from multiple transmitters at the same time. Additionally, since we focus on the physical interference model, another constraint is that, a transmitter *i* cannot be scheduled to transmit if the SINR at its receiver node *j* is not greater than the threshold, *β,* for a successful transmission.

3.2.4 Receiver-based Channel Assignment and Medium Access

The RBCA algorithm (Incel and et al. (2012)) is a TDMA based multi-channel MAC protocol that is particularly designed to work on tree-based routing topologies. In order to avoid pairwise, per-packet channel negotiation overheads, RBCA statically assigns the channels to the receivers (parents) of the routing tree, and the children of a common receiver transmit on that channel to communicate with the parent. At the channel selection stage, RBCA assigns the channels where the receiver experiences no interference or the minimum interference using the physical interference model. With this method, potential interference between simultaneous transmissions is eliminated.

For TDMA scheduling, RBCA runs a timeslot assignment algorithm with the key idea to schedule transmissions in parallel along multiple branches of the routing tree, and to keep the sink busy in receiving packets for as many time slots as possible. Therefore, there is no collision and collided packets in our model since each node is assigned a guaranteed timeslot by using TDMA. Only packet losses are due to the unreliable links. It considers a TDMA protocol where time is divided into slots, and consecutive slots are grouped into equal-sized nonoverlapping frames. For the schedule computation, RBCA uses the same constraints of the data collection explained in Section 3.2.3. Performance of the RBCA algorithm was compared with other state-of-the-art multi-channel MAC protocols, such as TMCP (Wu and et al. (2008)), and it was shown that RBCA performs to be efficient in terms of eliminating interference and maximizing parallel transmissions.

The reason why we utilized the RBCA protocol is that, it was shown to perform well for WSNs to eliminate the impact of interference and improve the network performance in environments with perfect link qualities. However, its performance was not evaluated for WSNs operating in harsh smart grid environments with varying link qualities both in space and time. In this study, our aim is to explore its performance for WSNs in harsh environments.

3.3 IMPACT OF ROUTING TOPOLOGIES ON DATA COLLECTION PERFORMANCE IN WSNS

In (Incel and et al. (2012)), it was shown that, once interference is eliminated with multi-channel communication, the network performance is limited by the routing topology. To evaluate the impact of the routing topology on the network performance, we consider different routing topologies, namely, routing trees constructed considering the link qualities (PRR), CMSTs, capacitated minimum spanning trees considering link qualities (PRR) and MHSTs. These algorithms are briefly explained in the following subsections.

3.3.1 Capacitated Minimum Hop Spanning Tree - CMST

CMST is a minimum cost spanning tree that contains a root *(r)* node and subtrees which are connected to root node according to capacity constraint c. c means that subtrees attached to root (*r*) node cannot have more than *c* nodes (Arkin and et al. (2012)). When nodes in subtrees have weights, in this situation summation of weights in a subtree must be smaller than or equal to *c*. Edges between the root and subtrees are called as gates. In (Incel and et al. (2012)), the constraint of c was computed as $2_{n_k} - 1$, where n_k is the maximum number of nodes on any branch in the tree. In this respect, finding the lowest cost spanning tree according to the c constraint by applying the log normal shadowing calculation in smart grid environments, is the purpose of our CMST algorithm.

In order to construct CMST we utilize the following variables: a graph is given $G = V, E$ and number of nodes in G is $n = G$. Root $r \in G$. ai represents other nodes in G. Edge cost is shown with c_{ij} between vertices a_i and a_j. In this way, a cost matrix is formed and shown with $C = c_{ij}$. According to these parameters, CMST algorithm's steps are listed below (Rego and Mathew (2011)):

a. In the first step, all nodes that are 1-hop neighbors of the sink represent the root node of subtrees are connected to sink node (r).
b. Number of nodes in each subtree represents the cost of subtree and it is shown as $\sum_{n}^{i=0} c_{ri}$. Each of edge from root to subtree is a gate (g_i).

c. At each iteration, closest neighbor (a_j) is selected for the connected nodes except the root node.

d. Tradeoff function is computed for achieving potential savings by merging neighbor nodes instead of connecting them to the root node, directly with this equation: $t(a_i) = g_i - c_{ij}$.

e. Greatest $t(a_i)$ is searched for removing g_i gate that does not accord capacity constraint.

f. These steps are repeated until better improvements cannot be achieved.

These steps are performed to construct the CMST by Capacitated Minimum Spanning Tree Algorithm. CMST algorithm's pseudocode (Rego and Mathew (2011)) is explained in Algorithm 3.1. Pseudocode of the algorithm presents how the algorithm works to find the CMST (Incel and et al. (2012)).

Algorithm 3.1: CMST algorithm

1. **Input:** Capacity constraint (*c*) of the tree, cost matrix *C* and root node are given as inputs
2. **Compute:** Minimal cost spanning tree of a *Graph*, *G* according to root node *r* and *c* (capacity constraint)
3. **Set:** $T = C_{1r}, C_{2r}, . . ., C_{nr}$
4. **while** no improvement to tree
5.   **for each** node a_i
6. a_i equals to closest node that is in different subtree
7.   **Tradeoff function:** $t(a_i) = g_i - c_{ij}$
8. T_{max} equals to maximum $t(a_i)$
9.   *k* equals to *i*
10. $t(a_i)$ equals to t_{max}
11.   **when** cost of *i* + cost of *j* smaller than or equal *c*
12. T equals to $T - g_k$
13. T equals to $T \cup g_k$
14. **Output: GraphCMST = *T***

3.3.2 PRR-based Routing Protocol

PRR values of wireless links is important and widely used to model the link quality. PRR values of links except are calculated by using log normal shadowing model. According to this calculation, a PRR matrix is computed that includes each link's PRR value between a pair of nodes. This matrix is computed by using smart grid environments' parameters as shown in Table 3.2, i.e. 500kV Substation, Underground Transformer Vault and Main Power Room. Therefore, different PRR matrices are obtained for different smart grid environments. PRR values show the link quality between nodes. If the link quality does not exceed some threshold, the link between the nodes is assumed to be bad (disconnected) and this edge in the graph is removed from the tree. Each node's signal level is identified by using log normal shadowing propagation model and Radio Received Signal Strength Indicator (RSSI) value, which is a measurement of power received from radio signal. These are computed by using the topology information and channel parameters. Then, SNR between the nodes is calculated as shown in Equation 3.1 by using obtained RSSI values. According to SNR values, probability of bit errors are measured with respect to modulation type that is Non-Coherent Frequency Shift Keying (NCFSK). Then PRR matrix is formed in terms of Manchester encoding by using probability of error. As a result, PRR matrix is obtained to define link qualities of wireless links by using the channel parameters of smart grid environments. This method constructs routing trees according to link quality and provides more reliable packet transmission between the nodes. PRR matrix is obtained as presented in Equation 3.3.

$$\boldsymbol{PRR} = \frac{(\boldsymbol{Number\ of\ Received\ Packets})}{(\boldsymbol{Number\ of\ Sent\ Packets})} \tag{3.3}$$

According to Equation 3.3, PRR values of all links are computed between the nodes and a routing tree is constructed by utilizing these PRR values such that nodes select the neighbors as the parent with the maximum PRR value. The PRR-based routing algorithm is based on the MHST algorithm. Edges are selected according to their outages vertexes' weights. However, in this algorithm weights are determined according to PRR values and the number of hops. The only difference is that PRR values are considered to build the tree. In this respect, PRR-based routing algorithm steps are listed as follows:

a. List *X*, holds all edges and their vertices' weights, *w* that is determined according to number of hops to sink and nodes' *PRR* values into graph, *G*.
b. A flag array, *F* is used to store selected edges that are defined by dividing edge list, *E* into segments. If edge is selected, flag is set to 1 otherwise, 0. Selection is done according to weights of the edges.
c. List *X*, is scanned to find minimum outgoing edge that is hold in *N*, and successor of each vertex. Successors are stored in array, *S*.
d. Cyclic edges are removed from *N* and remaining edges are marked to form tree.
e. Successors in *S* are appended with their indexes and a list, *L* is formed.
f. List *C*, is formed by splitting *L* to find new ids with a flag array that is 1 when new id is found with maximum *PRR* value and closest to sink.
g. Subgraph's root node is found by using *C* list and if two subgraph has same root node, nodes in these subgraphs are removed from edge list, *E*.
h. When these steps are performed, edge list, vertex list, weight list with max *PRR* value and least distance to sink are obtained.

As shown, the steps of creating a PRR-based routing protocol are similar to the MHST algorithm. Only difference is that PRR values of nodes are added to constraints while weights are identified. In this manner, pseudocode of PRR-based routing tree algorithm is described in Algorithm 3.2.

3.3.3 CMST with PRR

CMST type topologies were shown to improve network performance with perfect link qualities (Incel and et al. (2012)). However, the impact of variable link qualities were not considered. In our approach, we combine the CMST algorithm with PRR based tree construction. Hence, we consider both link qualities and the constraint of *c* while constructing the tree.

Algorithm 3.2: PRR-based algorithm
1. **Input:** Weighted Graph, *G* 2. **Compute:** PRR-based Routing Tree, *T* for *G* 3. **Set:** *P* is partition of vertices in *G* 4. **Set:** *PRR* matrix that shows each node's *PRR* value in *G* 5. **Set:** *Q* stores edges in *G* and their weights with maximum *PRR* value and minimum number of hops 6. **Set:** $T \leftarrow \emptyset$ 7. **while** $Q \neq \mathbf{0}$ 8. *(u,v)* ← **remove edge according to minimum distance to sink and maximum *PRR* value from *Q*** 9. **if** *u* **in P-set** ≠ *v* **in P-set** 10. **edge** *(u,v)* **is added to** *T* 11. $P \cup (u,v)$ 12. **Output: GraphPRR = *T***

In this routing protocol, CMST with PRR-based algorithm is implemented. According to this algorithm, nodes choose neighbors that are closest to sink and also have maximum PRR value. In this way, CMST algorithm becomes more reliable and suitable in real channel conditions. Nodes can transmit to the sink on a trusted path with minimum cost. In this case, steps in creating CMST with PRR are the same as in the CMST algorithm (Incel and et al. (2012)). Only difference is that PRR check has been added to connect nodes with their neighbors. These are shown in the following steps. According to these steps, pseudocode of CMST with PRR algorithm is shown in Algorithm 3.3.

a. All subtrees are connected to root node *r*.
b. $\sum_{n}^{i=0} c_{ri}$ indicates cost of each subtree.
c. $PRR = prr_{ij}$ is a matrix that shows PRR values' of each node.
d. (g_i) is a gate from root to subtree that is removed from graph if PRR value cannot exceed threshold.
e. Closest neighbor (a_{ij}), that has maximum *PRR* value, is searched for every node except root node.

f. Tradeoff function is same with CMST. This is obtained with $t\ (a_i) = g_i - c_{ij}$.

g. These steps are repeated until best tree is constructed.

Algorithm 3.3: CMST with PRR algorithm

1. **Input:** *c:* Capacity constraint of the tree, *C:* cost matrix, *PRR = prr* matrix and *r:* root node are given as inputs
2. **Compute:** Minimal cost spanning tree of a Graph, *G* according to root node *r*, *PRR* matrix and *c* (capacity constraint)
3. **Set:** $TPRR = C_{1r}, C_{2r}, \ldots, C_{nr}$
4. **Set:** $P = PRR_{1r}, PRR_{2r}, \ldots, PRR_{nr}$
5. **while** no improvement to tree
6. **for each** node a_i
7. a_i equals to closest node that is in different subtree and has maximum *PRR* value
8. **Tradeoff function:** $t(ai) = gi - cij$
9. t_{max} equals to maximum $t(a_i)$

15. *k* equals to *i*
16. $t(a_i)$ equals to t_{max}
17. **when** cost of *i* + cost of *j* smaller than or equal *c*
18. *TPRR* equals to $TPRR - g_k$
19. *P* equals to $P - g_k$
20. *TPRR* equals to $T \cup c_{kj}$
21. **Output: GraphCMSTwithPRR = *TPRR***

3.3.4 Minimum Hop Spanning Tree – MHST

The simplest approach commonly used in WSNs is to minimize the number of hops to relay information towards the sink node. Using minimum number of hops minimizes the number of nodes participating in the relaying of information and hence considered to minimize the energy consumption. The reason why we also used the minimum hop spanning tree is that it is a simple approach and we are interested in showing the capacity improvements with other solutions compared to the simplest solution.

Connected graph, *G* is given and it includes a spanning tree which has subtrees. All vertices are connected by these subtrees. Different subtrees can be obtained from one graph. Minimum hop spanning tree is a spanning tree with number of hops less than or equal to the number of hops of every other spanning tree. There can be more than one minimum hop spanning trees of the same number of hops having a minimum number of edges. If all edges' number of hops are same in given graph, each spanning tree has minimum in this graph. In this respect, if graph has *V* vertices, each tree in this graph has *V—1* edges. The steps in creating a MHST are listed below (Vineet and et al. (2009)). These steps show that how MHST is constructed according to minimum hop weights. In this respect, the pseudocode of this algorithms is described in Algorithm 3.4.

a. All edges and their vertices' weights, w, that is determined according to number of hops to sink into graph, *G*, are put in a list, *X*.
b. Segments are constructed by dividing edge list, *E*. A flag array, *F* is hold for storing each edge's selection information such as if edge is selected, flag of this edge becomes 1 otherwise, becomes 0.
c. List *X*, is scanned to find minimum outgoing edge for each vertex and scanning values are stored in *N* that is used to find each vertex successor that is hold in *S* array.
d. Edges, which form cycles, are deleted from *N* and remaining edges are marked.
e. List *L*, is formed by subjoining each successor from *S* array with their indexes.
f. *L* list is split to find new ids by using a flag array, *F* such as if new id is found, flag becomes 1 otherwise, becomes 0. Vertexes with flag value, 1 are added to *C* list.
g. *C* is used to find each subgraph's root node that is called as super vertex. Each edge is controlled to find they have same super vertex or not. If they have same super vertex, they are removed from *E* that is edge list.
h. According to these steps, new edge list and weight list are formed and vertex list is created to find minimum hop spanning tree.

3.4 PERFORMANCE EVALUATIONS

In this work, extensive simulations have been performed in Matlab, which is a numerical computing environment and a high level language that is used to simulate wireless sensor networks. The Matlab environment was utilized in the simulations since the models for the CMST and MHST routing algorithms have been implemented in this environment before, in previous work (Incel and et al. (2012)). To make the Matlab simulations realistic, we used a real physical layer model utilizing the Log-Normal Shadowing Model based on the measurements explained in Section 3.2.2 and summarized in Table 3.2. As indicated in (Gungor and et al. (2010)), this model is used for large and small coverage systems, and additionally, it provides more accurate multipath channel models than other models for indoor wireless environments with obstructions. Additionally, the physical interference model (Gupta and Kumar (2010)) for creating a realistic wireless communication environment is utilized. Simulation parameters are presented in Table 3.3.

Algorithm 3.4: MHST algorithm
1. **Input:** Weighted Graph, G
2. **Compute:** Minimum hop spanning tree T for G
3. **Set:** P is partition of vertices in G
4. **Set:** Q stores edges in G and their weights that is number of hops
5. **Set:** $T \leftarrow 0$
6. **while** $Q \neq 0$
7. $(u,v) \leftarrow$ remove minimum element from Q
8.   **if** u in $P\text{-}set \neq v$ in $P\text{-}set$
9.   edge (u,v) is added to T
10. $P \cup (u,v)$
11. **Output: GraphMHST = T**

In the evaluations nodes are randomly deployed over a 200 × 200 square meter terrain. Number of nodes are varied between 120 and 200 nodes. For each simulation, we run multiple experiments with different seeds and take the average of the measured values. For the data collection scenario, we assumed a periodic data collection model such that all the nodes generate one packet periodically at the beginning of each scheduling frame (one frame is equal to a period where all the data packets from all sources have been delivered to the sink). Packets are delivered over multiple hops. In the first set of simulations, we assumed best effort delivery such that there are no retransmissions.

Hence, if a packet is lost it is not scheduled for retransmissions. Impact of retransmissions is evaluated in Section 3.4.4.2.

Table 3.3: Simulation parameters of the experiments

Number of nodes	120 - 200
Size of the topology	200×200 m^2
Radio propagation model	Log-normal shadowing model
Number of frequencies	1, 8, and 16
Algorithms	CMST, CMST with PRR, MHST and PRR
Distance between the nodes	Randomly distributed
Modulation	Non-Coherent Frequency Shift Keying (NCFSK)
Encoding	Manchester
Output power	4.0 dBm
Noise floor	-93.0 dBm
Asymmetry	Symmetric links
Topology	Random

In this study, performance of the RBCA protocol and the routing tree protocols, explained in Section 3.3, are evaluated for 500 kV Substation, Underground Transformer Vault and Main Power Room smart grid environments where experimentally determined the *pathloss(η)* and *shadowingdeviation(σ)* parameters for each smart grid environment have been obtained from (Gungor and et al. (2010)), respectively. In the following, the network performance with each of the WSN routing tree algorithms, including CMSTs, CMSTs with PRR, MHST that is named as Minhop in the graphs, PRR – based routing algorithms, has been evaluated in terms of the following performance metrics:

a. ***Throughput:*** is the average data reception rate at the sink node for a frame period. It is simply the ratio of the delivered packets to the size of a frame (i.e., the number of timeslots required to complete the reception of the packets generated by all the source node at the sink node).

b. ***Delay*****:** is the time it takes for a data packet to travel across the network from a source node to the sink.

Simulations have been performed to show how the number of channels affects throughput and delay of routing protocols in three different smart grid environments and next the impact of number of retransmissions on throughput and delay has been addressed for 500 kV smart grid environment. Accordingly, in the following sections, simulation results are presented with respect to 500 kV Substation, UTV and MPR environments, respectively.

3.4.1 500 kV Substation

The parameters of 500 kV Substation environment, which are shown in Table 3.2 have been used in this set of simulations. Four different routing algorithms are used to show which algorithm works better in which smart grid environment in terms of throughput and delay when the number of channels increases.

3.4.1.1 Delay performance of multi-channel and routing algorithms in 500 kV substation environment

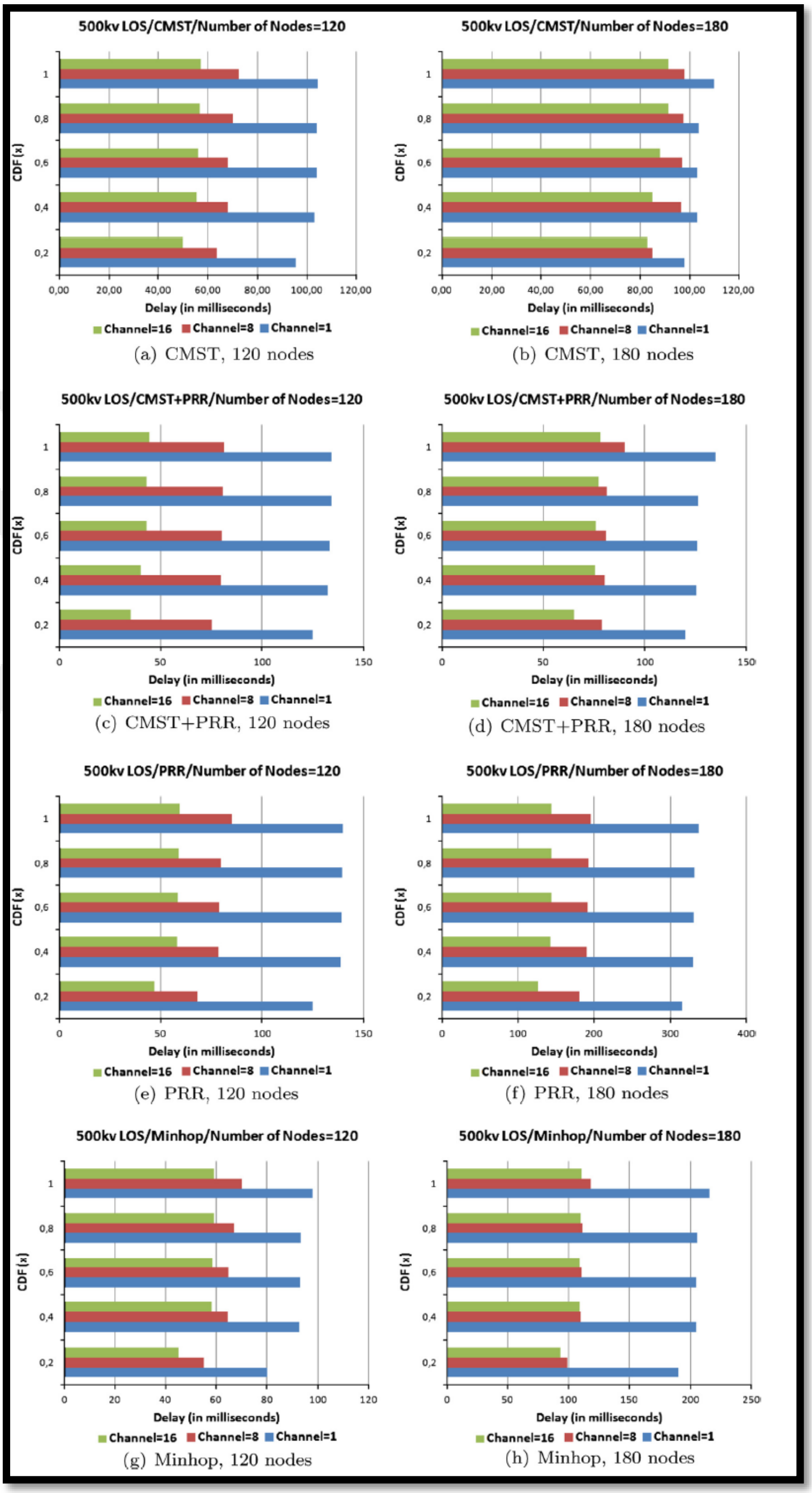
Figures seen in 3.1 and 3.2 show the cumulative distribution and confidence interval of delay for different routing tree algorithms with varying number of nodes where the number of channels is also varied. 1, 8 and 16 channels are used to show the effect of using multiple channels in real channel conditions. We also explored how delay of routing algorithms change when the number of nodes increases, hence the density of the network changes.

In Figures seen in 3.1 and 3.2, it is shown that as the number of channels increases, delay decreases for all the routing algorithms. This is because multiple channels eliminate interference, more simultaneous transmissions can take place and packets can be delivered to the sink in a shorter interval. In addition, it is shown that delay with these algorithms increases when number of nodes increases from 120 to 180 because the number of source nodes and the network density increases and more transmissions need to be scheduled. In Figures 3.1 and 3.2, it is also observed that the CMST with PRR routing tree shows the best performance in terms of delay with 120 nodes and 16 channels. In addition, when the number of nodes and channels increase to 180 and 16, respectively, CMST with PRR routing algorithm performs again better than other routing tree algorithms. In general, the CMST type trees perform better than others in terms of delay. This is because CMST algorithm specifies routing trees minimizing the delay by considering the CMST constraint as also shown in the previous work.

3.4.1.2 Throughput performance of multi-channel and routing algorithms in 500 kV substation environment

Throughput of the network with all the routing protocols increases when channels increase, as shown in Figure 3.3, because the number of lost packets decreases around 45 percentage. Routing protocols send packets through multiple channels and therefore, packets are transmitted to the sink node concurrently over multiple channels. Figure 3.3 shows the network throughput with 95 percentage confidence intervals with different routing trees according to different number of nodes where the number of channel increases from 1 to 16 in 500kV Substation environment. Since the delay is decreased with multiple channels the throughput of the network increases for each routing tree. In Figure 3.3, generally it is observed that the CMST with PRR routing tree shows the highest performance in terms of network throughput. On the other hand, in general MHST routing tree algorithm shows the lowest performance in terms of network throughput under the same conditions since it neither considers the link qualities nor the capacity limitation.

Figure 3.1: Average throughput with 95 percentage confidence interval for routing protocols when number of channel increases in 500 kV substation smart grid environment



(a) CMST, 120 nodes (b) CMST, 180 nodes

(c) CMST+PRR, 120 nodes (d) CMST+PRR, 180 nodes

(e) PRR, 120 nodes (f) PRR, 180 nodes

(g) Minhop, 120 nodes (h) Minhop, 180 nodes

Figure 3.2: Average delay with 95 percentage confidence interval for routing protocols when number of channel increases in 500 kV substation smart grid environment

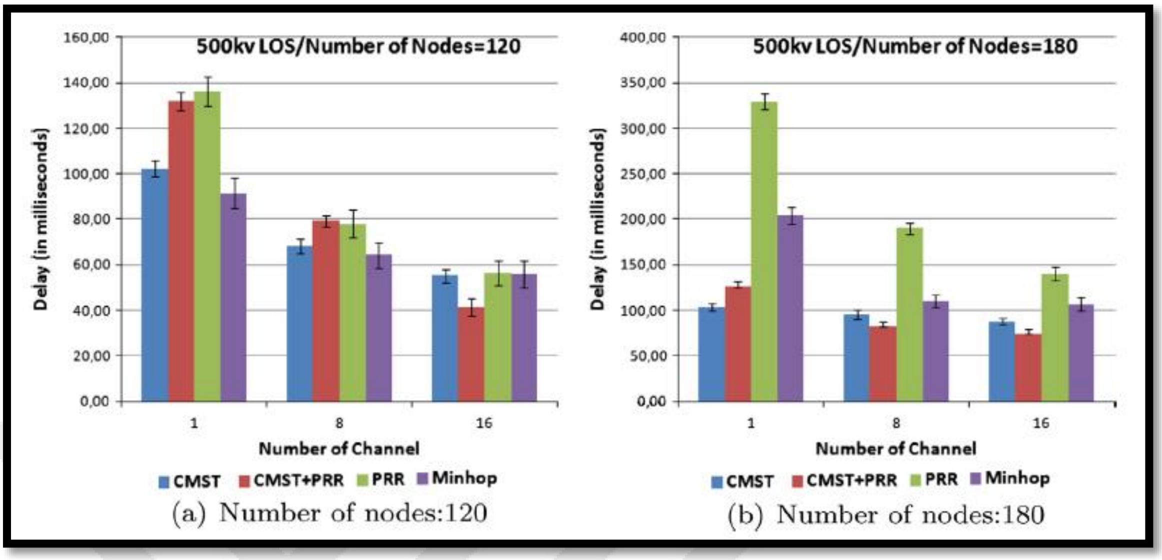
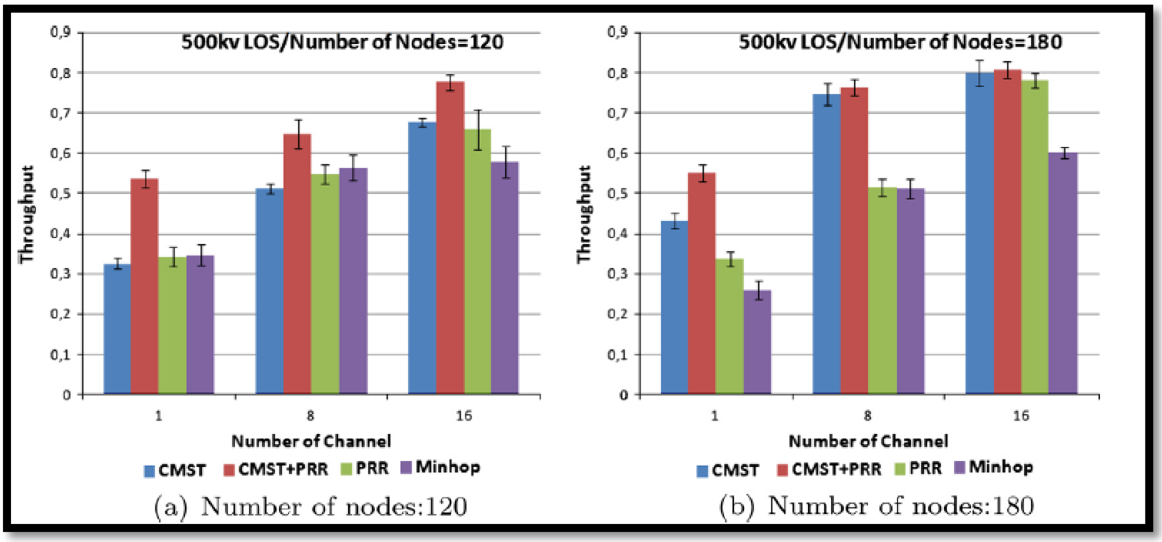


Figure 3.3: Average throughput with 95 percentage confidence interval for routing protocols when number of channel increases in 500 kV Substation smart grid environment.



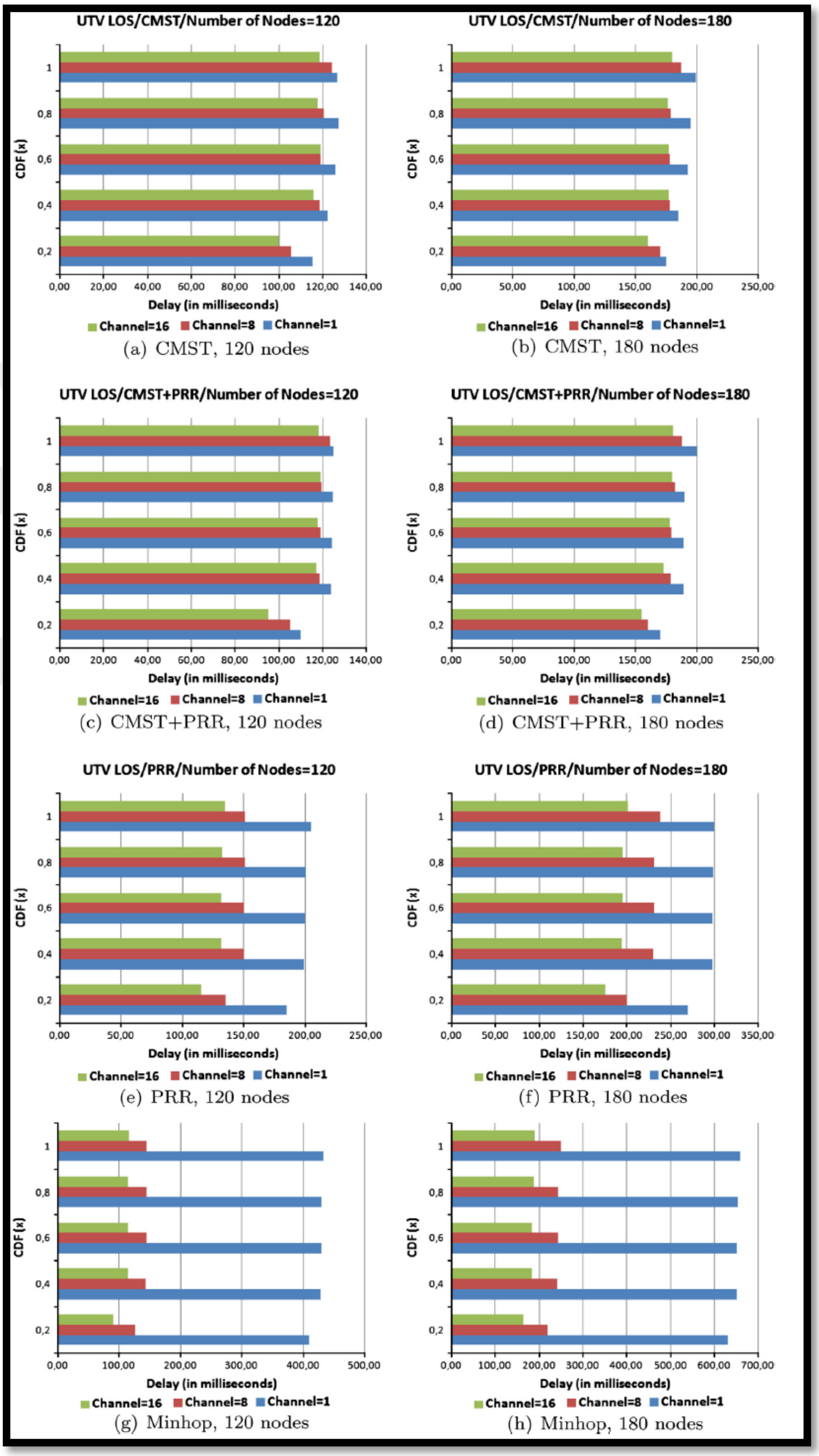
3.4.2 UTV

3.4.2.1 Delay performance of multi-channel and routing algorithms in UTV environment

In this part, effect of using multiple channels is investigated. PRR values are obtained by applying log normal shadowing propagation model in UTV environment. Environment parameters are shown in Table 3.2. In this regard, Figures seen in Figure 3.4 and 3.5 show the cumulative distribution of delay and average delay with 95 percentage confidence interval for different routing tree algorithms where the number of channels and the number of nodes increase from 1 to 16 and from 120 to 180, respectively.

In Figures seen in 3.4 and 3.5, generally, it is observed that delay of PRR-based and Minhop routing algorithms decreases when the number of channels increases. However, the delay with CMST and CMST with PRR-based are not affected with the increase in the number of channels, but they give better results than PRR and Minhop algorithms. First of all, compared to the 500kV Substation environment, the UTV environment is less harsh, link qualities are better and links are less affected by interference due to simultaneous transmissions. Since the impact of interference is not visible in this set, the impact of routing trees becomes more visible. The performance with only a single channel is already good with CMST and CMST with PRR trees. However, Minhop trees and PRR-based trees cannot perform well with a smaller number of channels. Increasing the number of nodes to 180 nodes does not change the situation, either. CMST and CMST with PRR based trees perform the best. Since we do not consider the impact of retransmissions in this set, both algorithms perform similar.

Figure 3.4: **Cumulative distribution function of delay for routing protocols when number of channel increases in UTV smart grid environment**



(a) CMST, 120 nodes

(b) CMST, 180 nodes

(c) CMST+PRR, 120 nodes

(d) CMST+PRR, 180 nodes

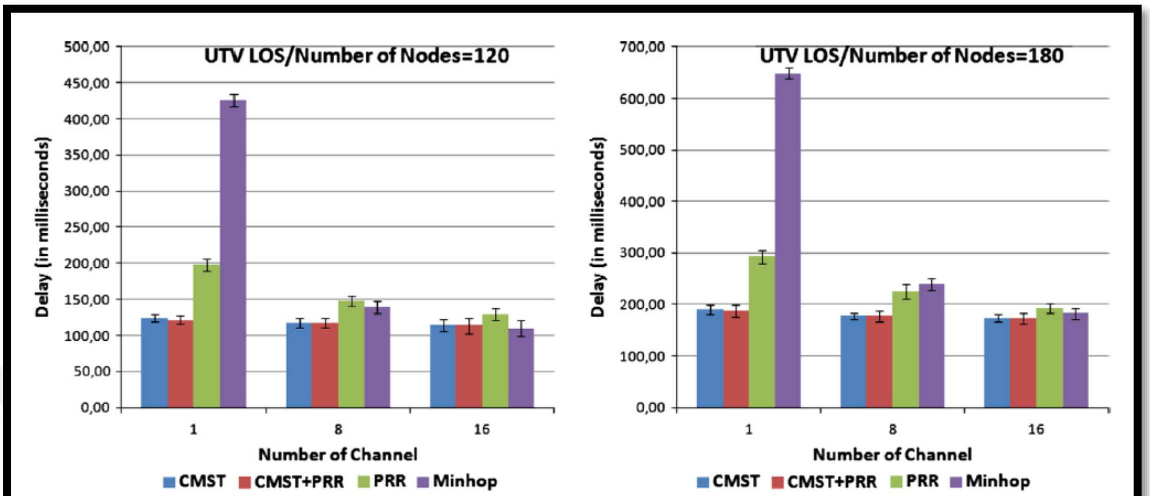
(e) PRR, 120 nodes

(f) PRR, 180 nodes

(g) Minhop, 120 nodes

(h) Minhop, 180 nodes

Figure 3.5: Average delay with 95 percentage confidence interval for routing protocols when number of channel increases in UTV smart grid environment

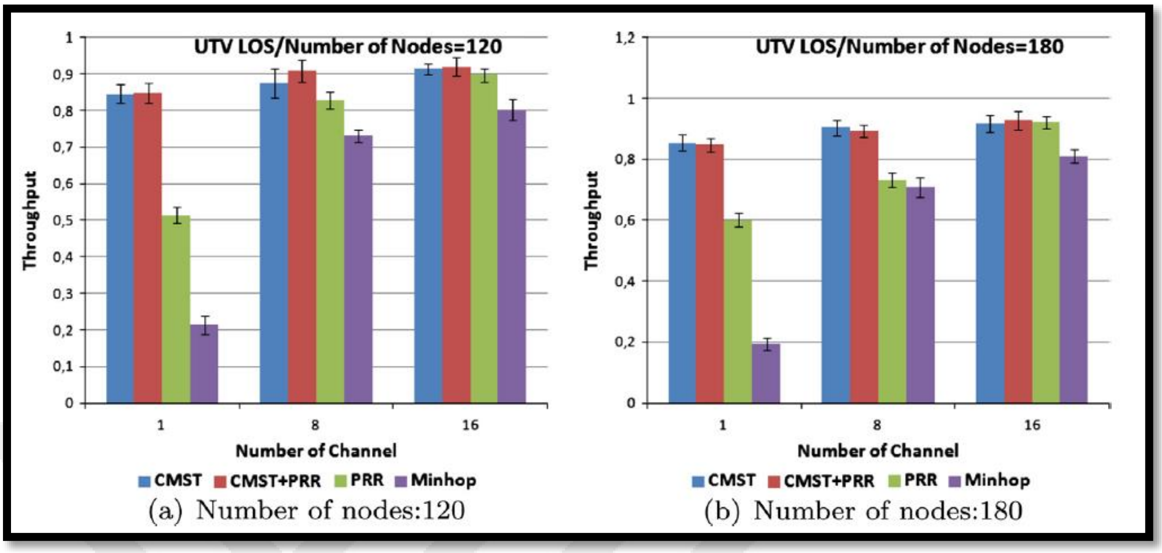


(a) Number of nodes:120 (b) Number of nodes:180

3.4.2.2 Throughput performance of multi-channel and routing algorithms in UTV environment

Figure 3.6, shows the throughput with all the evaluated routing tree algorithms with different number of nodes, where number of channel increases from 1 to 16. Similar to the delay results, it is observed that the throughput with CMST and CMST with PRR based trees do not change much with the increasing number of channels whereas Minhop trees and PRR-based trees perform better. It is also shown that throughput performance with CMST, CMST with PRR and PRR-based routing tree algorithms are close to each other when the number of channels is 16 for both 120 and 180 nodes. The throughput performance with CMST with PRR routing tree algorithm is a little better than the other evaluated routing tree algorithms because more reliable links are constructed by considering each link’s PRR value and therefore, packets are sent over reliable links and the number of lost packets decreases in CMST with PRR routing tree algorithm.

Figure 3.6: Average throughput with 95 percentage confidence interval for routing protocols when the number of channels increases in UTV smart grid environment



3.4.3 MPR

In this section, performance of the routing algorithms are evaluated in Main Power Room smart grid environment. We run our simulations by using MPR parameters that is shown in Table 3.2. As a result of simulations, we obtained throughput and delay performance of each routing tree in MPR environment by increasing the number of channels and the number of nodes.

3.4.3.1 Delay performance of multi-channel and routing algorithms in MPR environment

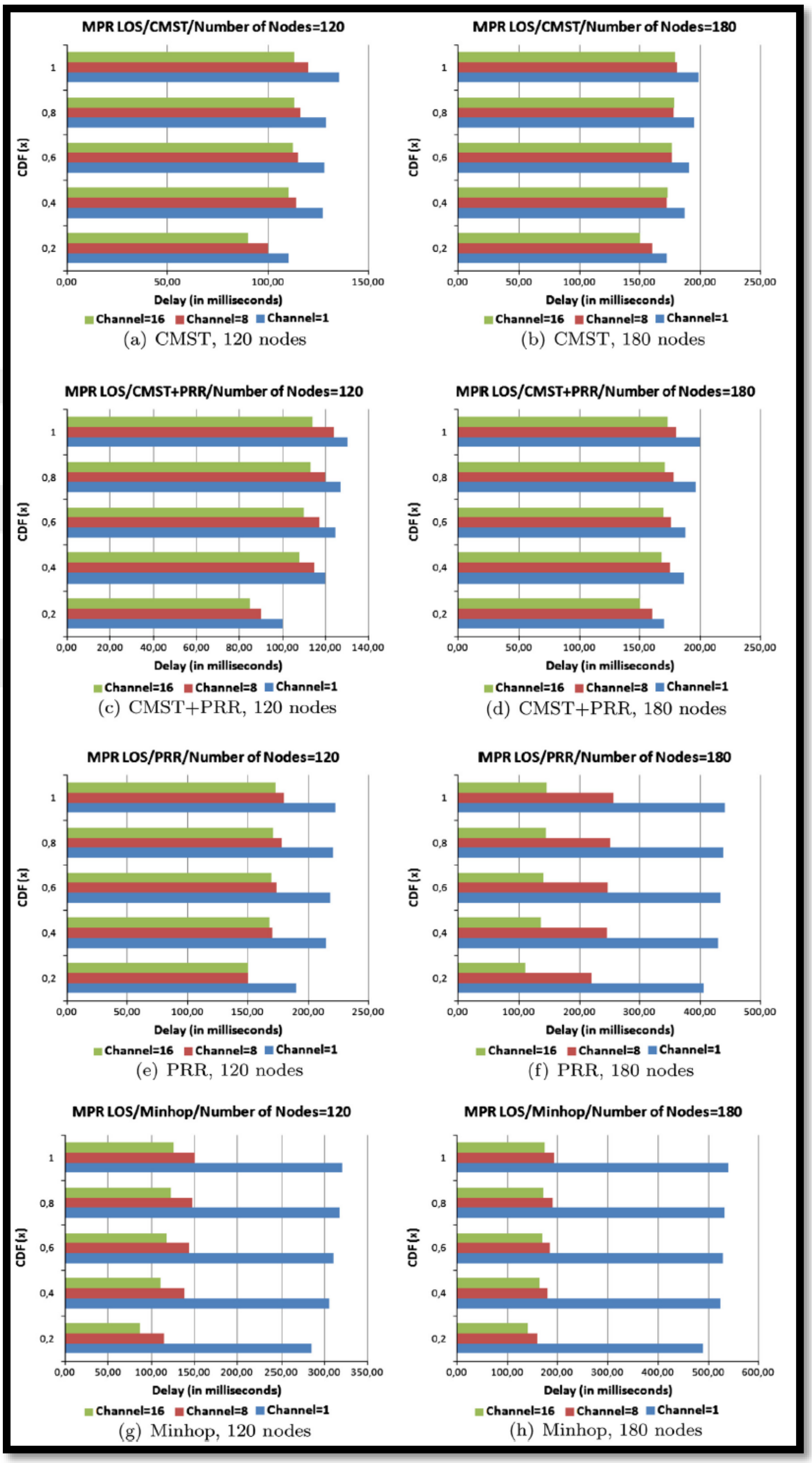
Figure seen in 3.7 and Figure 3.8 show the cumulative distribution and average delay performance with 95-percentage confidence interval for different routing algorithms in MPR environment, where the number of channels increases from 1 to 16 and the number of nodes increases from 120 to 180. It is observed that delay with Minhop and PRR-based routing trees decreases when the number of channel increases. However, the delay performance with CMST and CMST with PRR only slightly decrease with the increasing number of channels and their delay performances are close to each other. Results are very similar to the results obtained in Section 3.4.2. It is also shown that delay of routing trees increases when the number of nodes increase from 120 to 180. This is an expected result just because when the number of nodes increases, the number of source nodes and the network density increases and more time is required to complete the receptions at the sink node. In Figure seen in Figure 3.7 and in Figure 3.8, generally it is observed that the delay performance with CMST and CMST with PRR routing trees are similar with each other and show the best performance in terms of network delay.

3.4.3.2 Throughput performance of multi-channel and routing algorithms in MPR environment

MPR environment has better channel quality than the other smart grid environments in terms of path loss and shadowing deviation parameters that are shown in Table 3.2. Therefore, the throughput of our routing algorithms increase better than other evaluated smart grid environments. Figure 3.9 shows the confidence interval of throughput performance for different routing tree algorithms in Main Power Room environment, where the number of channels and number of nodes increase from 1 to 16 and from 120 to 180, respectively.

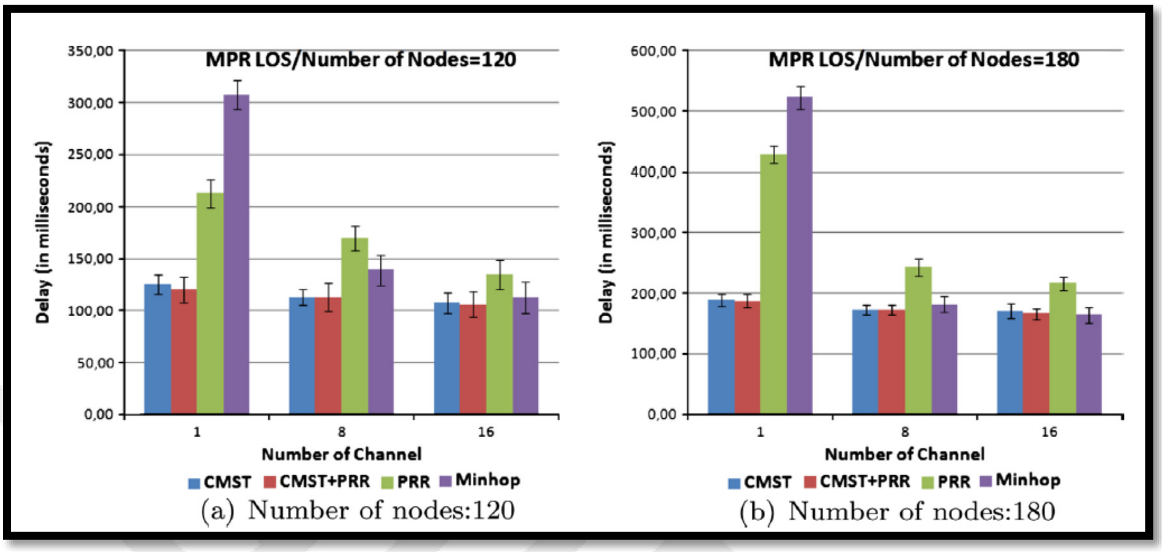
In Figure 3.9, generally it is observed that the throughput of all routing trees increases when the number of channel increases from 1 to 16, more increase is observed with Minhop and PRR based routing trees and a slight increase with CMST and CMST with PRR based trees. It is also shown that the number of nodes does not affect the throughput performance. This is because both the number of packets to be delivered and the delay increase, hence the throughput does not change and stays similar. Overall, CMST with PRR routing tree algorithm shows the highest performance in terms of network throughput, since this routing tree is specifically designed for minimizing schedule length and minimizing network delay for achieving maximum efficient operation of the WSN.

Figure 3.7: Cumulative distribution function of delay for routing protocols when number of channel increases in UTV smart grid environment.



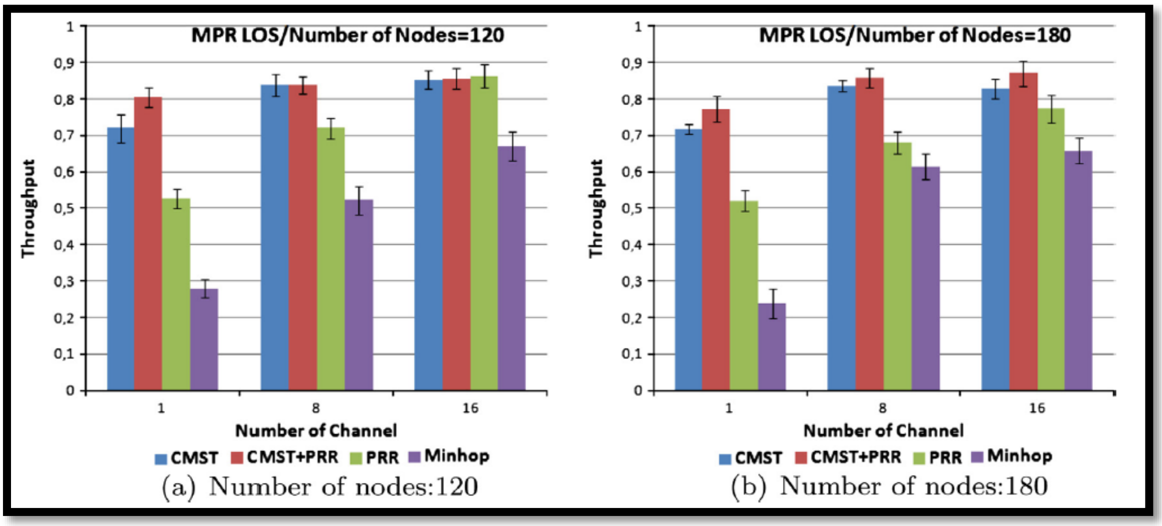
(a) CMST, 120 nodes
(b) CMST, 180 nodes
(c) CMST+PRR, 120 nodes
(d) CMST+PRR, 180 nodes
(e) PRR, 120 nodes
(f) PRR, 180 nodes
(g) Minhop, 120 nodes
(h) Minhop, 180 nodes

Figure 3.8: Average delay with 95percentage confidence interval for routing protocols when number of channel increases in MPR smart grid environment



(a) Number of nodes:120 (b) Number of nodes:180

Figure 3.9: Average throughput with 95 percentage confidence interval with routing protocols when the number of channels increases in MPR smart grid environment



(a) Number of nodes:120 (b) Number of nodes:180

3.4.3.3 Impact of the number of retransmissions with different routing trees in smart grid environment

In this section, effect of retransmissions is analyzed for 500 kV Substation smart grid environment to see how the throughput and delay of the routing trees change with the number of retransmissions. Simulations are performed with 120 nodes and for 16 channels.

3.4.3.4 Impact of number of retransmissions on the delay in 500 kV environment

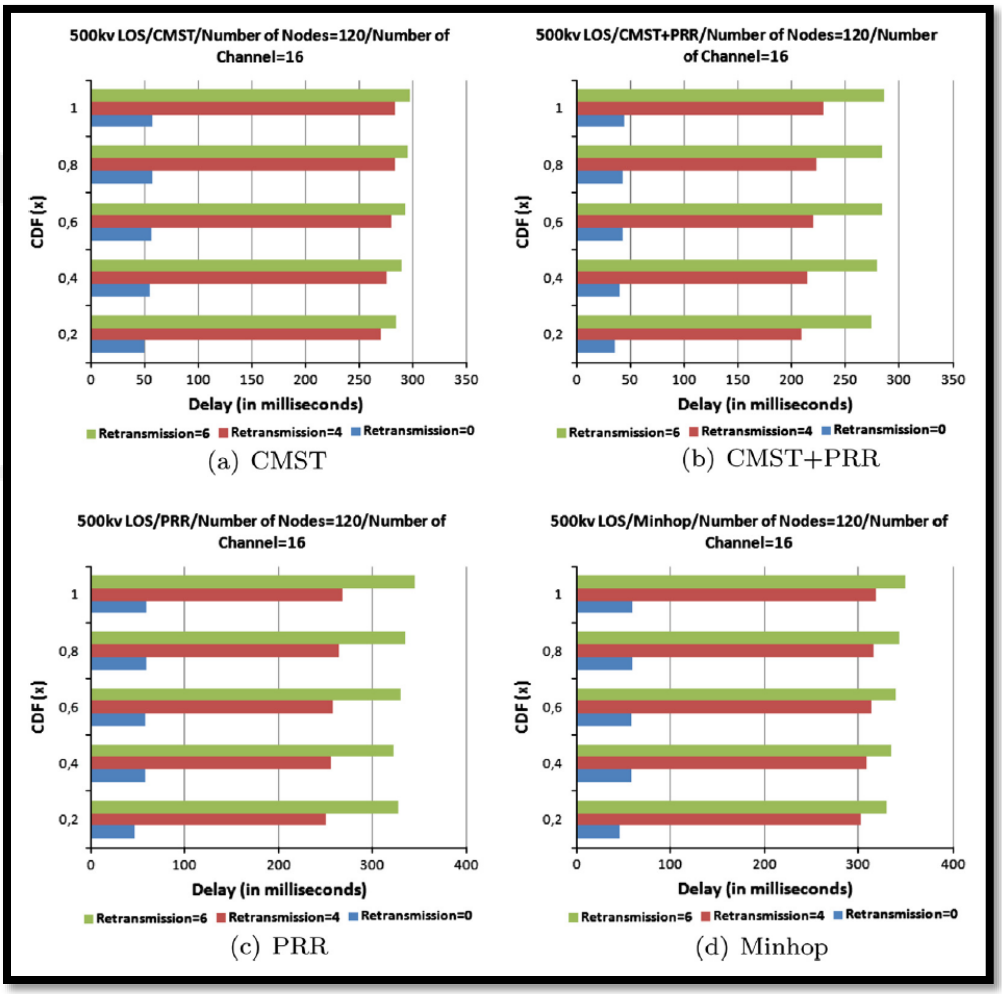
Figures 3.10 and 3.11 show the cumulative distribution of delay and average delay with 95 percentage confidence intervals with different routing tree algorithms in different network conditions, where the number of retransmissions in case of lost packets due to link unreliability increases from 0 to 6. Delay with routing algorithms increases when the number of retransmissions increases. Delay occurs with retransmissions because each node tries to send multiple times if a packet is not sent at the first try and hence more packets need to be scheduled for each frame period. We measure the delay with routing trees according to number of retransmissions such as 0, 4 and 6 and the delay with each routing tree is observed with respect to these number of retransmissions.

In Figure 3.10, it is observed that the CMST with PRR routing tree algorithms show the best performance in terms of network delay. This is because CMST with PRR both balances the number of nodes on the subtrees and considers the links with better qualities at tree construction phase; hence, it experiences less packet losses.

3.4.3.5 Impact of number of retransmissions on the throughput in 500 kV environment

Figure 3.12 shows the average throughput with 95 percentage confidence interval with different routing tree algorithms in Main Power Room environment, where the number of retransmission increases from 0 to 6. Number of retransmissions affects the throughput of our proposed routing algorithms because of the delay performance. As seen in Section 3.4.4.1, delay increases for all the tree types with respect to number of retransmissions. Therefore, throughput of routing trees decrease every time in this condition considering that the number of delivered packets to the sink increase little. Accordingly, trees with less delay provide more throughput than other trees if the number of retransmissions increases. In this context, CMST with PRR provides better throughput as shown in Figure 3.12 than others because as already stated in Section 3.4.4.1, it results in less delay than the other trees when the number of retransmissions increases and it delivers more packets than the other routing trees since it considers transmissions over reliable links.

Figure 3.10: Cumulative distribution function of delay for routing protocols when number of retransmission increases in 500 kV smart grid environment



In Figure 3.12, it is observed that the throughput performance of all the routing tree algorithms decreases when the number of retransmissions increases. This is because the delay increases while trying to transmit all the packets multiple times. In addition, it is also shown that CMST with PRR routing tree again carries out more reliable and more effective communication with retransmission than the other trees because it has less delay than others as shown in Figure 3.10. All of these results show that CMST + PRR routing tree is more efficient in smart grid environments when multi-channel communication and retransmission are applied.

Figure 3.11: Average delay with 95 percentage confidence interval for routing protocols when number of retransmission increases in 500 kV smart grid environment

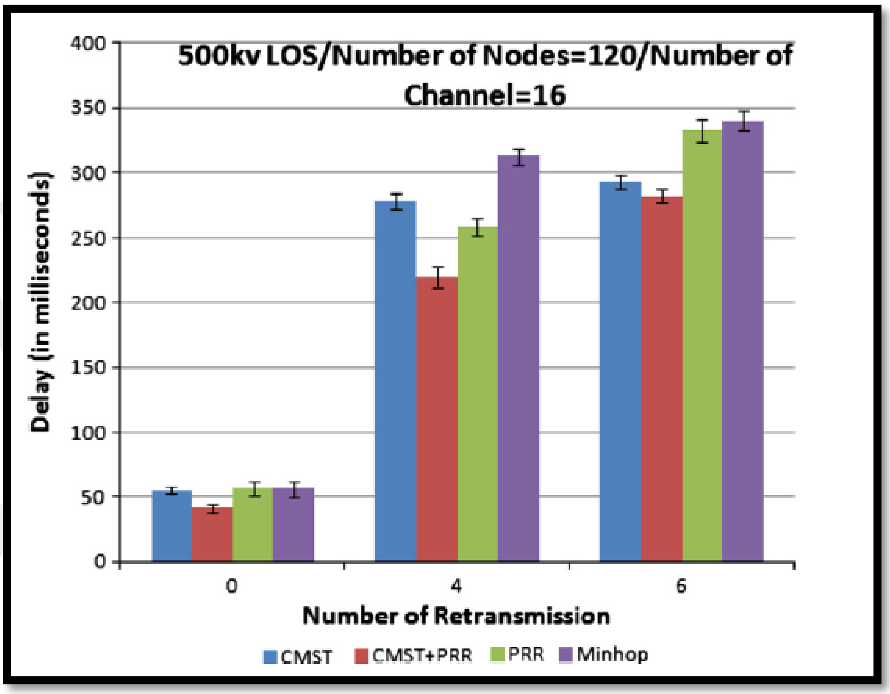
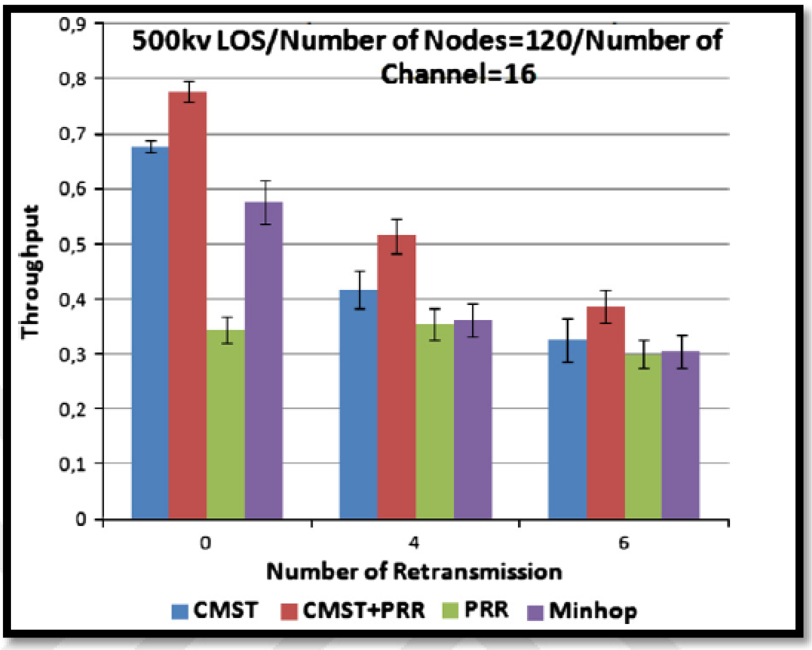


Figure 3.12: Average throughput with 95 percentage confidence interval for routing protocols when number of retransmission increases in 500 kV smart grid environment



3.5 OVERVIEW OF SIMULATION RESULTS

The extensive simulations have been performed considering real field tests performed in 500 kV Substation, UTV and MPR smart grid environments to measure network and throughput performance of different routing tree algorithms, such as CMSTs, CMSTs with PRR, MHST, PRR – based routing algorithms in various network conditions where the number of channels, number of nodes are increased from 1 to 16 and from 120 to 180, respectively. We also investigated the impact of the number of retransmissions on the throughput and delay for 500 kV Substation smart grid environment. Through these simulations, the wireless channel has been modeled using log-normal shadowing path loss model. As a result, the results of our performance evaluations can be summarized as follows:

a. Impact of multi-channel communication on the delay metric is examined for different routing trees in smart grid environments and CMST with PRR routing tree is found to perform better than others when the number of channels increases. This is because it minimizes the schedule length by constructing balanced trees according to each node's PRR value that must exceed certain threshold to build reliable paths.

b. Throughput of all tree types are measured by applying multiple channels in smart grid environments and their performance is compared with each other. We observe that CMST with PRR shows the best performance because it delivers the same amount of packets in a shorter interval compared to other routing trees. On the other hand, other trees construct paths without taking into consideration PRR values or balanced subtrees and therefore, their performance is lower than CMST with PRR routing tree algorithm.

c. Impact of the number of nodes is also investigated to assess the performance of different routing trees with changing density. We again observe that, CMST with

d. PRR routing tree performs better in delay and throughput performance than the other routing tree algorithms. Despite in some cases, CMST and CMST with PRR routing tree algorithms have similar results, in general, CMST with PRR performs better than CMST. This is because it constructs the paths also considering the PRR values of the links which is not implemented by CMST.

e. Impact of the number of retransmissions is considered to evaluate its effect on throughput and delay performance of different routing tree algorithms in smart grid environments. Number of retransmissions increases the reliability of the network, however, it decreases the throughput of the routing algorithms because it increases the delay by making multiple transmissions, as expected. Therefore, it must be applied carefully according to application's requirements in smart grid environments. Our simulations show that none of the evaluated routing tree algorithms perform very well when the number of retransmissions has been increased. Therefore, before applying retransmission, application requirements and network capabilities should be considered together to improve the overall network performance. However, if retransmissions has been applied for the application, according to our simulations CMST with PRR routing tree can be preferred because its throughput and delay performance is better than other routing algorithms with balanced subtrees and PRR threshold.

Table 3.4: Comparison of simulation results in smart grid environments

Propagation environment	Multi-channel	Number of nodes augmentation	Best routing tree
500 kV Substation – Delay	Decrease	Increase	CMST and CMST + PRR
500 kV Substation – Throughput	Increase	Increase	CMST and CMST + PRR
Underground Transformer Vault – Delay	Decrease	Increase	CMST and CMST + PRR
Underground Transformer Vault – Throughput	Increase	Increase	CMST and CMST + PRR
Main Power Room – Delay	Decrease	Increase	CMST and CMST + PRR
Main Power Room – Throughput	Increase	Increase	CMST and CMST + PRR

Based on the simulations above, it is observed that the performance of the routing tree algorithms differ in terms of network throughput and network delay in different network conditions. Before making a decision for network design in smart grid environments, WSN-based smart grid applications requirements as well as network abilities must be considered together to improve network performance. In summary, evaluated routing tree algorithms have been compared in Table 3.4 in terms of multi-channel condition, number of nodes augmentation and best routing tree algorithm.

3.6 DISCUSSIONS

In this chapter, delay and throughput of CMST, CMST with PRR, PRR-based and MHST routing trees in three smart grid environments are presented by considering different parameters extracted from real field tests. Simulations are performed to evaluate the impact of the number of channels, the number of nodes and retransmissions on delay and throughput in different smart grid environments. The comparative performance evaluations have been done to determine quantitatively how much communication delay and throughput of the network will change in real channel conditions, when frequency and retransmission increases. Consequently, simulation results provide a guideline for the design of new algorithms for the smart grid applications. In summary, the main contributions and findings of this study have been listed as follows:

a. Impact of real channel characteristics on the CMST, CMST with PRR, MHST and PRR-based routing algorithms are revealed by implementing the log normal shadowing model for different smart grid environments. Path loss and shadowing deviation parameters of different smart grid environments (Gungor and et al. (2010)) are used in order to compute log normal shadowing model equation for measuring proposed routing algorithms' throughput and delay performance.
b. The throughput and delay performance of different routing algorithms, such as CMST, CMST with PRR, MHST and PRR-based routing algorithms, have been compared in three different smart grid environments to determine which routing algorithm is more reliable when log normal shadowing model is applied. It is shown that the CMST with PRR-based routing tree shows the highest performance in terms of delay, since this routing protocol is specifically designed for minimizing delay and increasing the network capacity. It is also shown that the throughput performance of the CMST with PRR algorithm is better than other proposed algorithms for different smart grid environments.
c. When the number of channel increases, we show that throughput increases for all smart grid environments, including 500 kV Substation, Underground Transformer Vault and Main Power Room. Retransmissions also impact the delay and throughput of the network for smart grid environments. It is observed that CMST with PRR shows the best performance in terms of network throughput and delay because it constructs reliable communication channels by considering PRR values of the links at the tree construction stage. In this way, it decreases delay of transmission by avoiding multiple transmission.

4. CHANNEL-AWARE ROUTING AND PRIORITY-AWARE MULTI-CHANNEL SCHEDULING FOR WSN-BASED SMART GRID APPLICATIONS

4.1 INTRODUCTION

Reliable and timely data transmission from suppliers to consumers is critical in smart grid applications. To this end, WSNs are one of the most promising communication solutions that can meet the delay and reliability requirements of smart grid applications. However, recent field tests show that the smart grid infrastructure has harsh and complex environmental conditions, noise, interference, connectivity and multi-path fading problems during low-power wireless communications (Gungor and et al. (2010)). In these field tests, the average noise level was measured as -93 dBm in outdoor 500 kVsubstation environment. Note that this noise level is much higher than that of outdoor noise levels, which is measured as -105 dBm. In addition, smart grid has some specific system challenges (Bari and et al. (2014)). One such challenge is interoperability, since the smart grid is a large-scale system in which there are many interconnected power components, generating an enormous amount of data to be transmitted and analyzed. Therefore, interoperability issues need to be investigated while developing new protocols and standards. The second challenge of the smartgrid is the security, which is required torealize remote power management in the smartgrid. Since energy is a valuable resource, providing security against malicious activities is an important concern in smartgrid.The third challenge of the smart grid is optimization and control of the grid. Analyzing the data collected by sensors and controlling the peak loads are difficult for the smartgrid. Therefore, optimization algorithms are needed to optimize the powergrid's operation.

Furthermore, network traffic loads and data types exchanged in the smart grid communication infrastructure keep changing and increase exponentially. Collected smart grid data are usually time-critical. However, conventional communication techniques only provide a best-effort service and do not guarantee QoS (Yaghmaee and et al. (2013)). Therefore, the smart grid requires a reliable and efficient communication framework to provide QoS requirements of the envisioned smartgrid applications. Moreover, the different types of traffic need to be prioritized based on application-specific delay requirements. Importantly,to improve network performance in smart grid environments, multi-channel communication can be utilized to overcome the impact of RF interference and achieve simultaneous transmissions over multiple channels. With the parallel transmissions, network performance can be improved in terms of delay. Note that although the effect of RF interference might be mitigated with multi-channel communications, recent studies show that network capacity of sensor networks is also constrained by network topology (Yigit and et al. (2014), Incel and et al. (2012)). Hence, it is imperative to construct reliable routing topologies in such environments to take advantage of multi-channel communications.

In the related literature, there have been some QoS-aware communication protocols, which are described in Section 2.2, proposed for wireless sensor networks. However, none of these protocols does not meet the application-specific smart grid requirements. To address these challenges, in this chapter, link-quality-aware routing algorithm (LQ-CMST) as well as the PCA-MC scheduling algorithm have been proposed for smart grid applications. Performance evaluations through extensive simulations show that the proposed algorithms significantly reduce communication delay in smart grid environments. Overall, our main contribution is to investigate the performance of multi-channel WSNs for smart grid and to quantify how priority and channel-aware communication will perform under different network traffic loads and the harsh smart grid channel conditions.

The remainder of the chapter is organized as follows: The network model and the proposed algorithms are explained in Section 4.2. Application scenarios and simulation models are introduced in Section 4.3. In Section 4.4, performance evaluations are discussed. Finally, the chapter is concluded in Section 4.5.

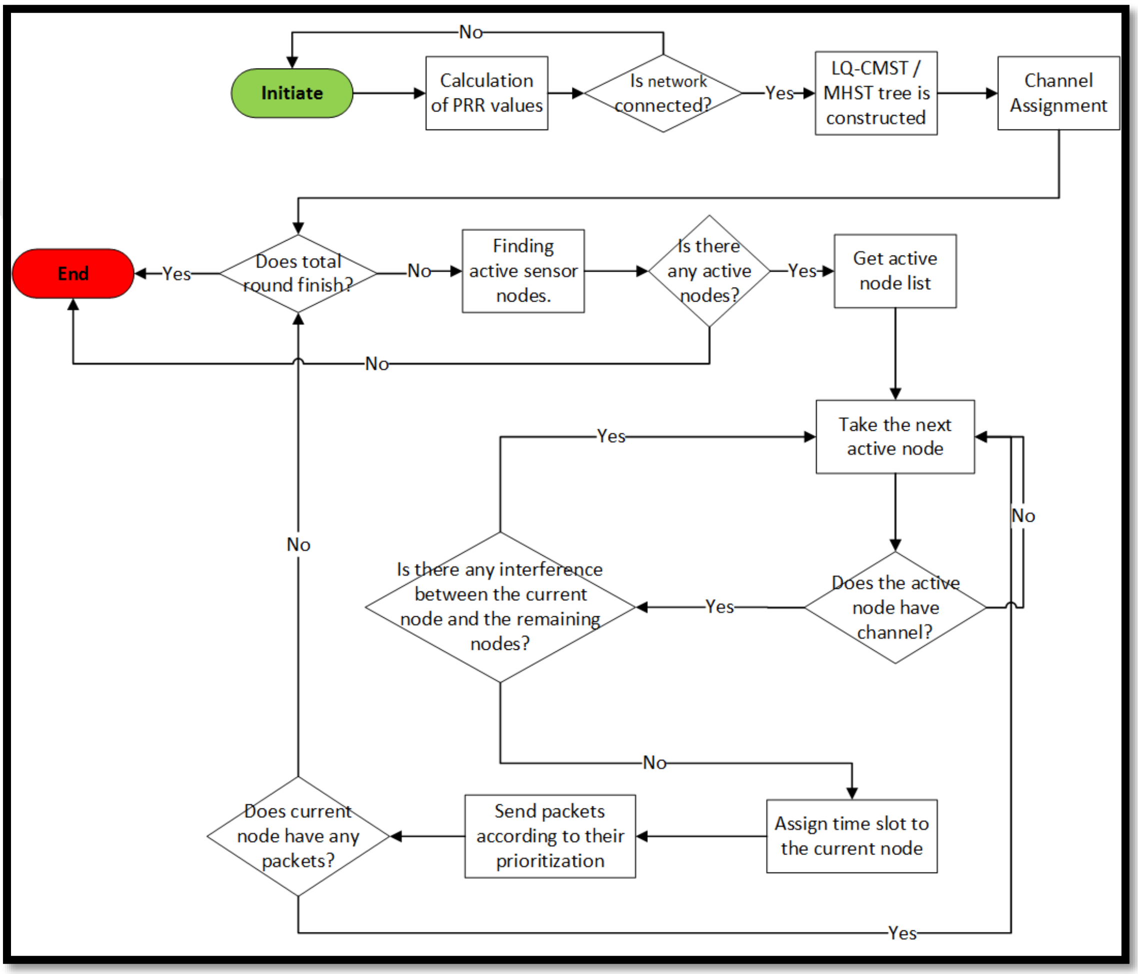
4.2 NETWORK MODEL AND PROPOSED ALGORITHMS

In this study, the Log-Normal Shadowing model is used to model the real channel conditions in smart grid environments. In the related literature, it has been shown that this model is used to model radio propagation environments with obstructions, e.g., smart grid environments (Gungor and et al. (2010)). The parameters of this model are shown in Table 4.1. In this model, the path loss at a distance *d* from the transmitter is given in Section 3.2.2 in Equation 3.2.

Table 4.1: Log-normal shadowing channel parameters of smart grid environments

Propagation environment	Path loss (η)	Shadowing deviation (X_σ)
500 kV Substation (LOS)	2.42	3.12

Figure 4.1: Flow chart of the proposed priority and channel-aware multi-channel scheduling algorithm.



Furthermore, the Modified RBCA algorithm (Incel and et al. (2012)) is used as a multi-channel MAC protocol. The main motivation of using the RBCA algorithm is that it performs well for WSNs, since it assigns channels statistically to the nodes while considering RF interference. Specifically, the RBCA algorithm schedules the transmissions over multiple branches of the routing tree and uses a TDMA time slot assignment algorithm to avoid packet collisions.

Algorithm 4.1: Channel Assignment

Input: ParentSet *parentS*, Channels *nch*, InterferingParents *interfP*, Children *children*, SINRMatrix *sm*, SINRThreshold *st*

Output: Create a channel assignment matrix *channelMatrix(numberOfParents,1)*

```
initialization
Find the interfering parent list
for i ← 1, parentS do
    c ← Children(i)
    interfP(i) ← 0
    channels(i) ← 0
    for j ← 1, c do
        if sm(i, j) > st and j ≠ c then
            interfP(i) ← parents(j)
Assign the channel to non-interference parents
while parentS ≠ Ø do
    maxInterfParent ← parentwiththemaxinterferingdegree
    interfList ← interfP(maxInterfParent)
    channelConflict ← 0
    for c ← 1, nch do
        if channelMatrix(interf) == c then
            channelConflict ← 1;
    if channelConflict == 0 then
        channelMatrix(maxInterfParent) ← c
    channelConflict ← 0
parentS ← parentS \ maxInterfParent
```

In this study, we also make some modifications to the RBCA's time slot assignment algorithm and scheduled the transmissions in parallel throughout multiple branches while considering data prioritization. Here, it is important to note that although the effect of interference might be mitigated with multi-channel communications, recent studies show that network capacity of sensor networks is also constrained by network topology (Yigit and et al. (2014), Incel and et al. (2012)). Hence, it is imperative to construct reliable routing topologies in smart grid environments to take advantage of multi-channel communications. To address this challenge, in this study the link-quality- aware routing algorithm, LQ-CMST, has been proposed. In this algorithm, variable link qualities are considered while constructing the network tree, whose root is the sink node. Specifically, the LQ-CMST algorithm obtains a minimum-hop spanning tree in the network so that the cost of each subtree connected to the sink node does not exceed a predefined capacity. The LQ-CMST algorithm is based on the greedy scheme (Yigit and et al. (2014), Incel and et al. (2012)), in which constructed subtrees are connected to the sink node, if the link-quality of the routing tree exceeds a predefined threshold. In addition, to achieve further performance improvement, the PCA-MC scheduling algorithm has been proposed. In Figure 4.1, the flow chart of the proposed PCA-MC scheduling algorithm has been shown. The proposed scheduling algorithm is based on the calculation of the minimum schedule lengths by using a TDMA-based multi-channel scheduling algorithm. Specifically, after constructing the routing tree, the channel assignment is made by considering RF interference between the nodes. In other words, if the SINR value between the nodes exceeds the predefined threshold, the same channel can be assigned to these nodes. Otherwise, the same channel cannot be assigned to these nodes. Moreover, the Modified RBCA algorithm is used for assigning a minimum number of frequencies to the receivers. The RBCA algorithm is preferred in this study because according to (Incel and et al. (2012)), if the transmissions are scheduled on different channels, the effects of interference can be mitigated. As illustrated in Algorithm 4.1, interfering links are found based on the SINR values of the nodes. Specifically, if there is an available channel, the parent, which has maximum interfering degree, has been assigned a channel. If no available channel exists, the parent node is marked as the interfering node, which is resolved in the time slot assignment phase. As a result, Algorithm 4.1 iteratively assigns the channels to the parent nodes and gives the channel assignment matrix as an output.

Time slot assignment is done after the channels are assigned to the parent nodes. To this end, Algorithm 4.2 takes active nodes with packets in transmission mode and creates a list, including the nodes that are sorted in ascending order according to their distance to the sink node, and the parent is set as an input. It also gives an output list of time slots assigned to the nodes. Here, this algorithm first controls the existence of the conflict in the same time slot by considering three cases: Conflict occurs (1) if the current node is addressed by any other nodes, (2) if the parent of current node makes transmission, (3) if the other nodes send packets to the current node's parent. Furthermore, Algorithm 4.2 also checks channels of other nodes and if the same time slot and channel are used by the other nodes, the time slot is assigned to current active node. Otherwise, the time slot cannot be assigned to the node. This process continues until the nodes in the sorted list finish.

Algorithm 4.2: Time Slot Assignment

Input: ActiveNodes *nnodes*, SortedList *sortedL*, ParentSet *parentS*, Channel *ch*

Output: Create a time slot assignment matrix *timeSlot(nnodes, 1)*

```
initialization
Check conflict status of the node
for n ← 1, sortedL do
    nid ← sortedL(n)
    parent ← parentS(nid)
    conflict ← 0
    addressed ← find senders sending to current node
    addressedParent ← find senders sending to parent node
    Check if current node is addressed by any other nodes
    for a ← 1, addressed do
        if addressed(a) makes transmission in the current time slot t then
          conflict ← 1
          Exit from the loop
    Check if current node's parent is in transmission mode
    if parent(n) makes transmission in the current time slot t then
       conflict ← 1
    Check other nodes address the current node's parent
    for a ← 1, addressedParent do
        if addressedParent(a) makes transmission in the current time slot t then
          conflict ← 1
          Exit from the loop
    if conflict == 1 then
       Make the sorted(n) idle
       Continue with the next node
    Assign time slot if there is no interference
    else
        if any other node do not have same channel and time slot with n
        then
            timeslot(n ,1) ← assign time slot t
```

Table 4.2: Applied traffic loads

Types	**RT (Pkt/s)**	**NRT & BE (Pkt/s)**	**Average created traffic (Pkt/s)**
Low traffic load – Type I	2	12	260
High traffic load – Type II	12	2	1560

Algorithm 4.3: Delay-aware data collection algorithm.

Input: parentSet *parentS*, activeNodes *nnodes*, PRR *PRRM*, totalRound *tRound*, hopCount *hc*

Output: Delay of RT, NRT, and BE packets, *delayRT, delayNRT, delayBE*

```
initialization
Send the packets according to their priority
for t ← 1, tRound do
    for nid ← 2, nnodes do
        RTPacket(nid) ← RT packets of nnodes(nid)
        NRTPacket(nid) ← NRT packets of nnodes(nid)
        BEPacket(nid) ← BE packets of nnodes(nid)
        Node successfully transmits packet to sink node.
        if prrM(nid, parentS(nid)) > threshold then
          if hc(nid) == 1 then
            if RTPacket(nid) > 0 && RT sending time then
              deliveredRTPackets ← deliveredRTPackets + 1
              RTPacket(nid) ← RTPacket(nid) – 1
              delayRT ← t
            else if NRTPacket(nid) > 0 && NRT sending time then
              deliveredNRTPackets ← deliveredNRTPackets + 1
              NRTPacket(nid) ← NRTPacket(nid) – 1
              delayNRT ← t
            else if BEPacket(nid) > 0 && BE sending time then
              deliveredBEPackets ← deliveredBEPackets + 1
              BEPacket(nid) ← BEPacket(nid) – 1
              delayBE ← t
        Node transmits packet to intermediate node.
        else
          parentOfNode ← parentS(nid)
          RTPacketOfPNode ← parentofNode's RT packets
          NRTPacketOfPNode ← parentofNode's NRT packets
          BEPacketOfPNode ← parentofNode's BE packets
          if RTPacket(nid) >0 && RT sending time then
            RTPacketOfPNode ← RTPacketOfPNode + 1
            RTPackets(nid) ← RTPacket(nid) - 1
          if NRTPacket(nid) >0 && NRT sending time then
            NRTPacketOfPNode ← NRTPacketOfPNode + 1
            NRTPackets(nid) ← NRTPacket(nid) - 1
          if BEPacket(nid) >0 && BE sending time then
            BEPacketOfPNode ← BEPacketOfPNode + 1
            BEPackets(nid) ← BEPacket(nid) - 1
If all the packets of active nodes finish, total round is ended.
```

4.3 SIMULATION MODEL

4.3.1 Application Scenario

In general, smart grid applications, including emergency response, periodic power grid monitoring, and wireless meter reading, have different communication delay requirements. For instance, emergency response is one of the time-critical smart grid applications to predict the problems in the power grid before they occur. To this end, the operational power grid problems can be minimized through timely transmission of emergency packets. Therefore, we classify and prioritize data packets into three classes based on their delay requirements. To this end, emergency packets (named as real-time (RT) traffic) will be given the highest priority. The packets, including the temperature, pressure, consumption statistics, are given the second priority (named as non-real time (NRT)). The third class is the control packets (named as best effort (BE)). In this study, three main scenarios are considered by classifying traffic flows based on their priority:

a. In the first scenario, traffic flows are classified based on their priority and multi-channel scheduling that is employed.
b. In the second scenario, all traffic has been treated in a best-effort manner and all the packets are transmitted without any prioritization.
c. In the third scenario, performance evaluations have been conducted under low and high network traffic loads.

4.3.2 Simulation Parameters of the Experiments

In this study, to evaluate the proposed approaches, the MATLAB-based network simulator has been used. Simulations have been performed 100 times with different seeds. We have a 200 x 200 m^2 deployment area and a single sink node for gathering information. The number of nodes in the network is 120 unless otherwise is specified. Different numbers of channels, including 1, 8 and 16 channels, have been studied to evaluate the performance of the proposed algorithms. The Log-Normal Shadowing propagation model is also used to realize the real channel conditions in our simulations by using the smart grid path loss and shadowing deviation parameters shown in Table

4.1. Low and high network traffic loads presented in Table 4.2 are offered to the network to assess the delay performance of the proposed protocols (Yigitel and et al. (2011)). All the simulation parameters used in this study are shown in Table 4.3.

Table 4.3: Simulation parameters

Number of nodes	120
Size of the topology	200 x 200 m^2
Radio propagation model	Log-Normal Shadowing Model
Algorithms	LQ-CMST, PCA-MAC
Distance between the nodes	Randomly distributed
Modulation	Non-Coherent Frequency Shift Keying (NCFSK)
Encoding	Manchester
Output power	4.0 dBm
Noise floor	-93.0 dBm
Topology	Random

4.4 PERFORMANCE EVALUATIONS

The radio parameters, modulation and encoding schemes used in our performance evaluations are listed in Table 4.4. Note that comparative performance evaluations of the proposed protocols have been conducted based on smart grid channel parameters and modulation and encoding schemes of the existing wireless sensor network platforms. To better evaluate the advantages of the pro- posed LQ-CMST algorithm, the proposed routing algorithm has been compared to the MHST algorithm (Incel and et al. (2012)). Specifically, the MHST algorithm aims to reduce the number of hops to transmit data packets towards the sink and constructs the minimum hop spanning trees in the network.

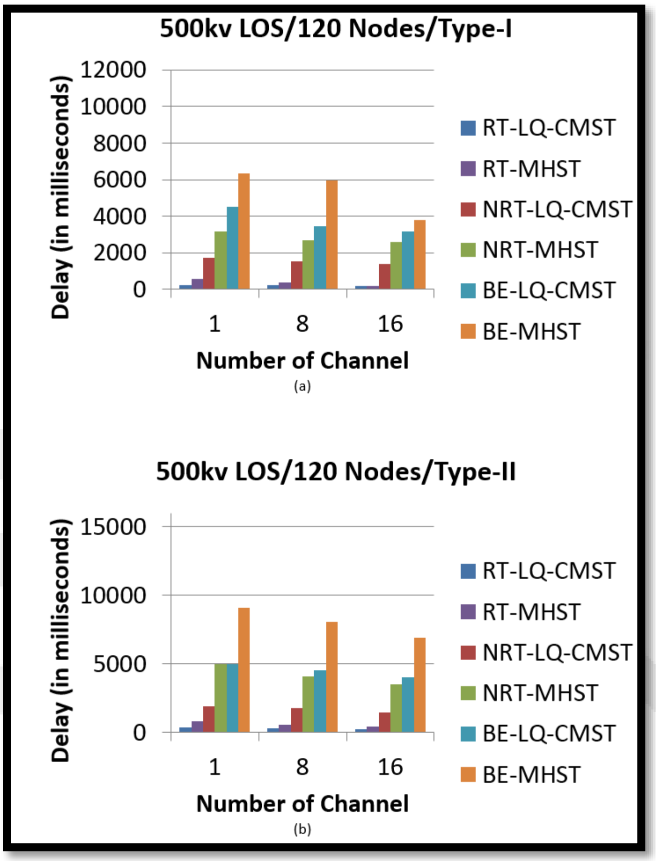
4.4.1 Analyzing the Effect of Number of Channels on Delay Performance

In the first scenario, there are three packet types, RT, NRT or BE traffic, and different numbers of channels and traffic loads. Figure 4.2 shows the average latency when the LQ-CMST and the MHST routing algorithms are used. In this figure, we have observed that the LQ-CMST routing algorithm decreases the average latency of all traffic classes, i.e., the RT, NRT and BE traffics, compared to the MHST routing algorithm. This is because it considers real channel conditions and link-quality variations, while constructing the data paths. Although the LQ-CMST algorithm leads to lower communication delay compared to the MHST algorithm, both the routing algorithms have the same service differentiation mechanism that guarantees that high priority channels, carrying the RT traffic, are preferred compared to the lower priority channels, carrying NRT and BE flows. In order to study the performance of the proposed routing algorithm under different traffic loads, we also run the simulations by congesting the network with more RT data packets. As shown in Figure 4.2b, while the number of RT packets increases, the LQ-CMST and MHST algorithms still provide delay requirements of the RT class, since it has the highest priority. Hence, communication delay of the NRT and BE packets increases. However, such increases are not important, since they do not include time-critical packets. Figure 4.2 also demonstrates that the communication delay increases with large numbers of contenders. This is because when large numbers of nodes want to access to the network and if there is only one common channel, network bottleneck occurs.

Table 4.4: The parameters and notations

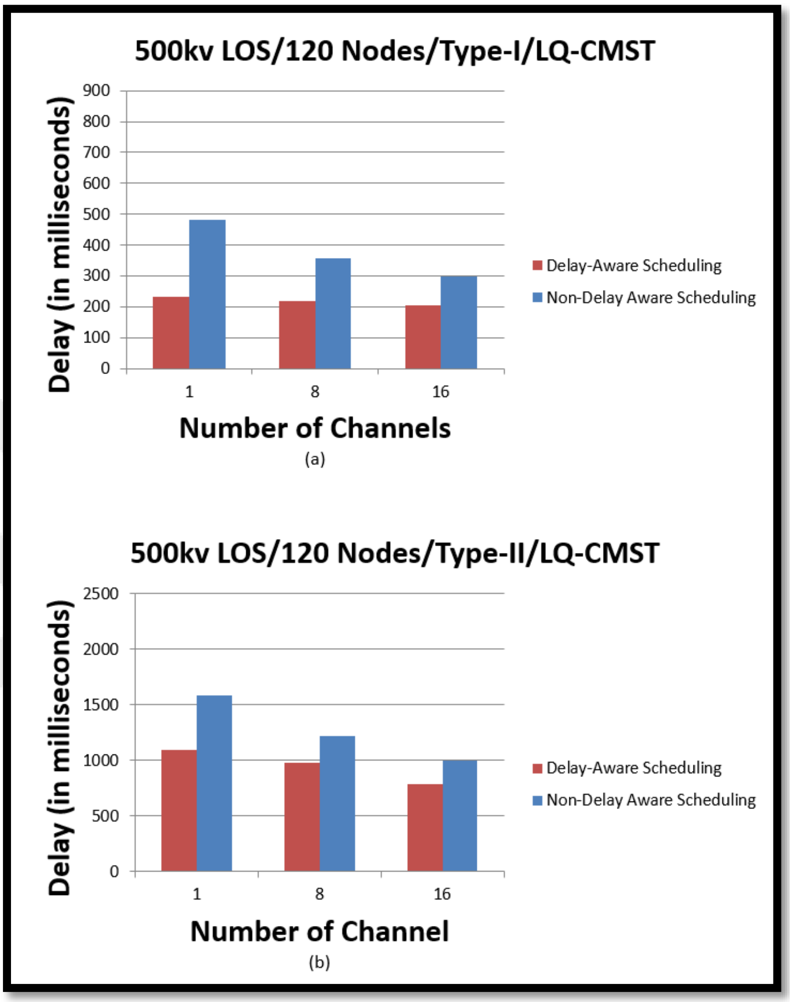
	Parameter	**Description**	**Values**
Radio	SNR	Signal to noise ratio	$\Psi = 10^{(rssi(i,j)-noiseFloor(j)/10)}$
	Q(.)	Standard Gaussian error function	$Q(x) = 0.5 * \mathrm{erfc}(x/\sqrt{2})$. $\mathrm{erfc}(x) = (2/\pi) \int_x^\infty e^{-t^2} dt$
	E_b / N_0	The energy per bit to noise power spectral density ratio	$E_b/N_0 = \Psi (B_N/R)$
	Modulation scheme	FSK	$P_b^{FSK} = Q\sqrt{\left(\frac{E_b}{N_0}\right)}$
		ASK	$P_b^{ASK} = Q\sqrt{\left(\left(\frac{E_b}{N_0}\right)/2\right)}$
		O-QPSK	$P_b^{OQPSK} = Q\sqrt{\left(\frac{E_b}{N_0}\right)_{DS}}$, $(E_b/N_0) = \frac{2_N \times (E_b/N_0)}{(N+4E_b/N_0(K-1)/3)}$
	Encoding scheme	NRZ	$PRR_{NRZ} = ((1-P_b)^{8*pL}) * ((1-P_b)^{8*(fL-pL)})$
		SECDED	$PRR_{secded} = ((1-P_b)^{8*pL} * (1-P_b)^8 + (8*P_b*(1-P_b)^7))^{(fL-pL)*3}$
	P_t	Output power	4 dBm
	P_η	Noise floor	-93 dBm
	fL	Frame size	400 bits
	pL	Preamble length	16 bits
	B_N	Noise bandwidth of Mica 2's transceiver chip	30 kHz
	R	Data rate of Mica 2	19.2 kbps
	N	No of chips per bit	16 chips / bit
Topology	*# of nodes*	Number of nodes	120
	D_x	Terrain dimeansion: *X*	200 m
	D_y	Terrain dimension: *Y*	200 m
	Topology	Topology	Random topology

Figure 4.2: Comparison of average delay of the two routing algorithms when number of channel increases in 500kv substation smart grid environment. (a) Low traffic load, (b) high traffic load.



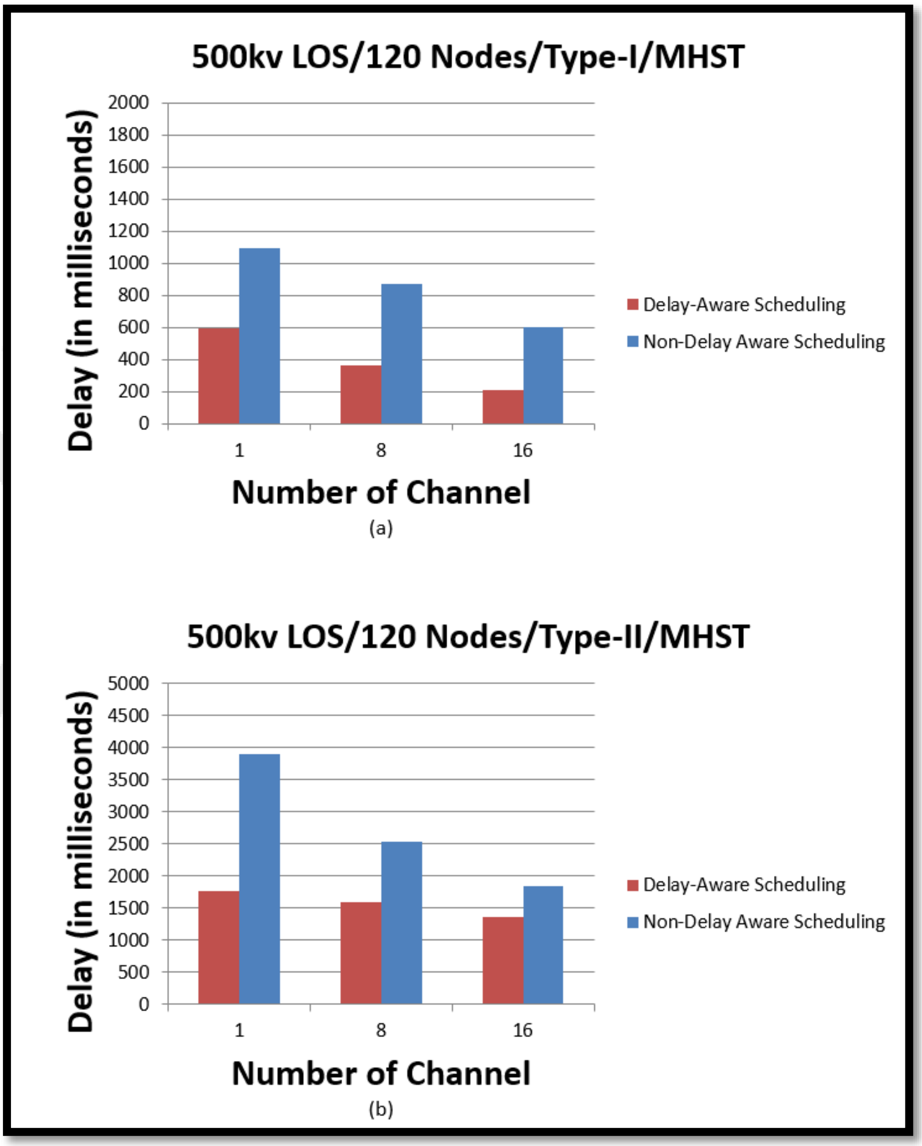
Figures 4.3 and 4.4 illustrate the effect of following priority and delay-aware multi-channel scheduling on the average communication delay, when low and high traffic loads are applied with increasing number of channels. We observe that when the proposed routing algorithms follow delay-aware scheduling, the average latency of the RT packets decreases significantly. It is also important to note that the delay performance of the LQ-CMST algorithm is better than the MHST algorithm with and without delay-aware scheduling, since it considers link qualities while constructing routing paths in the network.

Figure 4.3: Average delay of LQ-CMST routing algorithm with and without prioritization by increasing number of channel in 500kv substation smart grid environment. (a) Low traffic load, (b) high traffic load.



Additionally, we also show the impact of multi-channel scheduling on delay performance of routing algorithms. As shown in Figure 4.2, communication delay of all classes decreases when the number of channels increases, since packets are scheduled on more channels and therefore, schedule length decreases.

Figure 4.4: Average delay of MHST routing algorithm with and without prioritization by increasing number of channel in 500kv substation Smart Grid Environment. (a) Low traffic load, (b) high traffic load.



4.4.2 Analyzing the Effect of Modulation and Encoding Schemes on Delay Performance

In this section, the effect of modulation and encoding schemes on the delay performance of the proposed algorithms is analyzed. To quantify how the proposed algorithms can perform with different wireless sensor network platforms, such as MicaZ, Mica2, Mica, we change the modulation schemes to O-QPSK as in MicaZ, FSK as in Mica2, Amplitude

Shift Keying (ASK) as in Mica. Figures 4.5 and 4.6 illustrate that the average delay values of the LQ-CMST and MHST routing algorithms for different modulation schemes and number of channels, respectively. Focusing on the results of Figures 4.5 and 4.6, we observe that the O-QPSK shows the best result for both routing algorithms. After the O-QPSK, the FSK provides the second best result and lastly the ASK presents the third best result. We conclude that the modulation scheme is one of the most important design factors to provide QoS requirements of smart grid applications.

Figure 4.5: Comparison of modulation schemes for 500 kv substation LOS in terms of average delay of LQ-CMST routing algorithm vs. number of channel. (a) Low traffic load, (b) high traffic load.

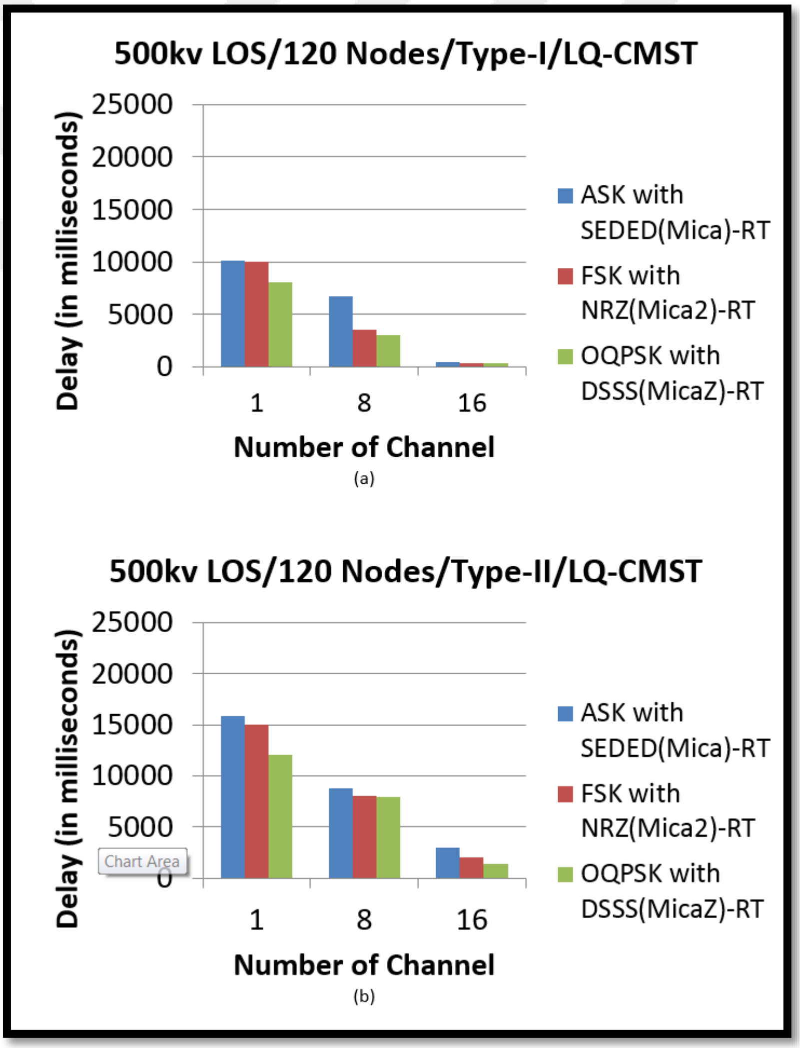
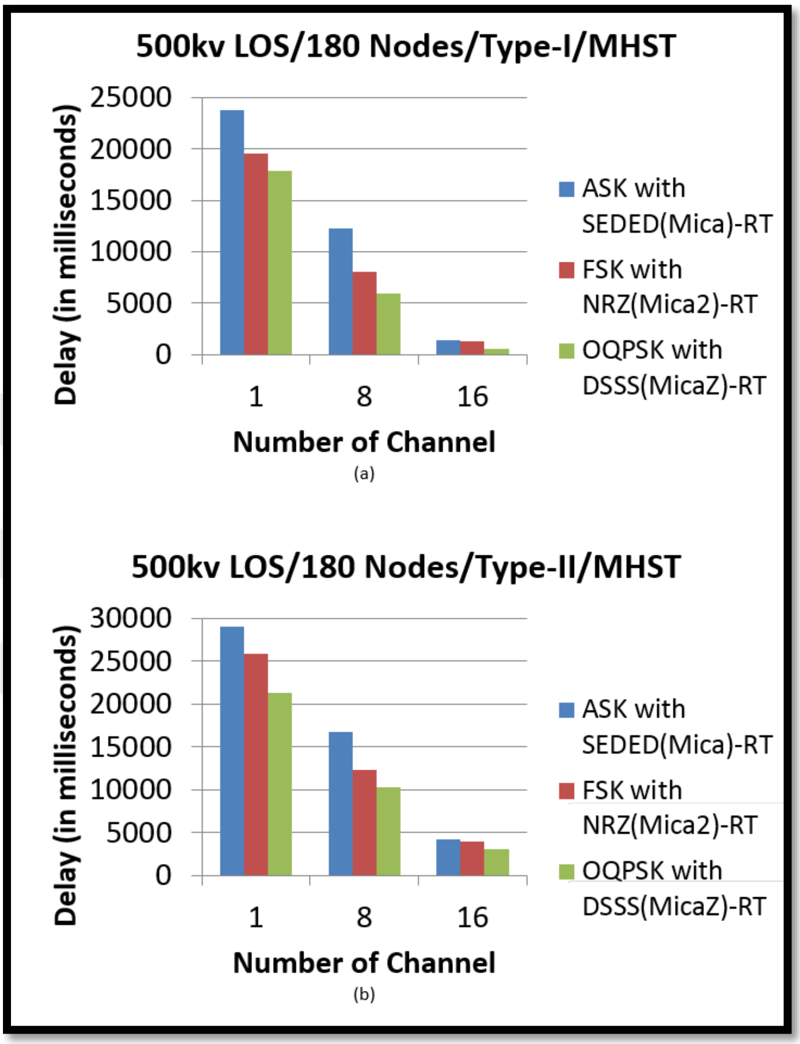


Figure 4.6: Comparison of modulation schemes for 500kv substation LOS in terms of average delay of MHST routing algorithm vs. number of channel. (a) Low traffic load, (b) high traffic load.



4.5 DISCUSSION

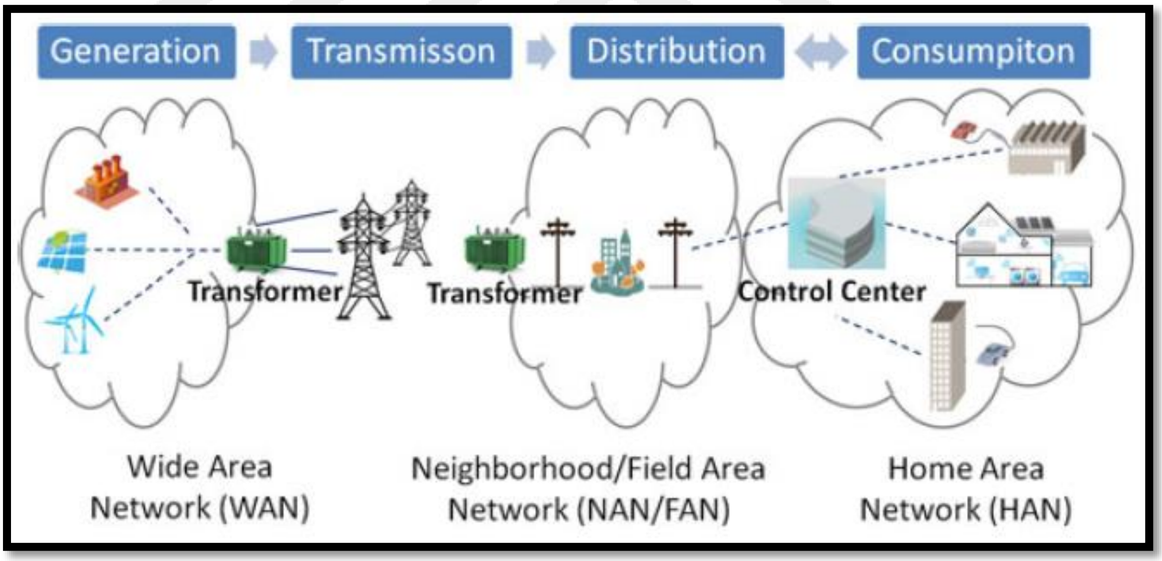
Recent field tests show that the smart grid infrastructure has harsh and complex environmental conditions, noise, interference, connectivity, and fading problems during low-power wireless communications. To address these communication challenges, in this chapter, the link-quality-aware routing algorithm, LQ-CMST and the PCA-MC scheduling algorithm have been proposed for smart grid applications. Furthermore, the effect of modulation and encoding schemes on the performance of the proposed algorithms is analyzed under harsh smart grid channel conditions. Comparative performance evaluations through extensive simulations show that the proposed algorithms significantly reduce communication delay in smart grid environments. Overall, the main contribution of this study is to investigate the performance of multi-channel WSNs for the smart grids and to quantify how priority and channel-aware communication will perform under different network traffic loads and harsh channel conditions of smart grid environments.

5.QOS-AWARE MAC PROTOCOLS UTILIZING SECTORED ANTENNA FOR WSNS-BASED SMART GRID APPLICATIONS

5.1 INTRODUCTION

The smart grid is a modern electric power system that integrates many devices with a state-of-the-art communication infrastructure and energy management techniques on the existing power grid. Many technologies are used for meeting the reliability, security, and efficiency requirements of smart grids. In this respect, accurate and RT collection of information from generators, transmission equipment, transformers, and substations, which are illustrated in Figure 5.1, are the most critical issues for smart grid applications (Al-Anbagi and et al. (2014)).

Figure 5.1: Architecture of WSN-based smart grid communication network



WSNs are widely used in smart grid applications owing to their many advantages. QoS requirements of many smart grid applications summarized in Table 5.1 (Gungor and et al. (2013), Shah and et al. (2013)), such as plug-in hybrid electric vehicle (PHEV), distribution generation, community energy storage, distribution automation, and outage alarming, vary in terms of delay and throughput. For instance, PHEV provides the information of electricity distribution system (Al-Anbagi and et al. (2014)), and if the information related to status of the transformers is delayed or not correctly transformed, unnecessary load control can occur and can make it difficult to provide the stability of the power grid. Although PHEV is not latency-tolerant, other smart grid applications, such as metering, are latency-tolerant. In addition, all of the collected data are not important for smart grid applications. Some of them are auxiliary control packets sending general information such as location information about the sensor nodes and do not require real-time communication (Yigitel and et al. (2011)).

Table 5.1: Quality of service requirements of smart grid applications

Application	**Delay**	**Throughput**
Advanced metering infrastructure	2 s	14 – 100 kbps
Demand response	2 s	56 kbps
Wide-area situational awareness	15 – 200 ms	600 – 1500 kbps
Distributed energy resources and storage	100 ms- 2 s	9.6 – 56 kbps
Plug-in hybrid electric vehicle	2 s – 5 min	9.6 – 56 kbps
Distribution automation	20 – 200 ms	9.6 – 56 kbps
Substation automation	15 – 200 ms	9.6 – 56 kbps
Emergency response	0.5 s	40 – 250 kbps
Outage management	2 s	56 kbps
Building automation	1 – 2 s	16 – 32 kbps

Various types of traffic, such as BE, NRT, and RT, are delivered by WSN-based smart grid applications. Management of these traffic types can be performed by making prioritization and service differentiation based on the requirements of various traffic types with different requirements (Yigitel and et al. (2011)). MAC layer mechanisms can support the QoS requirements of these applications because they manage the sharing of medium and have the capability to affect the performance of the smart grid communication networks. Therefore, implementing an efficient MAC protocol and a compatible routing protocol is important for QoS. However, there exist many design challenges while designing an efficient MAC protocol and a routing protocol. One of these challenges is that high latency can occur during data collection process because of variable channel capacity of WSNs. In WSNs, the interference level perceived at the receiver determines the capacity of each wireless link. Hence, the capacity of each link is environment-dependent, providing QoS provisioning a compelling issue. Second, sensor nodes are resource-constraint, and therefore, they have limited memory, processing capability and data rate. These make it difficult to develop QoS-aware scheduling for smart grid applications. Finally, each smart grid application has specific QoS requirements because some of them are delay-sensitive or need high bandwidth. Therefore, designing an efficient protocol that meets requirements of each application is a challenging task.

In this chapter, we present two protocols that aim to address prioritization, delay, and reliability aware data transmission for smart grid communication networks. The proposed protocols make service differentiation (prioritization) between the traffic classes based on their requirements in order to achieve better performance. Our first approach, the QODA-MAC, uses omnidirectional antennas for neighbor discovery. The QODA-MAC retrieves neighbor information and makes scheduling according to the traffic types including BE, NRT, and RT. The second approach, named QFSA-MAC, utilizes directional antennas, as opposed to QODA-MAC, to discover the neighbors by concentrating the transmission power towards a certain direction (Felemban and et al. (2010)). In QFSAMAC, the use of the directional antenna enhances the spatial reuse of the wireless channel that provides simultaneous communication between the nodes without interference. In this way, it can connect the nodes far away from each other and decreases the number of hops from source node to sink node when compared with omnidirectional antennas. Similar to QODA-MAC, QFSA-MAC makes the scheduling by making service differentiation and uses the same routing protocol for forwarding packets towards the sink node. In addition, both QODA-MAC and QFSA-MAC have two modes of operation, prioritized and unprioritized modes that provide switching from one mode operation to another according to the application requirements. For instance, if RT traffic occurs, prioritized mode can become active; otherwise, unprioritized mode can be used to provide fairness by allowing other nodes to access the channel. Although many studies have been proposed to meet the QoS requirements of smart grid applications (Al-Anbagi and et al. (2014), Hurni and Braun (2010), Sun and et al. (2010), Singh and Tepe (2009)), QODA-MAC and QFSA-MAC are the first QoS-aware MAC protocols that consider service differentiation of different traffic classes by considering the impact of antenna for smart grid communication networks. Performance of QODAMAC and QFSA-MAC is evaluated with comprehensive simulations for various traffic classes such as BE traffic, NRT traffic and RT traffic, similar to (Yigitel and et al. (2011)), and their performance are compared with each other for smart grid communication networks. The key contributions of this work are listed as follows:

a. Quality of service-aware MAC protocols that aim service differentiation have been explored. QFSA-MAC, has been proposed to handle the challenges and communication requirements of smart grid applications by making service differentiation. The efficiency of sectored antennas and service differentiation in terms of delay, throughput and energy compared with omnidirectional antennas and without QoS-aware scheduling has been demonstrated for smart grid applications.
b. Our simulation results show that the QFSA-MAC protocol yields adequately service differentiation and meets the QoS requirements of smart grid applications. It provides better performance from the point of delay, throughput and energy compared with QODA-MAC protocol for both the prioritized and unprioritized modes of operation.
c. Efficiency of service differentiation is also demonstrated by comparing the average source with sink delays of proposed MAC protocols with and without delay-aware scheduling.

The remainder of the chapter is organized as follows: Important preliminary information to understand the basics of QODA-MAC and QFSAMAC is provided in Section 5.2. In Sections 5.3 and 5.4, system design details and key properties of QODA-MAC and QFSA-MAC are described. Simulation parameters and an application scenario are presented in Section 5.5. In Section 5.6, performance evaluation results are discussed. Finally, Section 5.7 concludes this chapter with a brief summary of simulation results.

5.2 PRELIMINARIES

5.2.1 Antenna Model

Impact of antennas, which are sectored and omnidirectional antennas, are explored in this study while designing the MAC protocols. The main purpose of using different types of antennas is to explore the impact of antenna type on meeting the QoS requirements of smart grid applications and use it as a parameter for service differentiation.

The omnidirectional antenna architecture is assumed for the QODA-MAC protocol in which sensor nodes are equipped with antennas that radiate the radio frequency electromagnetic fields uniformly in all directions in a plane. One major advantage of omnidirectional antennas compared with other types of antennas is they are easy to install and do not need steering to cover the area because their radiation cone covers 360°. On the other hand, QFSA-MAC is designed by using sectored antenna that is a type of directional antenna with a sector-shaped antenna pattern. *K* non-overlapping sectored antenna is used to cover the entire 360-degree range. Packets are transformed by selecting a sector and immediately received by the active sector. Concurrently, inactive sectors buffer the coming signals to transmit them when they become active. Nodes use a switch to select different sectors, and each one of them can activate one sector at a time (Felemban and et al. (2010)).

The QFSA-MAC and QODA-MAC are both designed to reduce interference and collisions for meeting the QoS requirements of smart grid applications. However, QFSA-MAC is more efficient than the QODA-MAC because directional antennas reduce the interference and allow parallel transmissions between the neighbors by increasing spatial reuse of the radio resources (Capone and et al. (2008)).

5.2.2 Network Model

5.2.2.1 Network model of QODA-MAC protocol

Network is modeled as a graph $G = (V, E)$ in which set of nodes and set of wireless links are represented with V and $E = \{(i, j)|i, j; \epsilon V\}$, respectively. Interference causes cumulative effects in a wireless network. To solve this, we use a physical interference model that uses SINR to make a successful transmission. Packets are received by the nodes if SINR values of the nodes exceed a definite threshold value. More information about the SINR calculation can be found in (Yigit and et al. (2014)). To measure link qualities, we will use a real physical layer model utilizing the log-normal shadowing model based on the measurement showed in Table 3.2. All the nodes except the sink node generate the packets according to different traffic loads. An example is presented in Table 5.2. RT packets are collected more frequently than BE and NRT packets because they are more delay-critical. Therefore, interarrival times of the NRT and BE packets are higher than RT. Traffic loads are calculated by calculating the number of sent RT, NRT, and BE packets in every second. For instance, in Type 1 load, in every second, one RT packet and in every 12 s, one NRT and one BE packets are sent. Total number of packets sent by one node is first computed, and then it is multiplied by the total number of nodes that is deployed in the area. Equation 5.1, which is used for calculating the traffic load, is also shown below. *RT_IAT* is the interarrival time of RT packets, *NRT_IAT* is the interarrival time of NRT packets, and *BE_IAT* is the interarrival time of BE packets.

$$TrafficLoad = \left(\left(\frac{\#OfRTPackets}{RT\_IAT}\right)\right) + \left(\left(\frac{\#OfNRTPackets}{NRT\_IAT}\right)\right) + \left(\left(\frac{\#OfBEPackets}{BE\_IAT}\right)\right) * \#OfNodes \quad \textbf{(5.1)}$$

There are some constraints in our data collection model. One of them is using half-duplex transceivers in which the nodes cannot make transmission while another node is making transmission. Another constraint is the physical interference model that focuses on the SINR value to avoid cumulative effects of interference in wireless links. Therefore, nodes can be scheduled to make transmission if their SINR value is larger than a certain threshold.

Table 5.2: Loads in simulations

	Packet rate	**Interarrival time**	**Average created load**
Types	Real-time (pkt/s)	Non-real-time and best effort(s)	Traffic load (pkt/s) for 180 nodes
Low traffic load – Type I	2	12	390
High traffic load – Type II	12	2	2340

In our previous study (Yigit and et al. (2014)), a TDMA-based multi-channel scheduling algorithm is used to schedule the nodes without service differentiation by considering interfering nodes and link qualities (PRR). However, in this study, time slots are assigned to the nodes according to delay requirements of coming packets, which can be RT, NRT, or BE. This means that RT packets have the highest priority, and therefore, time slots are primarily assigned to them. In this way, our aim is to provide QoS-aware schedule assignment while eliminating the impact of interference.

5.2.2.2 Network model of QFSA-MAC protocol

In QFSA-MAC, the network is modeled as a graph similar to the network model of the QODA-MAC protocol. A predetermined high capable sink node is served to this graph.Within the graph, the topology is random and nodes access the sink node over multiple hop. QFSA-MAC does not use a multi-cluster network as the one proposed in (Felemban and et al. (2010)) because communication between clusters needs additional dedicated channels, increases the interference, and causes packet collisions. QODA-MAC and QFSA-MAC protocols use the same interference model and the physical layer model to determine the link qualities among nodes.

A dynamic TDMA scheduling algorithm that allocates a changeable number of time slots according to traffic load of each data stream is used as an MAC protocol in our QFSA-MAC approach. In this way, QFSA-MAC can meet all traffic types such as high and low loads by dynamically assigning time slots to each node. Furthermore, QoS-aware scheduling has been achieved by the QFSA-MAC with service differentiation in which the packets are prioritized into three classes, RT, NRT, and BE, according to their QoS requirements. Within this context, QFSA-MAC protocol is the first protocol that uses sectored antenna with service prioritization for smart grid communication networks.

5.2.3 Calculation of Link Qualities

We consider all the factors including path loss, shadowing deviation, and noise for link quality function. Link qualities are calculated for each link from nodes to other remaining nodes. We used a real physical layer model utilizing the Log-Normal Shadowing Model based on the measurements explained in Section 3.2.2 and summarized in Table 3.2.

5.3 QUALITY OF SERVICE-AWARE OMNIDIRECTIONAL ANTENNA-BASED MEDIUM ACCESS LAYER PROTOCOL DESIGN AND ARCHITECTURE

In this section, we focus on convergecasting data towards the sink node with and without service differentiation in the context of periodic data collection where each node generates different number of packet types, that is, RT, NRT, and BE, at the beginning of every frame. We assume that the size of each packet is the same and the same channel is used by all the nodes in the network. Our main objective is to achieve the minimum schedule length and the maximum packet delivery ratio to meet the QoS requirements of smart grid applications. To this end, we use cross-layer QoS-aware TDMA-based MAC protocol. This protocol differs from other existing cross-layer TDMA-based solutions because it constructs the routing tree and makes different periodic scheduling using our previously proposed CMST with PRR routing tree algorithm (Yigit and et al. (2014)). Within this context, we first consider the scheduling of the nodes without service differentiation, and then we introduce a QoS-aware scheduling algorithm named as QODA-MAC with service differentiation.

5.3.1 Quality of Service-Aware Omnidirectional Antenna-Based Medium Access Layer Without Service Differentiation

In this section, we present the QODA-MAC without service differentiation and its important properties for adjustment of different types of traffic. In our previous study (Yigit and et al. (2014)) explained in Chapter 3, we used a multi-channel scheduling algorithm to minimize the schedule length and to maximize the throughput in smart grid communication networks, but we did not consider the impact of periodic data generation and different traffic types on schedule length. Within this context, in this study, we aimed to assess influence of different traffic types on the schedule length of TDMA-based scheduling algorithm.

Many smart grid applications, such as Advanced Metering Infrastructure (AMI) and capacitor bank control, must support RT traffic under different traffic loads. Therefore, we consider the AMI application where different traffic types are possible. We assume that RT, NRT, and BE packets are generated by AMI application and their transmission rates are different. For instance, RT packets are sent more frequently than the NRT and BE packets in an emergency situation because NRT and BE packets are not time-critical packets. NRT and BE packets are respectively the control packets including environment information such as vibration and the auxiliary packets including location information of the sensor nodes.

The QODA-MAC without service prioritization firstly constructs the routing tree by using capacitated minimum hop spanning trees considering link qualities (PRR) named as CMST with PRR routing tree algorithm that has been proposed in our previous study (Yigit and et al. (2014)). CMST with PRR algorithm is used in QODA-MAC protocol because it is more efficient compared with other routing tree protocols such as minimum hop spanning tree and considers the PRR values, calculating by using log-normal shadowing propagation model while constructing routing tree. After the routing tree is constructed, time slots are assigned to the nodes. We use the same time slot assignment algorithm as used in our previous study called as TDMA scheduling where time is divided into time slots. Proposed interference-aware TDMA scheduling algorithm uses breadth-first-search time slot assignment algorithm for time slot assignment. In each iteration, an edge is selected from the breadth-first-search order and is assigned minimum time slot that is different from the adjacent edges considering the SINR values. While sending packets, QODA-MAC without service differentiation does not make priority-based data forwarding, which means that it gives the same priority to all the packets.

5.3.2 Priority and Delay-Aware Quality of Service-Aware Omnidirectional Antenna-Based Medium Access Layer

In this section, QODA-MAC with service differentiation and its properties for QoS provisioning with respect to various traffic types shown in Table 5.2 is described. QODA-MAC with service differentiation protocol is an extension of QODA-MAC without service differentiations because it is based on QoS-aware TDMA medium access protocol that prioritizes the packets according to their production time and deliver them immediately to the sink node.

Figure 5.2: Flow chart of QODA-MAC with service differentiation protocol

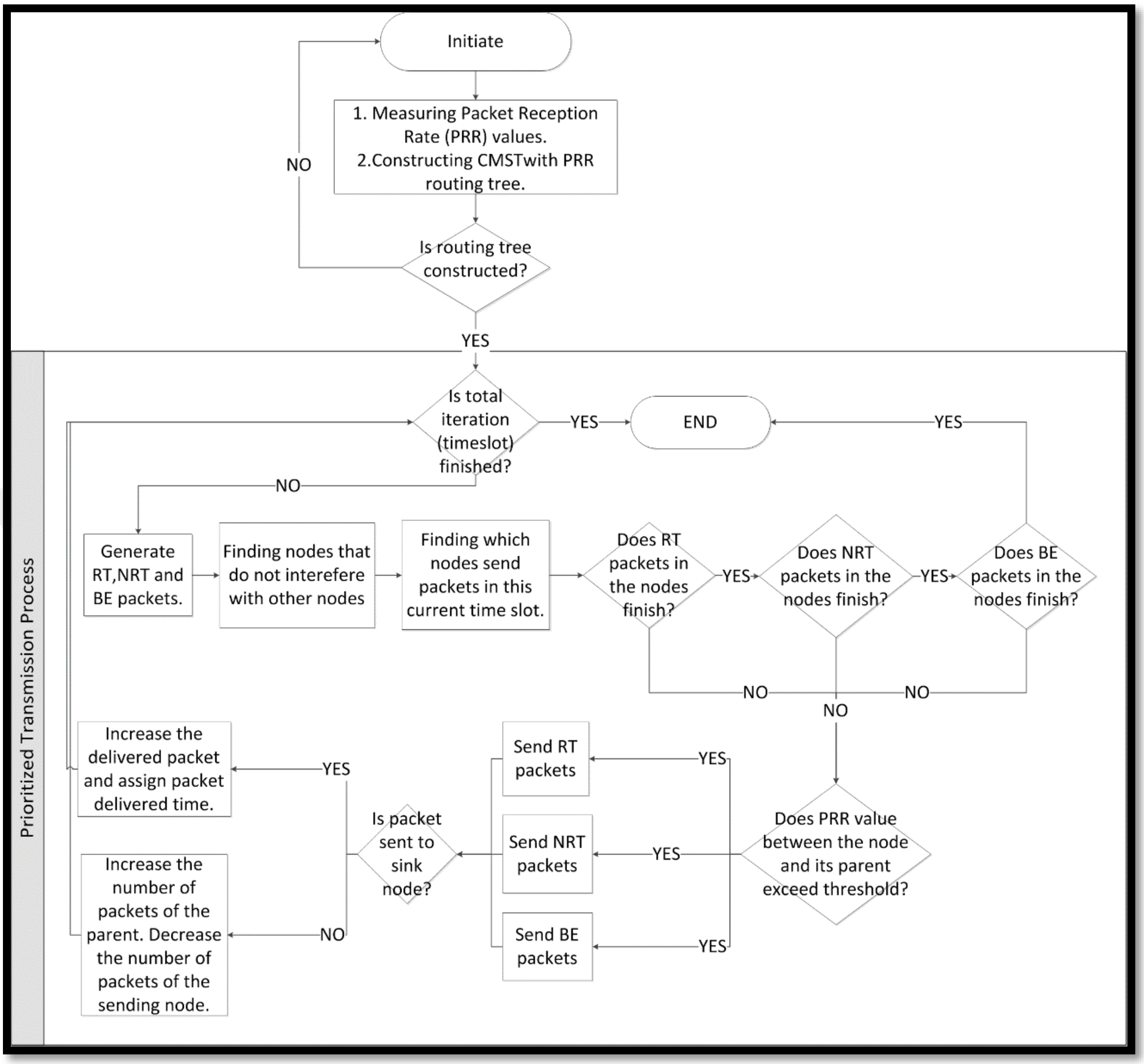


Figure 5.2 shows the flow chart for the operation of the QODA-MAC protocol with service differentiation. Firstly, PRR values of each nodes are measured, and then the routing tree is constructed using CMST routing tree algorithm considering the PRR values. After the routing tree is constructed, in every iteration, each node generates RT, NRT, and BE packets with different rates. Non-interfering nodes are found to decide which nodes can make transmission without interfering their adjacent nodes. Within this context, nodes have two types of mode including transmission and idle mode.

For instance, if the children, parent, and siblings of the node do not transmit, the node enters the transmission mode; otherwise, it stays idle to avoid interference among the other nodes. When the node is in transmission mode and has RT, NRT, and BE packets, the node firstly schedules the RT packets if the PRR value between the node and its parent exceeds a certain threshold. After then, the node respectively sends the NRT and BE packets when all the RT packets are transmitted. In this way, QODA-MAC with service differentiation protocol transmits the RT packets more rapidly than NRT and BE packets and achieves the QoS-aware scheduling by prioritizing packets according to their delay requirements.

5.4 QUALITY OF SERVICE-AWARE FOUR-SECTORED ANTENNA-BASED MEDIUM ACCESS LAYER DESIGN AND ARCHITECTURE

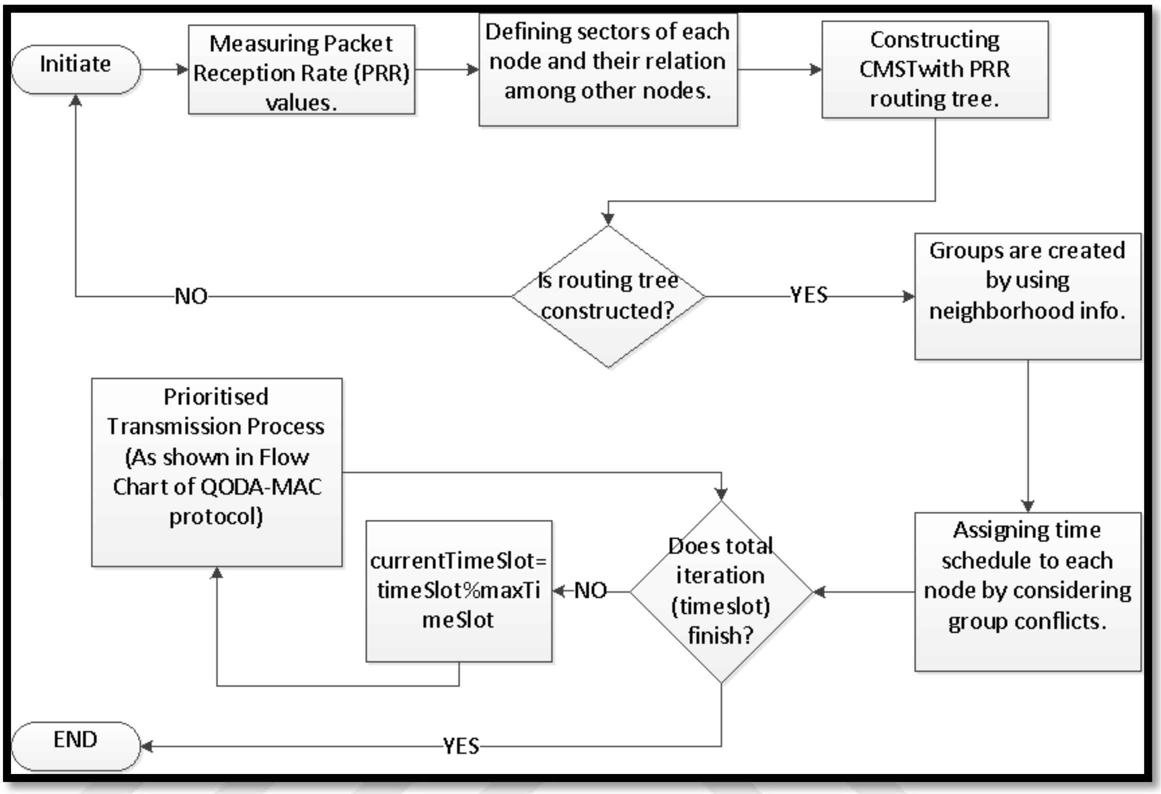
The QFSA-MAC protocol is designed for enabling QoS-aware and reliable communication between the sink node and the sensor nodes. Data transmission at uplink traffic is in the direction of sensor nodes to the sink node. The QFSA-MAC protocol is based on the dynamic TDMA protocol and formed in two ways: one prioritize the packets according to their traffic class shown in Table 5.2 and the other does not prioritize the packets and do not make service differentiation for QoS provisioning. In this respect, the QFSA-MAC protocol with service differentiation is the first protocol that combines sectored antennas with service differentiation to meet the requirements of QoS provisioning for smart grid applications.

The QFSA-MAC protocol is designed with using sectored antennas as opposed to QODA-MAC protocol that operates with omnidirectional antennas and groups the sensors together to form the multiple sensor groups. Contention may occur because of the directional beamforms of the sensor nodes in case of simultaneous transmission made by both sensor groups. To avoid the contention events, the QFSA-MAC protocol determines the contending groups by considering the directions of sectored antenna beamforms and properly assigns the time slots. Each sensor node in QFSA-MAC protocol is active in a certain time slot when they are scheduled for communication and enters in a sleep mode at all other times for saving energy. Sensor nodes within the individual groups are scheduled by using our proactive contention avoidance scheme shown in Algorithm 5.2, which controls the time slots of siblings and children of each node during time slot assignment, at upstream nodes in smart grid communication networks. Calculating the neighborhood information for assigning time slots may be difficult owing to changing environment conditions or to its overhead. In this respect, a contention-based MAC scheme can be used. However, in this work, our aim is to show the effect of service differentiation (prioritization) and the effect of using directional antenna for meeting the QoS requirements when the same type of MAC scheme is used, slotted in our case.

Complete neighborhood information is required before assigning time schedules to the sensor nodes. Our first protocol, QODA-MAC, uses omnidirectional antenna, and therefore, it can simply access all the neighborhood information by sending broadcast message. However, the proposed QFSA-MAC protocol uses sectored antennas, and hence, it can cover *360 / NumberOfSectors* azimuth degree, and the neighbor discovery process must be repeated for each sector to cover all directions. In the literature, some of the neighbor discovery protocols (Zhang and Datta (2005)) using directional antennas utilize an omnidirectional antenna to find the neighbors. But using an omnidirectional antenna coupled with a directional antenna increases the cost of sensor networks and decreases the efficiency of neighbor discovery process because it has less communication range than the directional antenna when the same transmission power is used. Therefore, the QFSA-MAC protocol does not use omnidirectional antenna and utilizes a directional neighbor discovery mechanism. On the other hand, directional antennas have also some possible problems including deafness and interference due to higher gain (Kolar and et al. (2004)). Deafness is one of the problems that may occur when a node receives the transmission coming from its particular sector and does not receive the signals coming from its other sectors. The node is locked in a specific sector and becomes deaf in all the other sectors. A second possible problem of the directional antennas is the interference due to higher gain that occurs because of the strength of the focused beam. This culminates in larger range of the signal that can reach the other ongoing transmissions in the same direction and may cause the interference. The QFSA-MAC protocol solves all these problems caused by the directional antennas by using buffers for coming packets to other sectors and by utilizing an efficient interference model.

In the following parts of this section, the steps of the QFSA-MAC protocol, which are also shown in Figure 5.3, are described.

Figure 5.3: Flow chart of quality of service-aware four-sectored antenna-based medium access layer with service differentiation protocol.



5.4.1 Neighbor Discovery and Routing Tree Construction

Complete neighborhood information is required for the efficient operation of the QFSA-MAC protocol. Network architecture is initially set up by randomly deploying sensor nodes without having any neighborhood and location information. Each sensor node has multiple sectored antennas that cover the whole azimuth. A sensor can sense the packet transmission from its two or more sectors, but the packet is actually received over a single sector. This is achieved by selecting the sector that has the maximum reception power level while receiving a packet. Therefore, in Algorithm 5.1, received signal strength indicator, which is a measurement of the power received from the radio signal, is measured for each node pair by considering path loss. Then, neighborhood relations between two nodes and the sectors that these nodes can communicate on are found by exploring sectors having the maximum power. For instance, Figure 5.4 describes the neighbor–sector relation algorithm that firstly finds that the node *C* sends and receives packets on its sector 1, and the node *A* communicates with *C* on its sector 4, then add node–sector pairs *(C, 1)* and *(A, 4)* that are neighbors of each other to *RelationMatrix*. After all the neighborhood relations are found by each sector, a routing tree is constructed by using our previously proposed CMST with PRR routing algorithm. The process of constructing *RelationMatrix* is carried out at the beginning of simulation and when the topology changes. It is therefore a rare operation.

Algorithm 5.1: QFSA-MAC node-sector relation algorithm

Input: s (#sectors), nnodes (#nodes), pathL (path loss), outP (output power), rssi (received signal strength indicator)

Output: Create relation holder matrix as *RelationMatrix (N, N)*

initialization
for $i \leftarrow 0, nnodes$ **do**
  for $j \leftarrow i + 1, nnodes$ **do**
    $maxPower_i \leftarrow 0$
    $maxPower_j \leftarrow 0$
    for $k \leftarrow 1, s$ **do**
      $rssi(i, j) \leftarrow outP(i) + pathL$
      $secPower_i \leftarrow rssi(i, j) + rand(1)$
      if $secPower_i > maxPower_i$ **then**
        $maxPower_i \leftarrow secPower_i$
        $maxPowerIndex_i \leftarrow k$
      $rssi(i, j) \leftarrow outP(j) + pathL$
      $secPower_j \leftarrow rssi(j, i) + rand(1)$
      if $secPower_j > maxPower_j$ **then**
        $maxPower_j \leftarrow secPower_j$
        $maxPowerIndex_j \leftarrow k$
    RelationMatrix(i, j) ← $maxPowerIndex_i$
    RelationMatrix(j, i) ← $maxPowerIndex_j$

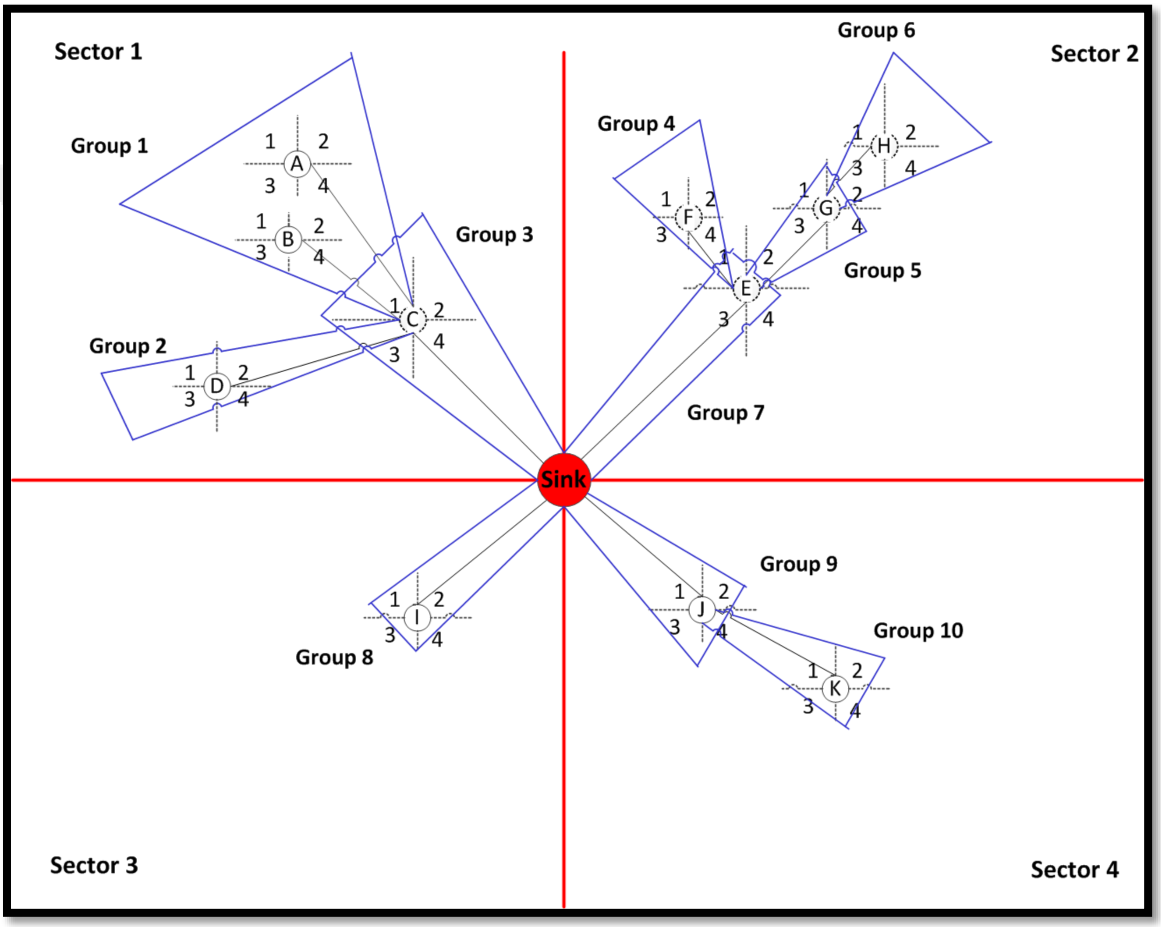
The CMST with PRR routing algorithm considers the variable link qualities and uses neighborhood information retrieved from Algorithm 5.1 while constructing the routing tree. PRR values of each node in the network are measured, and nodes connect to the neighbors nearest the sink node with highest PRR value and capacity constraint *c*. This increases the reliability of CMST with PRR algorithm because it considers real channel conditions. Constructed subtrees are connected to the root node *r* if the PRR value of the link between the nodes exceeds a threshold. Nodes are searching closest neighbors having the highest PRR except the sink node. Neighbors are merged after the computation of tradeoff function instead of connecting them directly to the sink node for having some potential savings. As a result, parent–child relations are specified and routing tree is constructed. A more detailed explanation about the tradeoff function and how the PRR values are calculated can be found in Section 3.3.2.

5.4.2 Group Creation

The QFSA-MAC protocol divides the nodes and creates groups using neighborhood information for increasing slot reuse and for minimizing schedule length. We are inspired from (Felemban and et al. (2010)), using sectored antenna for WSNs and utilizing the Bellman–Ford shortest path algorithm while creating groups of the QFSA-MAC protocol. Our group creation algorithm differs from the group formation algorithm of (Felemban and et al. (2010)) in routing tree construction and the network architecture. Felemban and et al. (2010) use the Bellman–Ford shortest path algorithm for determining parent–child relation; however, we utilize from CMST with PRR algorithm and consider real channel conditions while constructing paths. Furthermore, Felemban and et al. (2010) divide the sensors into clusters, but they do not consider communication between cluster heads. On the other hand, we also divide the network into a set of clusters and take care of communication between clusters until the sink node receives the information sent from sensor nodes.

Group creation starts with the determination of paths from sensor nodes to the sink node. These paths are constructed utilizing CMST with PRR routing tree algorithm using the collected neighborhood information. As a result of routing tree algorithm, a capacitated minimum hop spanning tree is created specifying parent–child relations. A common node conflict can occur in case of simultaneous transmission when two nodes, *A* and *B* shown in Figure 5.4, communicate with another node, *C*, on the same sector of *C*. This can be avoided if *AC* and *AB* communicate in different time slots. When the node pairs are allocated time slots using this strategy, conflicts among the node pairs are avoided. However, assignment of new time slot in case of conflict situation reduces delay performance. Therefore, we dynamically allocate the time slots and use the same time slot if the nodes do not interfere with each other. In this way, we reduce the schedule length and increase delay performance while eliminating conflicts.

Figure 5.4: Group creation



In the QFSA-MAC protocol, a group is defined as a set of sensor nodes that has the same time slot and parent–child neighborhood relation. In each group, there is only one parent node, and all the other nodes are the children of the parent node. The QFSA-MAC protocol firstly starts the group formation from the sink node. Each sector of sink node is related with a different group, and each member of these groups is the children of the sink node. In the second phase of the group creation, new smaller groups are created considering the sectors of child nodes. For instance, if a child node *C* is not inside in a group for each of its sector and has a child node communicated with C over a sector, the node in this sector and the node *C* create a group. This process continues from parents to child nodes until all of each sector of all nodes are included in a group. Figure 5.4, illustrates this process for node *C*. Because sector 1 of the *C* is already included in a group named as group 1, other sectors of the node *C* form additional groups including groups 2 and 3.

5.4.3 Dynamic Time Slot Assignment

Time slot assignment of the QFSA-MAC protocol algorithm consists of two phases: one is the assignment of time slots to the constructed groups and the other is the assignment of time slots to the nodes inside the groups. The hop distance of the parent node of each group to the sink node is specified. Then, groups are sorted in descending order according to their distance to the sink node. Groups are sorted in descending order because time slot assignment begins from the farthest group to the sink node. If some groups have the same distance to the sink node, groups that have larger number of child nodes is firstly considered. After the groups are sorted, time slots are assigned to each group inside the sorted group by considering conflicts among the groups. Time slot assignment process continues until time slot is assigned to all the groups. After time schedule assignment of the groups is finished, time slot assignment begins for the nodes inside the groups.

Nodes inside the groups are scheduled while considering interference between the sensor nodes. Algorithm 5.3 shows how time slots are assigned to the sensor nodes. The main purpose of this algorithm is assigning the least number of time slot to each node while preventing interference for reducing time schedule length. Firstly, the node inside a group is marked as current visited node. Time slots of children and siblings of the nodes are controlled before assigning the time slot to the node for providing interference-free time slot assignment. If its children and the siblings do not have the same time slot, time slot is assigned to the node; otherwise, time slot is increased by 1 and assigned to the node. In each iteration, time slot (named as *preAssigned* in Algorithm 5.2) is set to 1 to minimize the schedule length and to increase the slot reuse if it does not cause interference when assigned to a node. Furthermore, the preassigned group schedules can be also changed in this algorithm because it reorganizes all the nodes that can be parents of the groups for scheduling all the nodes and for constructing complete node schedule matrix.

Algorithm 5.2: QFSA-MAC time slot assignment and contention avoidance algorithm

Input: *sg* (*sorted groups*)

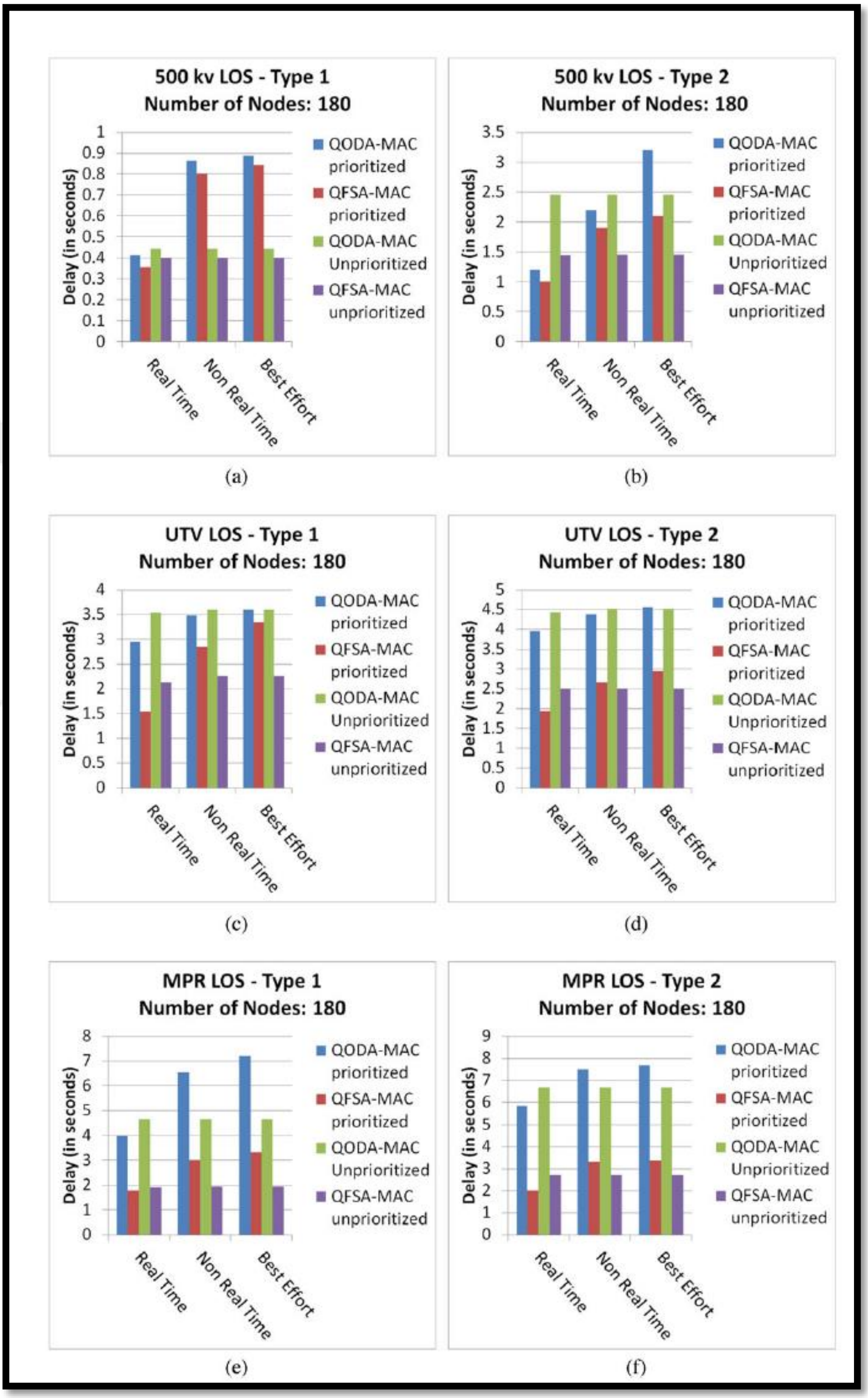
Output: Computed *nodeScheduleMatrix*

```
Initialization
preassigned ← 1
nodeScheduleMatrix ← empty matrix with size of number of nodes
childrenOfNode ← find children of the current visited node
siblingsOfNode ← find siblings of te current visited node
for g ← 1, sg do
  for node ← 1 , g do
      preAssigned ← 1
      currentVisitedNode ← node
      for c ← 1 , childrenOfNode do
          if  timeslot of c = = preassigned then
              preAssigned ← preAssigned + 1
      for s ← 1, siblingsOfNode do
          if timeslot of s == preassigned and s ≠ currentVisitedNode then
              preAssigned ← preAssigned +1
       nodeScheduleMatrix (currentVisitedNode) ← preAssigned
```

5.4.4 Quality of Service - Aware Data Transmission

After time slots are assigned to all the nodes, data transmission phase starts. In this phase, a node makes transmission in its own schedule by turning on its corresponding sector and enters sleeping mode by turning off its antenna in other times until its time schedule begins. When the node is active, it can communicate only one of its sectors at a given schedule. In addition, received packets from other sectors of the node are buffered and sent when the time slot of the corresponding sector comes.

Figure 5.5: Comparative average source to sink packet delay of all the protocols for two types of traffic in different smart grid environments



The QFSA-MAC protocol has two modes of operation; one is sending all type of packets without service differentiation and the other is assigning the priorities of the packets according to their traffic class for providing QoS provisioning. These modes of the QFSA-MAC protocol are described as follows:

Unprioritized QFSA-MAC: In the literature, sectored antennas have been used to increase the performance of WSNs (Felemban and et al. (2010)). However, until this time, no study utilizing the benefits of sectored antennas for smart grid applications for QoS-aware communication has been proposed. Within this context, the QFSA-MAC protocol is the first protocol wherein the sensor nodes are equipped with sectored antennas and deployed in a smart grid communication environment. Furthermore, studies about the sectored antennas or the directional antennas (Felemban and et al. (2010), Cho and et al. (2006)) also do not consider the impact of periodic data generation and different traffic types (low/high load traffic) on the performance of WSNs. However, the QFSA-MAC protocol takes into consideration all of these issues because they are important for providing QoS requirements of smart grid applications.

The QFSA-MAC protocol categorizes the packets into three different classes, RT, NRT, and BE, and generates each class of the packets in different times; an example scenario is shown in Table 5.2. Because the RT packets are generated in an emergency situation, these types of packets are generated more frequently than the other types to inform the central point as quickly as possible. For instance, when the AMI application of the smart grid is considered, it continuously monitors the system and rarely sends the control packets and auxiliary packets about the system situation. However, in case of emergency, it generates time-critical emergency packets and immediately sends them to utilities. Therefore, the QFSA-MAC protocol considers the real-world conditions by generating different packet types in variable traffic loads.

The QFSA-MAC protocol without service differentiation has the same flow with QFSA-MAC with service differentiation until it enters the data forwarding phase. It firstly measures the PRRs of the nodes, defines the sectors and their relations between the other nodes, then constructs the routing tree using CMST with PRR algorithm. After it constructs the routing tee, it forms the groups using the neighborhood information and assigns the time slot to each nodes and their each sector by considering the interference among the nodes. However, the QFSA-MAC without service differentiation does not prioritize the packets according to their QoS requirements. It forwards the packets towards the sink node when the schedule of the node comes on one of its sector. Therefore, it is not as efficient as the QFSA-MAC with service differentiation mode for providing the QoS requirements of time-sensitive smart grid applications.

The QFSA-MAC with service differentiation: In the literature, many protocols based on the QoS-aware with service differentiation have been proposed for smart grids, but none of them do not use the sectored antennas with service differentiation together. Therefore, the QFSA-MAC protocol with service differentiation is the first protocol that prioritize the packets according to their traffic class by utilizing the sectored antennas for smart grid applications. In this way, QFSA-MAC with service differentiation benefits from all the advantages of sectored antennas such as power efficiency and delay reduction to provide QoS provisioning.

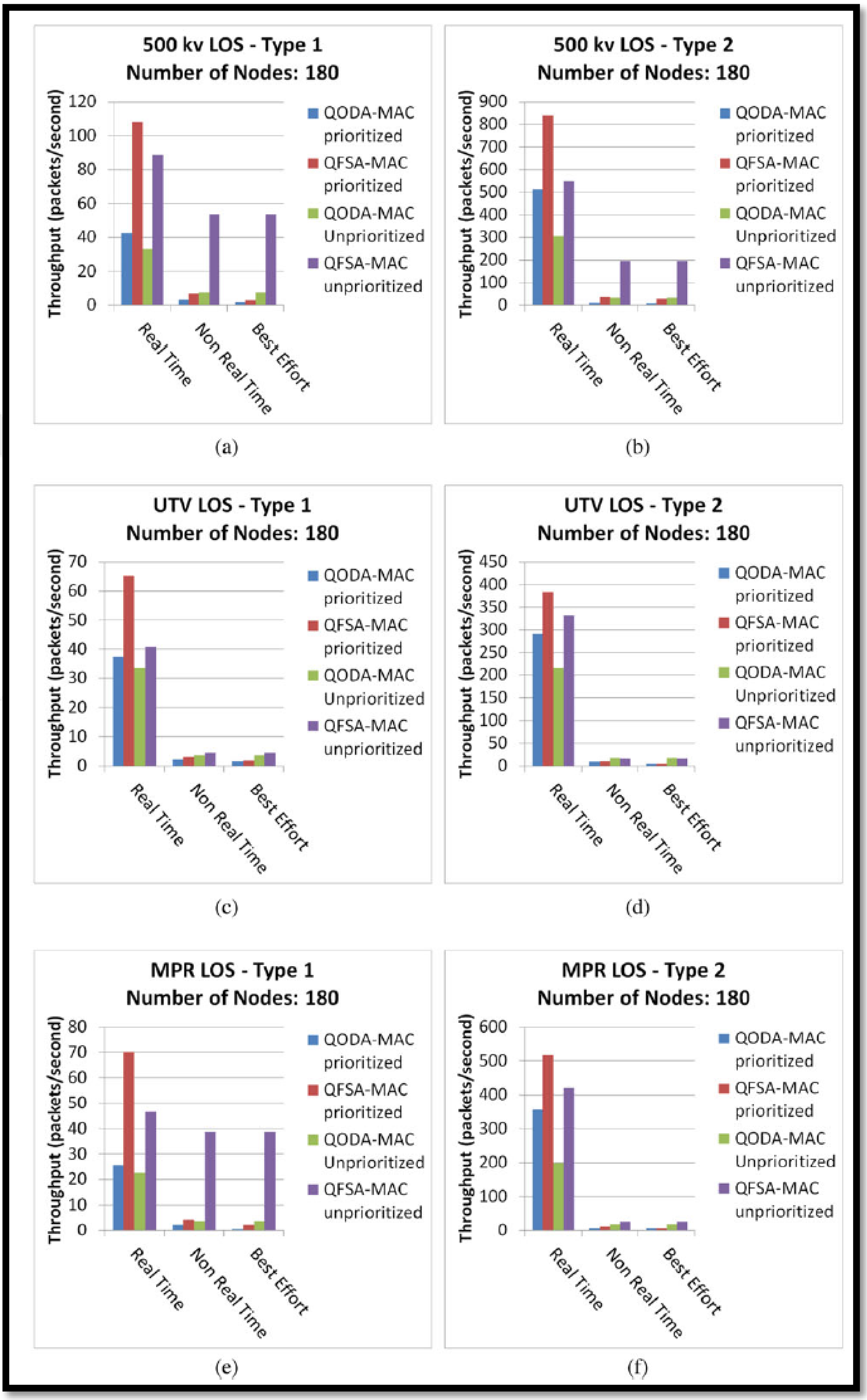
Figure 5.3 shows the flow chart operation of the QFSA-MAC protocol with service differentiation. Same as the QFSA-MAC protocol without service differentiation, it firstly measures the PRR values of each node, defines the sectors and relations of the nodes, and constructs the routing tree. Then, groups in which each consists of a parent node, child nodes and their sectors, which are the sectors of the nodes used for communication with their parent, are created. After the groups are formed, time slots are assigned to all groups and the nodes inside the groups by considering interference among the nodes and conflicts between the groups. Afterwards, the data forwarding phase of QFSA-MAC protocol with service differentiation starts. Firstly, the PRR value between the node and its parent is controlled. If the PRR value among the node and its parent exceeds a threshold, the node initially sends the RT packets towards to its parents or the sink node if the node is a child of the sink node; otherwise, the node sends the NRT packets if all the RT packets are sent. When the node transmits all the RT and NRT packets, it sends the least time-critical BE packets last. In this way, the QFSAMAC protocol with service differentiation sends the time-critical RT packets faster than the NRT and BE packets and meets requirements of different traffic classes.

5.5 APPLICATION SCENARIO AND SIMULATION PARAMETERS

5.5.1 Application Scenario

The QoS requirements of WSN-based smart grid applications described in detail in (Gungor and et al. (2013)) vary in terms of delay, reliability, and data rate, which are explained in (Shah and et al. (2013)). We choose the AMI WSN-based smart grid application as an example scenario because low latency and higher bandwidths are important for some AMI applications such as real-time metering application. AMI enables two-way communication between the utilities and the meters and is an integrated system of smart meters, data management systems, and communication networks (Gungor and et al. (2013)). In this way, it provides the participation of not all the collected or distributed information is important for the application. Some of the packets are control packets including environment information such as vibration, and some of them are auxiliary packets including location information of the sensor nodes. Accordingly, first traffic class is the metering packets, which are the most prioritized packets to be scheduled for relaying packets towards the sink node, transmitted by our network. Second priority is given to control packets because these packets are the periodic packets and less important than the metering packets. Auxiliary control packets, which forms the third traffic class, are transmitted by the network. As a result, we categorize the packets into three traffic classes, which are BE, NRT, and RT, in the order of least to high priorities. All types of packets are generated periodically according to their generation time that is shown in Table 5.2. For instance, in Type 1, each node generates two RT packets in every second and NRT/BE packets in every 12 s. This is a real-world scenario because packets interarrival times vary according to condition of the network in the AMI application. Furthermore, higher traffic load, Type 2, is also presented to the network to analyze the performance of proposed algorithms by increasing the number of packets and reducing interarrival times of each traffic class. We will use this application scenario for evaluating the performance of QODA-MAC and QFSA-MAC.

Figure 5.6: Comparative average throughput of all the protocols for two types of traffic in different smart grid environments



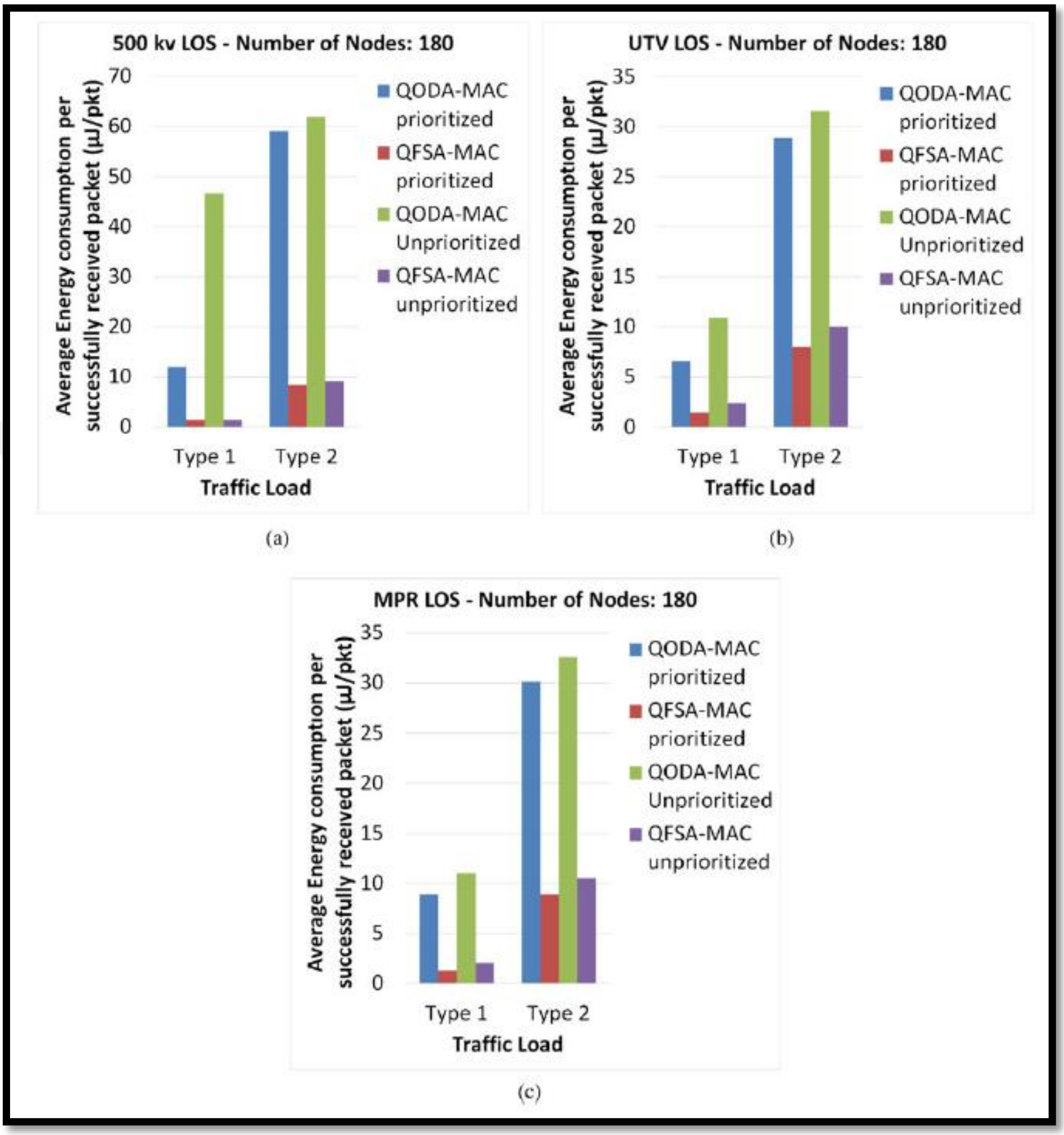
5.5.2 Simulation Parameters

In this study, extensive simulations of the proposed protocols, QODA-MAC and QFSA-MAC, have been performed by using Matlab (MathWorks in Natick, Massachusetts, USA) environment. Simulations have been performed 100 times with different seeds in different smart grid environments (Gungor and et al. (2010)). Log-normal shadowing model is used for making the simulations more realistic by using parameters shown in Table 3.2. Square shape area, 200 x 200 m^2 is used in the simulations. The payload of the sensor data is 50 bytes. The number of nodes in the network is 180 nodes unless otherwise specified. Deployed sensor nodes are equipped with two types of antennas: one is an omnidirectional antenna utilized by the QODA-MAC protocol and the other is a sectored antenna used by the QFSAMAC protocol. We are inspired with the work in (Felemban and et al. (2010)) that uses four-sectored antennas and proves that it provides the lowest of slot needed, and therefore, we use the four sectors in our sectored antennas. High and low traffic loads presented in Table 5.2 are offered to the network to evaluate the performance of the proposed protocols under different traffic loads. Because QODA-MAC and QFSA-MAC have routing capability, CMST with PRR routing tree algorithm is used as the routing protocol, and the significant parameters, which are used in the simulations, are shown in Table 5.3.

Table 5.3: Simulation parameters

Number of Nodes	180
Size of the topology	200 x 200 m^2
Radio propagation model	Log-normal shadowing model
Algorithms	QODA-MAC, QFSA-MAC
Antenna models	Omnidirectional antenna, sectored antenna
Number of sectors	4
Distance between the nodes	Randomly distributed
Modulation	Non-coherent frequency shift keying
Encoding	Manchester
Output power	4.0 dBm
Noise floor	-93.0 dBm
Asymmetry	Symmetric links
Topology	Random

Figure 5.7: Comparative average energy consumption of all the protocols for two types of traffic in different smart grid environments



Performance evaluations have been carried out to evaluate the performance of QODA-MAC and QFSA-MAC protocols according to different performance metrics. The performance metrics utilized during the simulations are the end-to-end delay, throughput, and average energy consumption. Delay is the elapsed time for transmission of packets from a source node to the sink, Throughput is the number of delivered packets in a specified amount of time, and average energy consumption is the energy consumption of the protocols for each successfully transmitted packet at the sink node.

5.6 PERFORMANCE EVALUATION

In this section, performance analysis of the QODA-MAC and QFSA-MAC protocols is provided. The analysis includes comparison of the all modes (with/without prioritization) of QODA-MAC protocol running on omnidirectional with the QFSA-MAC protocol on sectored antennas for varying data generation rates and traffic loads. The simulations have been performed in different smart grid environments such as 500 kV substation, underground transformer vault, and main power room, where the parameters path loss and shadowing deviation have been obtained from (Gungor and et al. (2010)).

Fast data transmission from sensor nodes to the sink node is crucial for RT applications. Therefore, this is the primary goal of our proposed MAC protocols including QODA-MAC and QFSA-MAC. Each proposed protocol has two types of modes: one prioritizes the packets and sends them according to their QoS requirements and the other prioritizes the packets and transmits them without giving precedence. Within this context, comparative analysis has been carried out for all modes of MAC protocols for showing their efficiency with and without service differentiation. Furthermore, performance of the algorithms is measured for two different traffic loads, low load (type 1) and high load (type 2), shown in Table 5.2.

Figure 5.5 shows the average end-to-end delay for all protocols. Prioritized QFSA-MAC protocol reduces end-to-end delay and achieves fast data transmission for all traffic classes when compared with prioritized/unprioritized QODA-MAC protocol and unprioritized QFSA-MAC protocol for all traffic classes. Delay performance of prioritized QODA-MAC protocol is better than the unprioritized QODA-MAC protocol shown in Figure 5.5 for RT traffic for all traffic loads. On the other hand, unprioritized QFSA-MAC protocol achieves lower delay for all RT, NRT, and BE traffic classes in all traffic loads. This means that all modes of QFSA-MAC protocol is more efficient than the modes of QODA-MAC protocol for time-critical or non-time-critical smart grid applications because the QFSA-MAC protocol utilizes the spatial reuse capability of the directional antennas and in this way, reduces the end-to-end delay. When the traffic load increases from low load (type 1) to high load (type 2), end-to-end delay of QFSA-MAC and QODA-MAC protocol increases because the number of generated and sending packets of all traffic classes increases too. Delay of NRT and BE traffic classes decreases when QODA-MAC and QFSA-MAC are in the unprioritized mode because no precedence is given to packet types. However, their delay is still higher than the RT traffic class in unprioritized mode of the protocols because interarrival time of the RT packets is smaller than them. As a result of the delay measurements of the protocols performed in different smart grid environments, 500 kV substation, underground transformer vault, and main power room, we observed that the lowest delay is achieved by all the proposed protocols in 500 kV substation smart grid environment as shown in Figure 5.5a and 5.5b.

Figure 5.6 shows the throughput of all the protocols in various smart grid environments. Throughput is based on the delivery ratio and inversely proportional to the delay. Because the delay performance of the prioritized QFSA-MAC protocol is better than its unprioritized mode and all the modes of the QODA-MAC protocol for RT traffic class, it has the highest throughput in all different smart grid environments, which is an advantage of the spatial reuse provided by the sectored antenna. On the other hand, for the NRT and BE traffic classes, unprioritized QFSA-MAC protocol achieves better performance than the others because it does not give precedence to RT packets and fairly sends all types of packet with minimum latency. Throughput of RT packets is higher than the throughput NRT and BE packets because sensor nodes more frequently generate the RT packets and their interarrival times are smaller than the other packet types. Furthermore, we also observed that although the prioritized QODA-MAC protocol gives precedence to RT packets, throughput performance of unprioritized QFSA-MAC protocol is better than it for all the traffic classes in terms of RT, NRT, and BE. This is because unprioritized QFSA-MAC protocol provides high packet delivery ratio by minimizing interference and packet collisions in the shared medium while utilizing the dynamic TDMA medium access protocol.

Average energy consumption for each successfully received packet at the sink node of the protocols is compared in Figure 5.7. It is seen that prioritized QFSA-MAC protocol consumes notable less energy than all modes of the OQDA-MAC protocol for all traffic loads. This is because of the dynamic nature of the QFSA-MAC protocol where it allocates the time slots dynamically and avoids waste of energy by waiting for other nodes. It is also shown that energy efficiency of all protocols increases when they are in prioritized mode. The reason behind is that the sink node receives more packets with low delay when the protocols are in prioritized mode as shown in Figures 5.5 and 5.6. Furthermore, we observed that unprioritized QODA-MAC protocol shows the worst performance because it uses TDMA-based MAC protocol in which the nodes wait for their slots in making transmission and consume energy during waiting time.

In summary, as shown in the results, the QFSA-MAC protocol is proven to outperform the QODA-MAC protocol because the QFSA-MAC protocol takes the advantage of sectored antennas. Sectored antennas strengthens the receiver power and reduces variance of fading rate. Furthermore, sectored antennas also extend the range for reaching far-away nodes, and their power requirements are less than the omnidirectional antennas in covering the same range. Because of these benefits of sectored antennas, the number of transmitted packets increases with low delay and less energy in the QFSA-MAC protocol. In this way, the QFSA-MAC protocol overcomes several challenges such as application-specific QoS requirements and variable channel capacity (Akyildiz and et al. (2007)) that influence the design of WSNs. Furthermore, the QFSA-MAC protocol yields many open research issues (Cesana and Fratta (2006)) with accurate delay modeling and suitable utility functions. From the simulations, the following results can be obtained:

a. Prioritized QFSA-MAC protocol achieves better performance than either unprioritized QFSAMAC or all modes of the QODA-MAC protocol.
b. Compared with prioritized QODA-MAC protocol, which utilizes the omnidirectional antenna, prioritized QFSA-MAC protocol can effectively allocate the limited wireless channel resources of RT traffic, which is the reason why the performance of RT packet is better, but NRT and BE packets are worse than unprioritized QFSA-MAC protocol.
c. Compared with the prioritized and unprioritized QODA-MAC protocol, unprioritized QFSAMAC protocol realized better throughput, delay, and energy performance.
d. As a result of the simulations, prioritized QFSA-MAC protocol achieves QoS provisioning for time-critical smart grid applications by exploiting the spatial reuse and collision avoidance capabilities of sectored antennas.

5.7 DISCUSSION

In this chapter, we propose QODA-MAC and QFSA-MAC, two new priority-based and QoS-aware MAC protocols that coordinate the medium access based on the traffic class with efficient service differentiation mechanism to support QoS for smart grid applications. In the first scheme, named QODA-MAC protocol, sensor nodes are equipped with omnidirectional antennas and assign the time slots by considering the interference and channel conditions. On the other hand, the second approach, named QFSA-MAC protocol, uses sectored antennas and dynamically assigns the time slots as opposed to the QODA-MAC protocol. Both QODA-MAC and QFSA-MAC protocols have two types of mode in terms of prioritized and unprioritized. The comparative performance evaluations of proposed MAC protocols have been carried out, and our results reveal that all modes of QFSA-MAC protocol outperform QODA-MAC by providing lower latencies and higher throughput with less energy consumption in all smart grid environments. Furthermore, results also show that prioritized QFSA-MAC protocol successfully satisfies the QoS requirements of smart grid applications.

6. PERFORMANCE ANALYSIS OF HAMMING CODE FOR WSN-BASED SMART GRID APPLICATIONS

6.1 INTRODUCTION

Smart grid can be considered as the modern power grid integrating electrical networks and information technologies. The basic components and technologies of a smart grid can be listed as: smart production, smart stations, smart deployment, smart meters, integrated communication and advanced control methods (Fadel and et al. (2015), Fan and et al. (2013), Gungor and et al. (2013), Yan and et al. (2013), Gungor and et al. (2010)). With these components and technologies, a smart grid provides many benefits, such as demand management, greater integration of renewable resources, efficient usage of renewable resources (both production and consumption side), energy saving and price advantage, and system balance (Bjelica and Pejovic (2017), Turan and Gökalp (2016), Janjic and et al. (2015), Fang and et al. (2012), Depuru and et al. (2011), Gungor and et al. (2011), Gungor and et al. (2010)) All of these benefits can be achieved with a reliable communication infrastructure. Therefore, error detection and correction becomes a critical issue for a Wireless Sensor Network (WSN)-based smart grid communication network. However, providing reliable communication between consumers and utilities in a smart grid communication environment is difficult due to harsh channel conditions, such as noise, path loss, fading and shadowing (Okeke and Eng (2015), Usman and Shami (2013), Gungor and et al. (2011), Gungor and et al. (2010)).

Although there exist few performance comparisons of error detection and correction codes for WSNs, these studies, which have been already described in Section 2.5, have not focused on WSN-based smart grid applications and their communication environments. Therefore, in this chapter, the performance of Hamming code with various modulation techniques, such as FSK, DPSK, OQPSK and BPSK, is measured in terms of throughput, BER, and delay in a 500kV LOS substation smart grid environment. Multi-channel scheduling and a LQ-CMST routing algorithm are used to transmit data from sender to sink node (Yigit and et al. (2016)). Therefore, the impact of multiple channels on the performance of Hamming code using different modulation techniques is also measured. In addition, the performance evaluation of Hamming code with OQPSK modulation is also conducted by varying packet size and output power to show how these aspects affect the performance of Hamming code with OQPSK modulation. Furthermore, our objective is to indicate if one of the modulation techniques involving Hamming code should be favored for smart grid communication environments when multi-channel scheduling is used.

Overall, the main contribution of this study is to investigate the performance of Hamming code with different modulation techniques, such as FSK, DPSK, OQPSK and BPSK, and to quantify how multi-channel communication combined with LQ-CMST routing protocol will affect the performance of Hamming code in terms of throughput, BER, and delay under harsh conditions of 500kV LOS substation smart grid environment.

The remainder of this chapter is organized as follows: In Section 6.2, Hamming code is described in detail. In Section 6.3, materials and models are explained. Performance analysis and simulation results are clarified in Section 6.4. The discussion of simulation results is presented in Section 6.5. Finally, the chapter is concluded in Section 6.6.

6.2 HAMMING CODE

Hamming code was the first FEC coding technique in existence and was invented by Richard Hamming in 1940 (Okeke and Eng (2015)). FEC is an error control technique used to transmit data through unreliable communication channels. The main purpose of FEC is to encode messages by using an ECC. FEC coding techniques are classified as block codes and convolutional codes (Manzoor and et al. (2013), Vuran and Akyildiz (2009)). The Hamming coding system is a kind of binary block code method used in telecommunications (Wicker 1995). With the Hamming coding method, single bit errors in a data packet can be found and corrected. Three bit errors are also detected using this method, but these errors cannot be corrected. Hamming codes are expressed as shown in Equations 6.1, 6.2, 6.3, and 6.4.

$$Code\ word\ length: n = 2^m - 1, for\ m \geq 2 \quad \textbf{(6.1)}$$

$$\#\ of\ information\ bits: k = 2^m - m - 1 \quad \textbf{(6.2)}$$

$$\#\ of\ parity\ bits: n - k = m \quad \textbf{(6.3)}$$

$$\#\ of\ error\ correction\ bits: t = 1 \quad \textbf{(6.4)}$$

6.2.1 Hamming Encoder

A Hamming encoder block encodes the information bits before transmission through the channel. In this study, Hamming (7, 4) code is used. This means that the code word length is 7 ($n = 7$) and the size of information bits and parity check bits is 4 ($k = 4$) and 3 ($m = 3$), respectively. First, the information bits (I_1, I_2, I_3, I_4) of length k bits is encoded by adding three parity bits (P_1, P_2, P_3) to form the code word (C) over the elements of a Galois Finite Field $GF(2^m)$. Next, d matrices, which are $k \times 1$ column vectors, as shown in Equation 6.5, are used to form the parity matrices (Malode and Patil (2010), Fu and Ampadu (2009), Moon 2005). As shown in Equations 6.6, 6.7 and 6.8, parity matrices (P_1, P_2, and P_3) are formed by adding d matrices.

$$d_1 = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}, d_2 = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}, d_3 = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}, d_4 = \begin{bmatrix}0\\0\\0\\1\end{bmatrix} \quad \textbf{(6.5)}$$

$$P_1 = d_2 + d_3 + d_4, where\ P_1 = \begin{bmatrix}0\\1\\1\\1\end{bmatrix} \quad \textbf{(6.6)}$$

$$P_2 = d_1 + d_3 + d_4,\ \text{where}\ P_2 = \begin{bmatrix}1\\0\\1\\1\end{bmatrix} \quad \textbf{(6.7)}$$

$$P_3 = d_1 + d_2 + d_4, \text{ where } P_3 = \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \end{bmatrix} \quad \textbf{(6.8)}$$

Information bits and parity bits can be mixed together in different ways (Mstafa and Elleithy (2014)). In this study, parity bits are put at the beginning of information bits. Hamming codes are linear block codes. Therefore, two matrices, which are parity-check matrix *H* and generator matrix G, are used. The information bits (*I*) are multiplied by the *G* matrix to obtain the code word (*C*). In Equation 6.9, the encoding equation and *G* matrix used in this study are shown.

$$C = I \times G, \text{ where } G = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix} \quad \textbf{(6.9)}$$

6.2.2 Hamming Decoder

A parity check matrix is used in the decoding process. The parity check matrix used in this study is shown in Equation 6.10. The received code word (*C*) of 7 bits (information bits (*K*) + parity bits (*H*)) is multiplied by the transpose of the parity check matrix H as shown in Equation 6.11 to obtain the syndrome vector (*S*). This shows whether or not an error occurs. If an error occurs (Howard and et al. (2006), Hamming 1980) it indicates that there is an error for a particular code word bit. If all the bits of the syndrome vector are zero, this means that the data has not been corrupted during transmission. However, if one of the data bits is corrupted due to bad channel conditions such as a noisy channel, the syndrome vector shows the place of the error in the code word bit. For instance, if the code word *C = 1011010* is received without any errors, the syndrome matrix will become *S = (0, 0, 0).* However, if the code word is received with an error, such as *C = 1011011,* the syndrome matrix will become *S = (1, 1, 1).* This means that the 7^{th} bit of code word is corrupted. If the 7^{th} bit of the corrupted code word is *1,* it is changed to *0* and the corrected code word is obtained. The last four bits are the original information bits and the first three bits are ignored.

$$H=\begin{bmatrix}1 & 0 & 0 & 0 & 1 & 1 & 1\\ 0 & 1 & 0 & 1 & 0 & 1 & 1\\ 0 & 0 & 1 & 1 & 1 & 0 & 1\end{bmatrix} \quad \textbf{(6.10)}$$

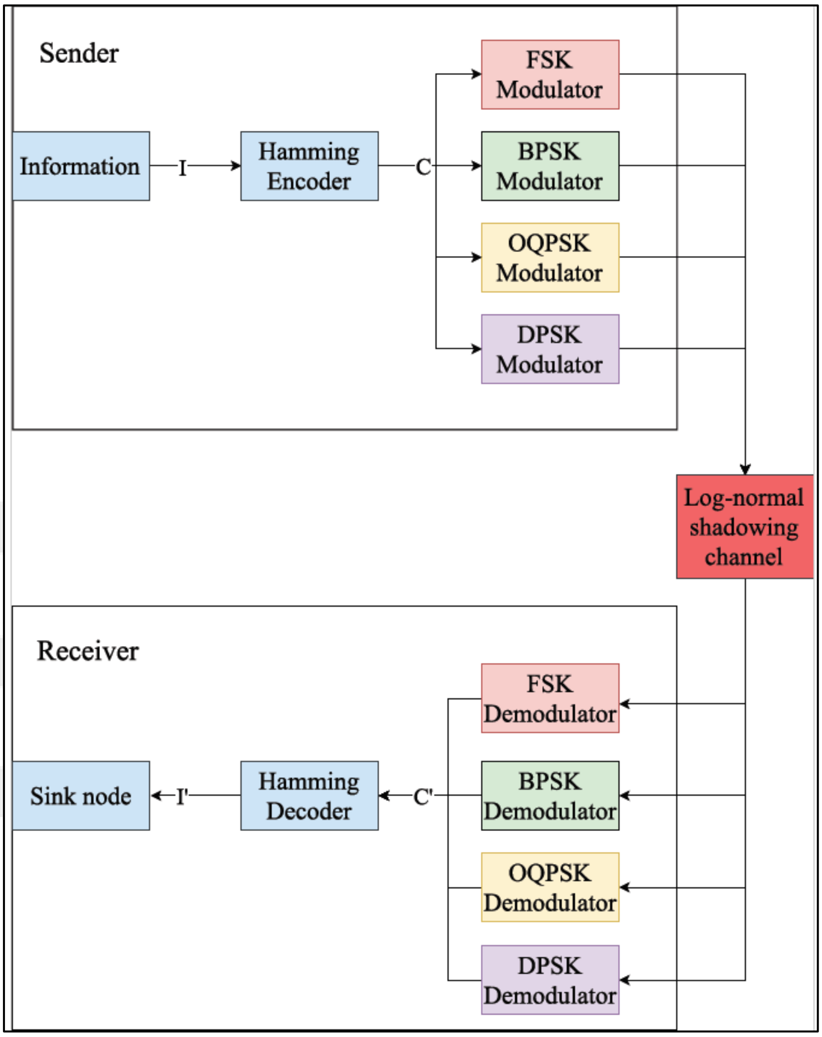
$$S = C \times H^T, where\ H^T = \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 1 & 1\\ 1 & 0 & 1\\ 1 & 1 & 0\\ 1 & 1 & 1\end{bmatrix} \quad \textbf{(6.11)}$$

6.3 MATERIALS AND METHODS

6.3.1 System Model

The K number of information bits (*I*) is given as an input to the Hamming encoder. The Hamming encoder takes these bits and encodes them as described in Section 6.2.1 to obtain the code word (*C*). The code word is passed to the digital modulator, which uses one of the modulation schemes, such as FSK, BPSK, OQPSK and DPSK, to transform the information bits into digital waveforms. After the modulation, the information bits are sent through the log-normal shadowing channel, which incorporates harsh channel conditions, such as noise, scattering, reflection and diffraction. These channel conditions can affect and corrupt the code word. After transmission of the code word over the channel finishes, it is demodulated by the demodulator using one of the FSK, BPSK, OQPSK, and DPSK demodulation schemes. The demodulated code word (*C'*) is then sent to the Hamming decoder to decode the code word into the original information bits (*I'*). Decoded information bits (*I'*) are controlled, and if there is no error, it is received by the sink node. The block diagram of this system model is shown in Figure 6.1.

Figure 6.1: Block diagram of the system model



6.3.2 Protocol Description

In this study, we modelled a WSN model composed of source nodes, relay nodes and a sink node. We also constructed a graph $G = (V, E)$ for this WSN model; the set of vertexes of this graph is shown as V, which represents the set of nodes. The set of edges of this graph is shown as E, which represents the wireless links. We used half-duplex data transmission, which means that data communication can be done in two directions - from sender to receiver and vice versa, but not at the same time. A RBCA algorithm, which is a MAC protocol, is used, together with the LQ-CMST routing protocol. The LQ-CMST proposed in (Yigit and et al. (2016)) is a routing protocol which considers link qualities (Packet Reception Rate (PRR)) while constructing a routing tree. The RBCA proposed in

(Incel and et al. (2012)) assigns the channels statically to the receivers by considering the interference experienced by the receivers (Yigit and et al. (2014)). After assigning the channels, RBCA makes a time slot assignment by using a TDMA protocol for parallel transmission scheduling, also called multi-channel scheduling, through the multiple branches of the LQ-CMST routing tree.

6.3.3 Channel and PRR Models

A log normal shadowing channel model, which is a radio propagation model that measures the path loss that occurs due to distance and obstructions, is used. The 500kV LOS substation smart grid environment path loss (γ) and shadowing deviation (X_σ) parameters shown in Table 4.1 are used to calculate the log-normal path loss equation, and is explained in Section 3.2.2 in Equation 3.2.

6.4 PERFORMANCE ANALYSIS

In this section, the performance of the Hamming code integrated with the different modulation schemes is evaluated using multi-channel scheduling. Furthermore, the results of the Hamming code are also compared with the results obtained without using any error control codes.

6.4.1 Simulation Parameters

An LQ-CMST routing protocol, multi-channel scheduling algorithm and hamming code were implemented in Matlab, and extensive simulations were conducted by using a Matlab simulation tool. The simulation parameters are shown in Table 6.1. A realistic channel model was used by utilizing a log-normal shadowing model.

In the performance evaluations, 120 nodes are used. These nodes are randomly deployed over a 200 × 200 square meter area. For each simulation, we run the experiments 100 times and an average of the measured results is taken. We assumed that each node generates one packet at the beginning of scheduling. Packets generated by the source nodes are forwarded through multiple hops to the sink node. A best effort delivery model with multi-channel scheduling is assumed. Therefore, no retransmission is done if the packet is lost.

Table 6.1: Simulation parameters

Parameters	Values
Modulation schemes	BPSK, DPSK, OQPSK, FSK
Output power	4 decibel (dB)
Noise floor	-93dB
Number of nodes	120
Size of topology	200 × 200 m^2

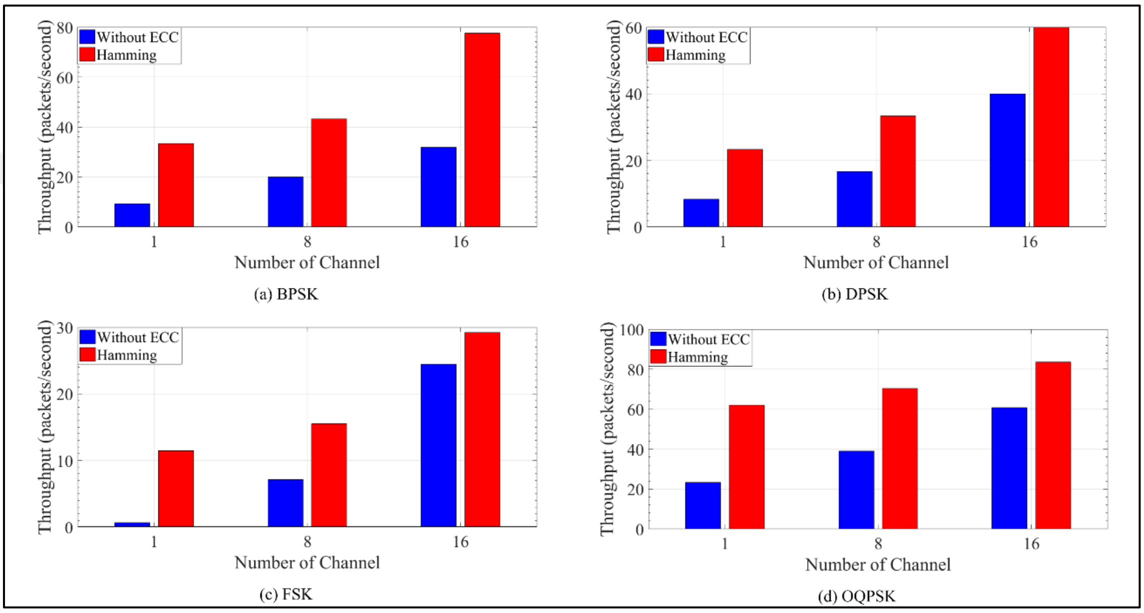
6.4.2 Simulation Results

The performance of the Hamming code integrated with different modulation schemes, such as BPSK, DPSK, FSK and OQPSK, is evaluated and compared with the results obtained without using an error correction code in a 500kV LOS substation smart grid environment. Throughput, delay, and BER are used as performance metrics. Simulations have been done to show how the modulation and number of channels affect the throughput, delay, and BER performance of the Hamming code. Then, the impact of packet size and output power on throughput, delay, and the BER performance of Hamming code, combined with OQPSK modulation, was addressed in a smart grid environment.

Figures 6.2 and 6.3 respectively show the throughput and delay performance of Hamming code and without ECC with varying modulation schemes, such as BPSK, DPSK, FSK, and OQPSK when the number of channels increases. The results show that the throughput of the network increases, and the delay of the network decreases with all of the Hamming code, and without ECC combined with different modulation schemes, when the number of channels increase, as shown in Figures 6.2 and 6.3. This is because multiple channels minimize interference to avoid packet loss, and provide simultaneous transmission to increase the number of packets transmitted to the sink node in a shorter period of time. Figures 6.2 shows that the throughput performance of the Hamming code is better than without ECC. In addition, in Figure 6.2, it is also observed that Hamming code with

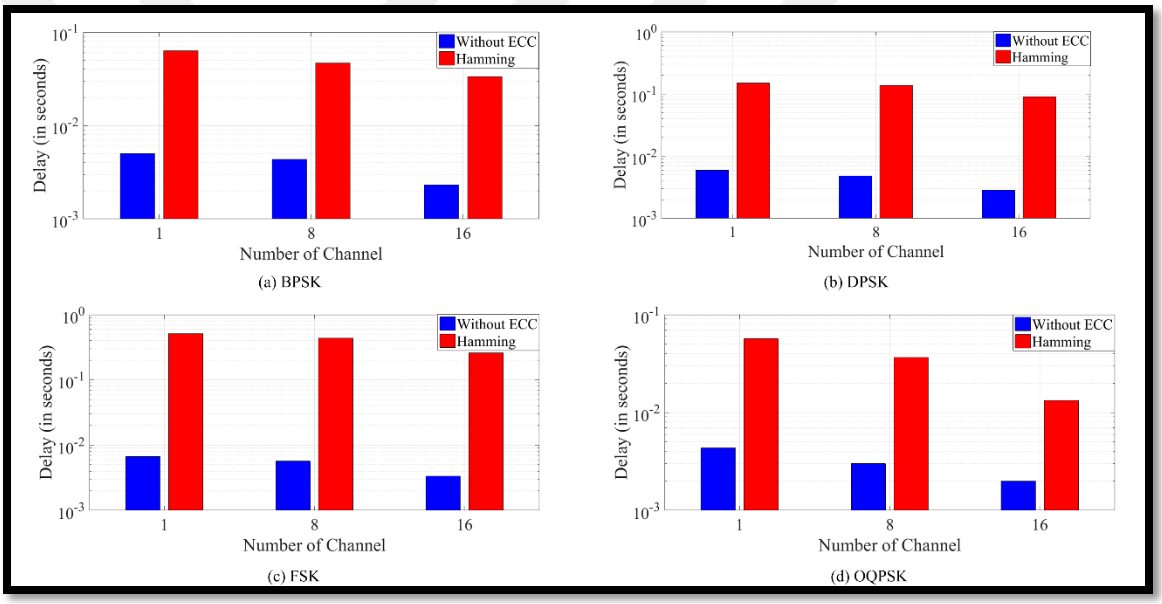
OQPSK modulation shows the best performance in terms of throughput using 16 channels. Figure 6.3 shows that delay performance of Hamming code is worse than without ECC. Furthermore, in Figure 6.3, it is also shown that without ECC with OQPSK modulation shows the best performance in terms of delay when number of channels is 16.

Figure 6.2: Throughput vs. number of channel for log-normal shadowing channel without ECC and Hamming code in 500kV LOS substation smart grid environment



In Figure 6.4, the BER performance of Hamming code and without ECC, is compared in terms of different modulation schemes, and a varying number of channels. It can be seen from this figure that when the number of channels increases, BER decreases for all the cases, such as Hamming code and without ECC combined with different modulation schemes, since the impact of interference is eliminated by multi-channel scheduling. Figure 6.4a shows the BER performance of Hamming code and without ECC with the BPSK modulation. The results show that Hamming code performs better with BER values of 10^{-6}, 10^{-9}, and 10^{-12} for 1, 8, and 16 channels, respectively, than does BER performance without ECC. Figure 6.4b shows the BER results of Hamming code and without ECC, integrated with the DPSK modulation scheme. The graph shows Hamming coded DPSK performs better with the BER values of 10^{-6}, 10^{-8}, and 10^{-9} for 1, 8, and 16 channels than does BER performance without ECC. Figure 6.4c shows the BER values of Hamming code, without ECC, when FSK is used as the modulation scheme. It can be seen from the figure that Hamming coded FSK has smaller BER values, which are 10^{-4}, 10^{-6}, and 10^{-8}, than BER values without ECC. The BER performance of Hamming code, without ECC, with OQPSK modulation is shown in Figure 6.4d. The results obtained show that Hamming code with OQPSK modulation has the lowest BER values of 10^{-8}, 10^{-10}, and 10^{-13} at channels 1, 8, and 16, respectively. As a result, it is also observed that the Hamming code with OQPSK modulation shows the best performance in terms of BER with 16 channels.

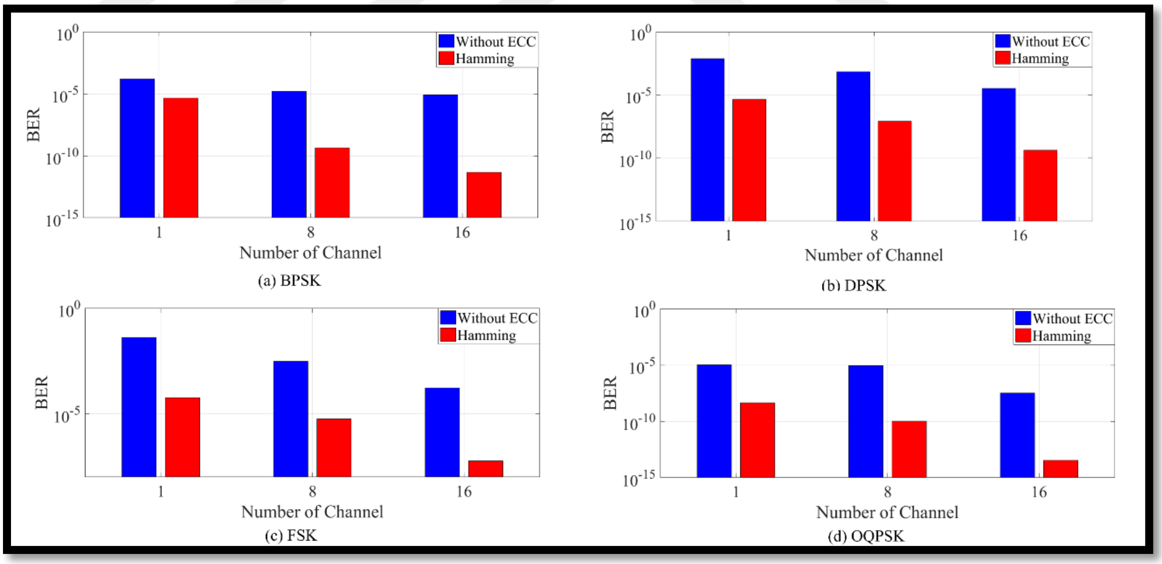
Figure 6.3: Delay vs. number of channel for log-normal shadowing channel without ecc and Hamming code in 500kv los substation smart grid environment



The simulation results show that Hamming code combined with the OQPSK modulation provides the best results for a 500kv LOS substation smart grid environment. For this reason, the performance of Hamming code combined with the OQPSK modulation is also evaluated for various output powers and packet sizes in Figures 6.5 and 6.6 respectively. Figures 6.5a and 6.5b show the BER and delay in terms of the performance of Hamming code with OQPSK modulation for variable output powers and number of channels. These figures show that BER and delay slowly decrease when the output power is more than 4 dBm. Furthermore, the minimum BER and delay results are obtained when the number of channels is 16. Figure 6.5c shows the throughput results of Hamming code with

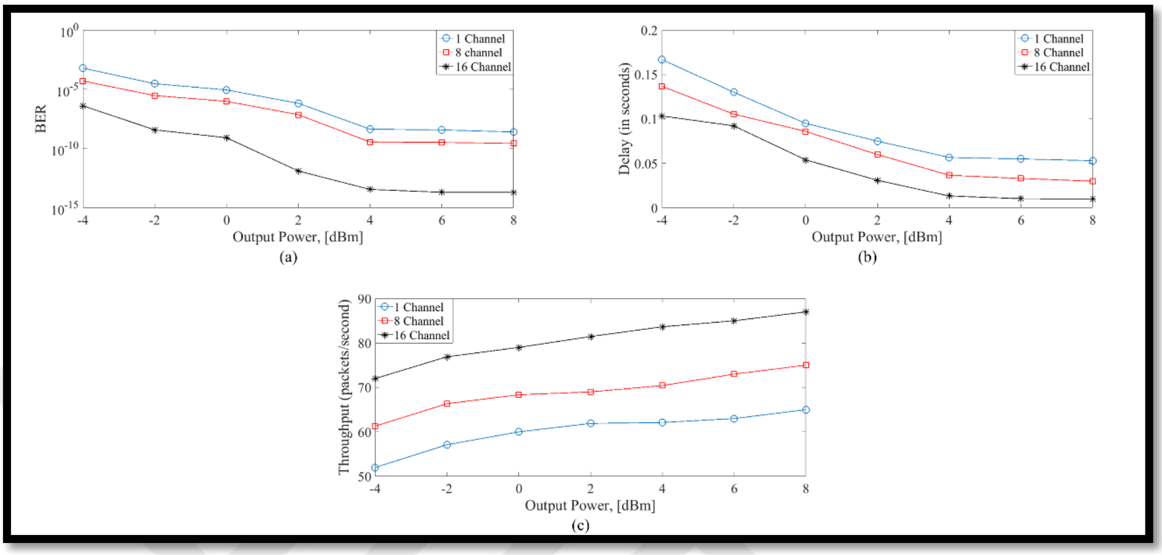
OQPSK modulation for different output powers. The results show that throughput slowly increases when the output power is increasing. In addition, the results also present that the highest throughput is achieved when the number of channels is 16. Figures 6.6a and 6.6b show BER and the delay results of Hamming code with OQPSK modulation for a variable number of channels and packet size. These results show that BER and delay increase as the packet size increases; similarly, the best BER and delay results are obtained when the number of channels increases to 16. Furthermore, it is also observed that delay sharply increases when the packet size is bigger than 180 bytes. This situation also affects the throughput results, as throughput and delay are directly proportional to each other. As shown in Figure 6.6c, throughput sharply decreases when the packet size is bigger than 180 bytes. In addition, Figure 6.6c shows that throughput increases until the packet size reaches 100 bytes and slowly decreases when the packet size is between 100 bytes and 180 bytes.

Figure 6.4: Ber vs. number of channel for log-normal shadowing channel without ecc and hamming code in 500kv los substation smart grid environment



The performance results clearly show that using an error correction code, such as Hamming code, increases performance in terms of BER, throughput and delay in a 500kv LOS substation smart grid environment. In addition, the choice of modulation scheme considerably affects the performance of a smart grid communication system.

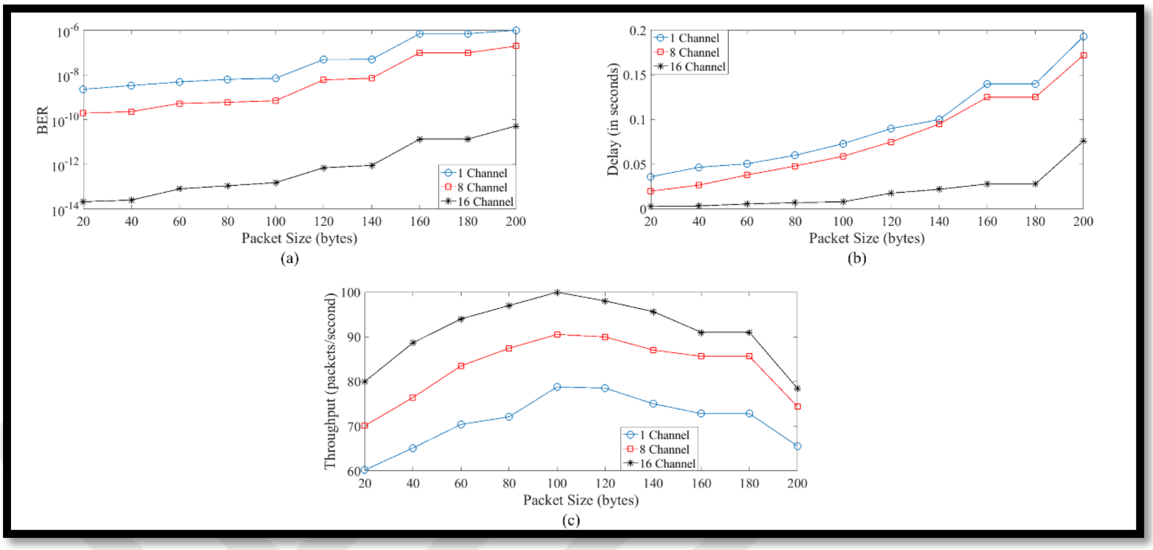
Figure 6.5: Throughput, ber, and delay vs. output power for log-normal shadowing channel using oqpsk with hamming code by increasing number of channel in 500kv los substation smart grid environment



6.5 DISCUSSON OF RESULTS

Examining the simulation results, we found that the Hamming code performed well only for applications which require low BER and high throughput. It minimizes the BER and maximizes the number of received packets compared to without ECC but increases the delay. This is because it adds parity bits, which causes extra overhead, to correct the error and Hamming encoding and decoding also cause additional communication delays. Performance results also show that the modulation scheme significantly affects the performance of Hamming code and without ECC. There also exist other studies (Panicker and Sukesh (2014), El-Nahal and Salha (2013), Kumar and Sharma (2010)) which show the impact of modulation scheme on the communication quality in different network systems. According to these studies, OQPSK modulation scheme outperforms the other modulation schemes similar to our study. This is because OQPSK provides higher data rate compared to BPSK, DPSK, and FSK and for the same bit error rate, the required bandwidth by OQPSK is less than the other modulation schemes.

Figure 6.6: Throughput, ber, and delay vs. packet size for log-normal shadowing channel using oqpsk with hamming code by increasing number of channel in 500kv los substation smart grid environment



The impact of multi-channel scheduling and LQ-CMST routing on the performance of Hamming code are also evaluated. All the results show that network performance improves when multi-channel scheduling is used since multi-channel communication minimizes the impact of interference by achieving simultaneous transmission over multiple channels.

The performance of Hamming code combined with OQPSK modulation is also evaluated for different packet sizes and various output powers for WSNs in 500kV LOS substation smart grid environment. We observe that when the output power increases, performance of Hamming code improves. This is because high output power increases the reliability of the network by decreasing number of packet losses as expected. On the other hand, the same result cannot be obtained with the increasing of packet size. High packet size affects adversely the delay and BER performance of Hamming code combined with OQPSK modulation. Therefore, although throughput increases until the packet size reaches 100 bytes, packet size must be chosen carefully according to applications' requirements in 500kV LOS substation smart grid environment.

Overall, our main contribution has been to investigate the performance of Hamming code with different modulation schemes in a 500kv LOS substation smart grid environment, and to measure the impact of multi-channel scheduling on the performance of Hamming code. To the best of our knowledge, no existing study has evaluated the performance of Hamming code with different modulation schemes, and with a varying number of channels in a 500kv LOS substation smart grid environment. Hence, we expect that this study will provide valuable insights into the development of error correction codes combined with different modulation schemes in a smart grid environment.

7. A NEW EFFICIENT ERROR CONTROL ALGORITHM FOR WIRELESS SENSOR NETWORKS IN SMART GRID

7.1 INTRODUCTION

The smart grid is a modern electric power system that provides power efficiency by integrating novel technologies including new energy management techniques and new metering and sensing technologies into the traditional power grid (Zeng and et al. (2012)). Providing reliable communication links between the electric power utilities and consumers is an important issue of the smart grid. Robust communication can be achieved if the data is transmitted with no error. However, achieving error-free transmission in WSN based smart grid communication systems is di_cult since communication channels suffer from many factors such as noise, path loss, fading, shadowing, reflection, and diffraction (Akande and et al. (2014)). Therefore, using a proper error control technique is the most crucial issue to minimize the BER with a lower delay in the smart grid applications that are presented in Table 7.1 (Gungor and et al. (2013)) based on their domains, such as generation side, T&D (transmission and distribution) side, and consumer side. Various error control techniques such as forward error FEC are used to achieve reliable and secure data transmission over a channel. In these techniques, data are encoded using various algorithms before transmission, and then the receiver decodes the encoded data to get the original data. The effciency of these error control techniques changes according to the communication channel. Therefore, the performances of these techniques differ even under the same channel conditions.

In the literature, performance comparison of error correcting codes for WSNs is widely done by many authors (Alrajeh and et al. (2015), Leeson and Patel (2015), Okeke and Eng (2015), Akanda and et al. (2014), Islam 2010, Vuran and Akyildiz (2009), Balakrishnan and et al. (2007)). However, performance comparison of error detection and correction codes by combining various modulation techniques for WSN based smart grid communication networks is not available in the literature. In this respect, we first analyzed the performance of Hamming code, using different modulation schemes, in a 500kV LoS (line-of-sight) substation smart grid environment in (Yigit and et al. (2018)). We found that Hamming code with OQPSK modulation demonstrates the best performance. In this chapter, performance comparison of other FEC algorithms such as BCH and RS codes, combined with the modulations including DPSK, FSK, and OQPSK are analyzed and compared for the first time in a WSN-based smart grid communication network. We utilized these ECCs and modulation schemes as ECC and modulation schema since these are well-known codes and schemas, and their performance has been evaluated for WSNs (Akande and et al. (2014), Balakrishnan and et al. (2007)). Our performance evaluations show that they can efficiently improve network performance in terms of throughput and BER. Moreover, BCH and RS codes, and DPSK, FSK, and OQPSK modulation schemas, are easy to implement and their source codes are available for other researchers.

Table 7.1: WSN-based smart grid applications

Application	Domain
Residential energy management	Consumer side
Smart metering	Consumer side
Automated panel management	Consumer side
Building automation	Consumer side
Demand-side load management	Consumer side
Overhead transmission line monitoring	T&D side
Conductor temperature rating system	T&D side
Underground cable system monitoring	T&D side
Outage detection	T&D side
Real-time generation monitoring	Generation side
Remote monitoring of wind and solar turbines	Generation side
Distributed generation	Generation side

A new AEC protocol for WSN-based smart grid applications is also proposed. We used RS codes with OQPSK modulation for our AEC protocol because, according to our previous performance measurements, RS codes with OQPSK modulation give the best result regarding throughput and BER in a 500kV LoS substation smart grid environment. Different RS codes such as RS(39,35), RS(45,35), RS(51,35), RS(57,35), and RS(63,35) were used to change these codes according to channel conditions adaptively. In the first step, AEC assigns the RS codes to the nodes according to the transmission distance between the sender node and its parent, and performs the _rst transmission according to this assignment. This assignment was done based on a look-up table that consisted of the suitable RS codes for each distance range (Pham and et al. (2017)). This look-up table was constructed for many simulations. In the second step, a switching criterion was defined according to the number of ACKs of P previously transmitted packets (Yu and et al. (2012)) that were received inside a window. The packet error rate (PER) of these packets was measured and compared with the predefined threshold to determine whether to switch to a weaker or stronger RS code. A suitable RS code was chosen based on a second look-up table that stored the BER levels of RS codes and the appropriate RS codes that could solve these BER levels. This table was constructed using a heuristic method.

The aim of AEC is to maintain the reliability required by the smart grid application, while balancing the tradeoff between network overhead and reliability. Performance of AEC was analyzed and compared with static RS and without-FEC mechanisms. The simulation results show that the proposed solution can decrease delay by transmitting less redundant bits and obtaining higher throughput than the static RS scheme.

Additionally, LQ-CMST algorithm as well as the multi channel scheduling algorithm were used for data transmission (Yigit and et al. (2016), Yigit and et al. (2014)). Therefore, performance evaluations were also done by varying the number of channels to quantify how multi-channel communication affects the performance of ECCs and AEC in 500kV LoS substation smart grid environment.

Overall, our contributions in this study can be summarized as follows:

a. We performed an in-depth analysis of the performance of RS code, BCH code, and an un-coded channel in terms of throughput, BER, and delay for a WSN-based smart grid application in a 500kV LoS smart grid environment. The impact of multi-channel scheduling and type of modulation scheme on the performance of BCH code, RS code, and un-coded channel were presented.
b. A new AEC scheme was proposed to meet the reliability requirements of WSN-based smart grid applications according to a switching threshold.
c. The AEC controls the channel conditions and switches to a stronger or weaker code when the PERwindow is larger than the threshold. The simulation results reveal that our proposed scheme achieves better delay, throughput, and BER results than the static RS coding strategy. In addition, the impact of multi-channel scheduling on the

performance of AEC was also evaluated. The results show that multi-channel scheduling improves the performance of AEC in terms of delay, throughput, and BER.

d. To the best of our knowledge, there is no study that compares performance of ECCs and proposes a new scheme to detect and correct bit errors for WSN-based smart grid applications. Therefore, studies performed in this work are the first studies to present the comparative performance evaluations of RS and BCH codes, using different modulation schemes, by applying multi-channel scheduling in a 500kV LoS substation smart grid environment. Furthermore, this study is also important since it proposes a new AEC scheme for WSN-based smart grid applications.

The rest of this chapter is organized as follows. The proposed AEC algorithm is described in Section 7.2. The experimental setup, channel and system models are presented in Section 7.3. Performance evaluations are discussed in Section 7.4. Finally, the chapter is concluded in Section 7.5.

7.2 ADAPTIVE ERROR CONTROL ALGORITHM

In this section, we describe our proposed AEC algorithm that uses different RS codes with OQPSK modulation. We prefer to use RS codes with OQPSK modulation since they give the best results according to the simulation results presented in Section 7.4.1. Here, AEC consists of three steps:

a. Initializing the RS codes of nodes;
b. Creating a look-up table using a heuristic model;
c. Switching between the RS codes based on the threshold.

7.2.1 Initializing the RS Codes of Nodes

Our proposed AEC algorithm used different RS codes such as RS(39,35), RS(45,35), RS(51,35), RS(57,35), and RS(63,35). These RS codes were assigned to the nodes according to their distance to their parents. In this respect, we created a look-up table, shown in Table 7.2 that includes which RS code should be used at which distance. The pseudocode, which was used for creating this look-up table, shown in Algorithm 7.1. In this algorithm, firstly, we calculated the distances of the nodes to their parents. Secondly, we normalized the distances because nodes were deployed randomly to a 200 × 200 m^2 area and the distances of the nodes to their parents always changed. To handle this change, we had to normalize the distances between the nodes and their parents. As the normalized distance increased, the RS codes with higher code word values (also with more redundant bits) were used. Then, we grouped these normalized values into five categories depending on our RS values (having five different RS values). Finally, we assigned an RS code to each node, depending on their normalized distance. For instance, RS(39,35) was assigned to a node if the normalized distance of the node was between 0 and 0.22, as shown in Table 7.2.

Table 7.2: RS code according to normalized distance between node and its parent

Normalized distance between node and its parent	RS codes
$0 < d \leq 0.22$ m	RS(39,35)
$0.22 < d \leq 0.34$ m	RS(45,35)
$0.34 < d \leq 0.44$ m	RS(51,35)
$0.44 < d \leq 0.55$ m	RS(57,35)
$0.55 < d \leq 1$ m	RS(63,35)

7.2.2 Creating a Look-up Table with Using a Heuristic Model

Providing an optimal solution for specifying which ECC should be used in which BER level was difficult because of the variable channel conditions of WSNs. Therefore, we proposed a heuristic solution that was based on the greedy scheme to determine which RS code provides better results at which BER level. Simulations were run many times for each RS code, and the BER ranges of these RS codes were found as shown in Table 7.3. Based on the calculated BER, we determined the efficient RS code to find out which RS code could send the packet successfully. As a result of this mechanism, we found which BER range could be corrected in which RS code. For instance, we obtained $10^{-4} \leq BER < 10^{-2}$ BER range when we used RS(39,35) with eight channels; and we saw that RS(57,35) could solve this BER range as shown in Table 7.3. Further, RS(63,35) could also solve this BER range, but we used RS (57,35) to reduce the overhead by sending fewer redundant bits.

Algorithm 7.1: Assigning RS codes according to distance

Input: *pA* (*parentArray*); *nL (nodeList); grpSize (groupSize)*

Output: *assignedInitialFECValues*

1. **for** n ← *1 to nL* **do**
2. myParent ← pA(node);
3. distanceArray(node, myParent) ← calculateEuclideanDistance(node, myParent);
4. **end for**

— Normalized Distance —

5. minDistance ← min(distanceArray);
6. maxDistance ← max(distanceArray);
7. biggestDiffDistance ← maxDistance – minDistance;
8. **for** *nodeIndex* ← *1 to size(distanceArray)* **do**
9. currentNodeDistance ← distanceArray(nodeIndex);
10. normalizedDistance ← (currentNodeDistance - minDistance) / biggestDiffDistance;
11. normalizedDistanceArray (nodeIndex) ← normalizedDistance;
12. **end for**

— Sort Normalized Distance —

13. sortedNormalizedDistanceArray ← sort(normalizedDistanceArray);

— Group Normalized Distance —

14. startIndex ← 0;
15. sliceSize ← (sortedNormalizedDistanceArray / grpSize);
16. remainSize ← mod(sortedNormalizedDistanceArray, grpSize);
17. endIndex ← 0;
18. **for** *groupIndex* ← 1 *to grpSize* **do**
19. **if** *remainSize* ≠ *0* **then**
20. endIndex ← startIndex +1;
21. distanceGroups(groupIndex) ← sortedNormalizedDistanceArray(startIndex + endIndex);

```
22.        remainSize ← remainSize – 1;
23.      else
24.        endIndex ← startIndex +sliceSize;
25.        distanceGroups(groupIndex) ← sortedNormalizedDistanceArray(startIndex,
     endIndex);
26.      end if
27.      startIndex ← endIndex;
28.  end for
       ─ Assign Initial FEC Values ─
```

Table 7.3: BER levels of RS codes and the appropriate RS codes that can solve these BER levels

RS codes	Number of channel	BER_{min} and BER_{max}	Optimal RS code
RS(39,35)	1	$10^{-3} \le BER \le 1$	RS(63,35)
	8	$10^{-4} \le BER < 10^{-2}$	RS(57,35)
		$10^{-2} \le BER \le 1$	RS(63,35)
	16	$10^{-6} \le BER < 10^{-4}$	RS(51,35)
		$10^{-4} \le BER \le 1$	RS(57,35)
RS(45,35)	1	$10^{-7} \le BER < 10^{-5}$	RS(51,35)
		$10^{-5} \le BER \le 1$	RS(57,35)
	8	$10^{-8} \le BER < 10^{-6}$	RS(51,35)
		$10^{-6} \le BER \le 1$	RS(57,35)
	16	$10^{-9} \le BER \le 1$	RS(63,35)
RS(51,35)	1	$10^{-11} \le BER < 10^{-9}$	RS(57,35)
		$10^{-9} \le BER \le 1$	RS(63,35)
	8	$10^{-12} \le BER < 10^{-9}$	RS(57,35)
		$10^{-9} \le BER \le 1$	RS(63,35)
	16	$10^{-14} \le BER \le 1$	RS(57,35)
RS(57,35)	1	$0 \le BER \le 1$	RS(63,35)
	8	$0 \le BER \le 1$	RS(63,35)
	16	$0 \le BER \le 1$	RS(63,35)
RS(63,35)	1	$0 \le BER \le 1$	RS(63,35)
	8	$0 \le BER \le 1$	RS(63,35)
	16	$0 \le BER \le 1$	RS(63,35)

7.2.3 Switching between the RS Codes Based on the Threshold

Changing RS code in each transmission is not an efficient means in wireless channels since the channel conditions are variable. Therefore, we define a switching mechanism with inspiration from (Yu and et al. (2012)). This mechanism is based on the ACKs of S previously transmitted packets received inside a window. The PER inside this window was computed as shown in Equation 7.1 by taking the ratio of ACK packets to the S previously transmitted packets.

$$PER_{window} = 1 - \frac{ACK_S}{S} \quad \textbf{(7.1)}$$

where PER_{window} is the packet error rate within the window, ACK_S is the number of acknowledgments that is received within the window, and S is the number of previously received packets within the window.

To understand the channel conditions correctly, S should neither be too small nor too large. For higher values of S, using the entire history of packet transmission can cause higher BER since outdated history causes indefinite current channel estimation. On the other hand, smaller values of S prompt frequent changes in the RS code. Therefore, in this study, we chose S = 15, as this provided better throughput in 500kV LoS substation smart grid environment. Different switching threshold values such as 0, 0.15, and 0.25 were used in AEC in order to analyze how BER, throughput, and delay changed depending on various threshold levels. Pseudocode of our AEC algorithm is shown in Algorithm 7.2. After initializing the RS code of the nodes, as described in Section 7.2.1, we assigned new RS values according to this algorithm. In this respect, we first calculated PER_{window}, and if PER_{window} was bigger or equal to our predefined threshold value, we looked at our heuristic table, shown in Table 7.3. We iteratively looked at each row of the look-up table and found the current RS code in the table based on the channel. Then, we visited each candidate RS code and controlled the current BER value. If the current BER was between the BER_{MIN} and BER_{MAX} of the candidate RS code, this code was assigned to the node. If there was no BER range that contained the current BER value in our heuristic table, the RS value of the node was not changed. On the other hand, if no error occurred during S transmissions, and if the current RS code was not our first RS code (RS(39,35)), we switched the current RS code to a less powerful RS code (containing less parity bits). Otherwise, if PER_{window} was less than the threshold, we used the same RS value for the next transmission. For instance, assuming that the current RS code of the node was RS(45,35) in channel 1, then the average BER value of S transmissions was 10^{-6}. In this state, AEC assigned the RS(51,35) to the node as a new RS code.

Algorithm 7.2: Assigning RS codes according to threshold and heuristic lookup table

Input: *th* (*threshold*); *pW (perWindow); rs (currentRScode); aRS (allRScodes); h (heuristicLookupTable); ch (channel); ber (currentBERvalue)*

Output: *nRS (nextRScode)*

```
if pW ≥ th then
  for i ← 1 to size of h do
    heuristicItem ← h(i);
    if heuristicItem.channelID == ch AND heuristicItem.RScode == currentRScode
    then
      for i ← 1 to size of aRS(i) do
        possible nRS ← aRS(i);
          if BERmin value of possible nRS < ber AND ber ≤ BERmax value of possible
          nRS then
            nRS ← possible nRS;
          end if
      end for
    end if
  end for
  if nRS is not assigned then
    nRS ← rs;
  end if
else
  if pW == 0 then
```

```
    if rs is the first of aRS then
      nRS ← rs;
    else
      nRS ← rs – 1;
    end if
  else
    nRS ← rs;
  end if
end if
```

7.3 EXPERİMENTAL SETUP AND BACKGROUND

In this study, we considered a WSN as a graph G = (V,E) in which a set of nodes and a set of edges were shown as V and E, respectively. We used multi-channel MAC protocol and LQ-CMST routing protocols which were proposed in our previous studies (Yigit and et al. (2016), Yigit and et al. (2014)). The main motivation behind using these protocols is that they were shown to perform well for WSN-based smart grid applications to improve the network performance by eliminating the impact of bad channel conditions such as interference, noise, and fading.

Table 7.4: Log-normal shadowing channel parameters of 500kv los substation smart grid environment

Path loss (γ) :	2.42
Shadowing deviation (X_σ) :	3.12

7.3.1 Log-normal Shadowing Model

In this study, log-normal-shadowing model was used to model channels in real channel conditions in a 500kV LoS substation smart grid environment. Log-normal shadowing channel parameters of a 500kV LoS substation smart grid environment are shown in Table 7.4 (Yigit and et al. (2016)). Path loss was computed in the log-normal shadowing model to calculate the link qualities using the equation 7.2.

$$P_L = P_{L_0} + 10\gamma log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad \textbf{(7.2)}$$

where P_L is the path loss with the unit of dBm (decibel), P_{L_0} is path loss measured in dBm at the reference d_0, d is reference distance, γ is path loss exponent, and X_σ is Gaussian random variable with standard deviation σ.

7.3.2 System Model

The system model consisted of the following steps: (1) random information symbols k came to the encoder for transmission; (2) the encoder converted each of these information sequences into a unique code word, which consisted of n symbol sequence; (3) the formed code word was sent to a digital modulator; (4) data was transformed into signal waveforms by the modulator using a modulation scheme; (5) the generated signals were sent over the log-normal-shadowing channel for transmission; (6) data could be corrupted during transmission because of the noise in the channel or other factors; (7) a demodulator demodulated the data by separating it from carrier waves; (8) the demodulated data was sent to the decoder, which was located at the receiver side and decoded the data into the original information sequence. The process flow of this system model is shown in Figure 7.1.

7.4 PERFORMANCE EVALUATIONS

In this study, extensive simulations were carried-out using the Matlab environment because the models for multi-channel MAC protocol and LQ-CMST routing protocol were implemented in this environment in previous works (Yigit and et al. (2016), Yigit and et al. (2014)). The simulation parameters and modulation schemes used in our performance evaluations are shown in Table 7.5.

Figure 7.1: The process flow of system model

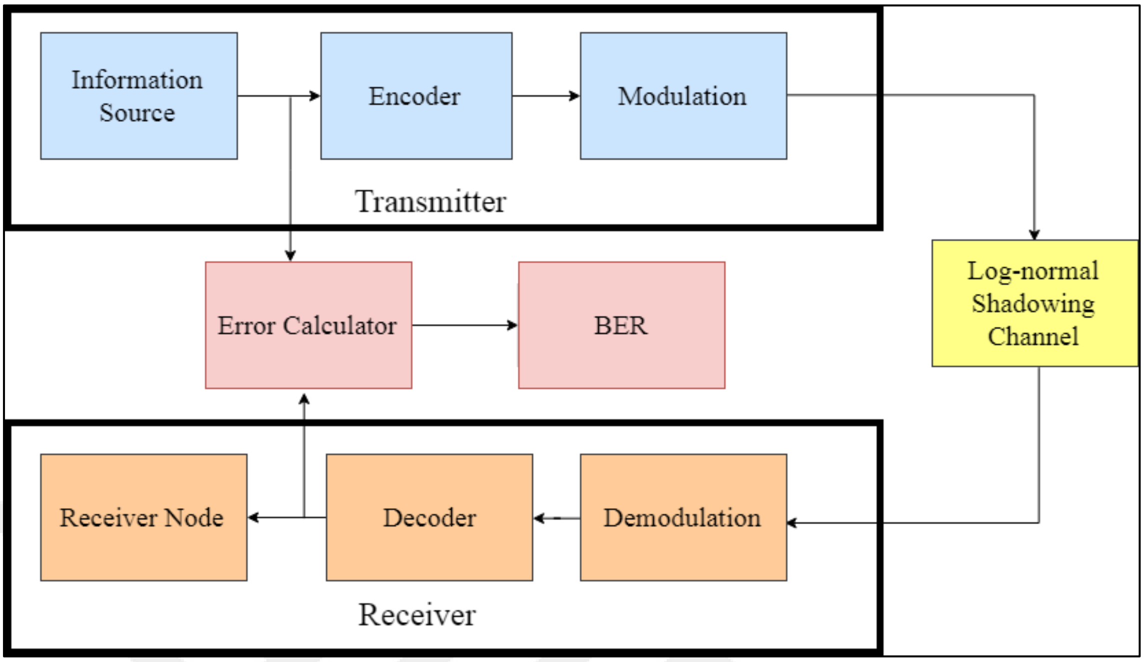


Table 7.5: Simulation parameters and notations

Parameter	Definition	Values & Notations
Q(.)	Standard Gaussian error function	$Q(x) = 0.5 \times erfc\left(\frac{x}{\sqrt{2}}\right)$, $erfc(x) = \frac{2}{\pi}\int_{x}^{\infty} e^{-t^2} d_t$
E_b/N_0	SNR (Signal to noise ratio)	$\frac{E_b}{N_0} = \psi \frac{B_N}{R}$
Modulation schemes	DPSK	$P_b^{FSK} = 0.5 \times \frac{1}{e^{E_b/N_0}}$
	FSK	$P_b^{FSK} = Q\left(\sqrt{(E_b/N_0)}\right)$
	OQPSK	$P_b^{OQPSK} = Q\left(\sqrt{((E_b/N_0)_{DS})}\right)$, $((E_b/N_0)_{DS} = \frac{(2N \times E_B/N_0)}{(N + 4\,E_B/N_0\,(K-1)/3)}$
P_t	Output power	4 dBm
P_n	Noise floor	-93 dBm
fL	Frame size	400 bits
#nodes	Number of nodes	120
D_x	Terrain dimension: X	200 m
D_y	Terrain dimension: Y	200 m
Topology	Topology	Random topology

7.4.1 Performance Evaluations of RS Codes and BCH codes with Different Modulation Schemes

Comparative performance evaluations of the RS and BCH codes and without-FEC algorithm were performed using different modulation schemes in a 500kV LoS substation smart grid environment. Further, BER, throughput, and delay were used as performance metrics in simulations. Figure 7.2 compares the BER of without-FEC (uncoded channel) against BCH and RS codes according to different modulation techniques such as DPSK, FSK, and OQPSK. It can be seen from these Figures that BER decreased as the number of channels increased, as multi-channel communication reduced the impact of interference and provided simultaneous transmissions over multiple channels. The results, depicted in Figure 7.2(a), show the BER performance of without-FEC, RS, and BCH combined with DPSK modulation. From the graph, it can be observed that RS with DPSK modulation had the best performance with the BER values of 10^{-7}, 10^{-8}, and 10^{-11} obtained for channels 1, 8, and 16, respectively. Figure 7.2(b) shows the BER values of without-FEC, RS, and BCH with FSK modulation. It can be seen from the Figure that BER values of 10^{-6}, 10^{-7}, and 10^{-9} in RS with FSK modulation is better than BCH and without-FEC. The performance of the without-FEC, RS, and BCH with OQPSK modulation is shown in Figure 7.2(c). The results obtained show that the RS with OQPSK modulation had the lowest BER values of 10^{-9}, 10^{-12}, and 10^{-14} at channels 1, 8, and 16, respectively. As a result, it is shown that RS with OQPSK modulation performed best in that it showed the least BER when the number of channels was 16. It also showed that when RS and BCH codes are used, there is a decrease in the BER performance for all modulation schemes.

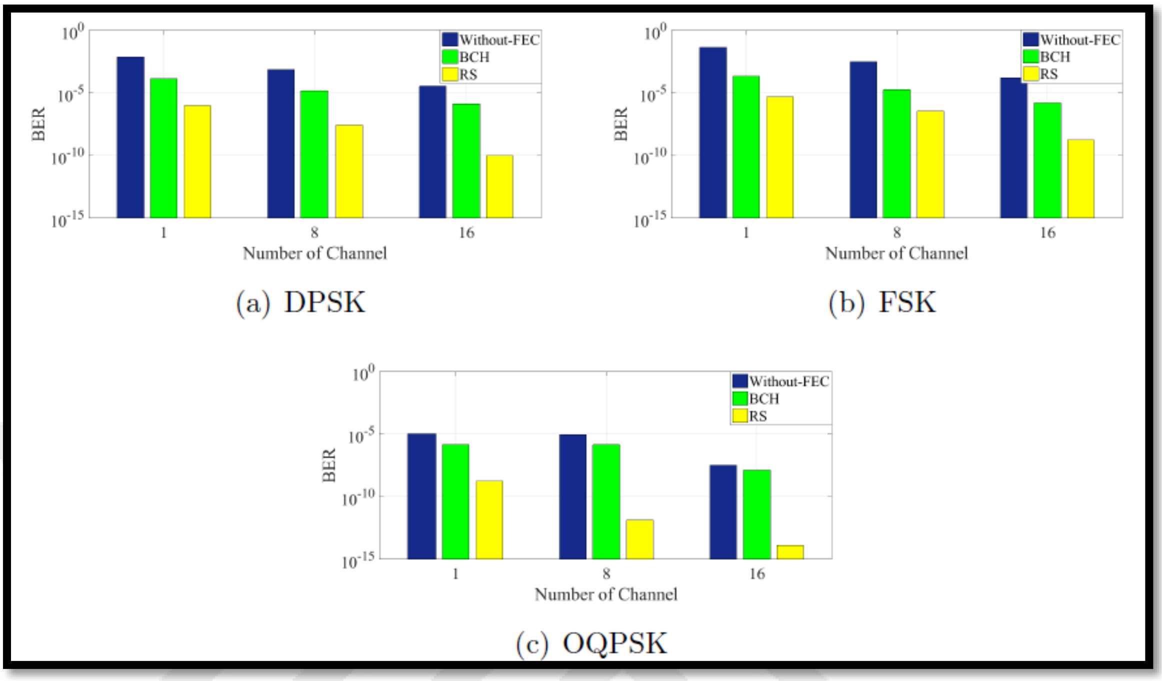
Figures 7.3 and 7.4 compare the delay and throughput of without-FEC (un-coded channel), BCH, and RS codes with different modulation techniques in a 500kV LoS substation smart grid environment. These results show that delay and throughput performances increase as the number of channels increases for all BCH and RS codes, and un-coded channels because multiple channels avoid interference and provide more simultaneous transmissions to deliver the packets to the sink in a shorter interval. Especially, the throughput results in Figure 7.4 show that the performance of BCH and RS codes are better than the un-coded channel, as ECCs detect and correct bit errors, which increases the number of successfully transmitted packets. In addition, Figure 7.3 shows that the delay performance of RS and BCH codes is worse than the un-coded channel because RS and BCH codes add redundant bits to the packets to detect and correct the bit errors that cause overheads during transmission and increases transmission delay. In Figures 7.3 and 7.4, it is also observed that the RS with OQPSK modulation is better than the BCH code in terms of throughput and delay.

7.4.2 Performance Evaluation of AEC Algorithm

Extensive simulations were performed to evaluate the performance of AEC. These were constituted as follows: AEC uses the transmission history of the nodes to estimate the channel conditions and therefore each node transmitted multiple packets. However, in the simulation model used for RS and BCH codes, whereby each node sent only one packet. Moreover, an OQPSK modulation was used as the modulation scheme since it exhibits better performance than DPSK and FSK modulation schemes. We implemented static RS and without-FEC (un-coded channel) in order to compare them with AEC. The network performance with each AEC, static RS, and without-FEC was evaluated in terms of throughput, BER, and delay. Furthermore, simulations were also performed to show how the multi-channel scheduling affects throughput, BER, and delay of these methods for different threshold values such as 0, 0.15, and 0.25, as in (Yu and et al. (2012)), in a 500kV LoS substation smart grid environment.

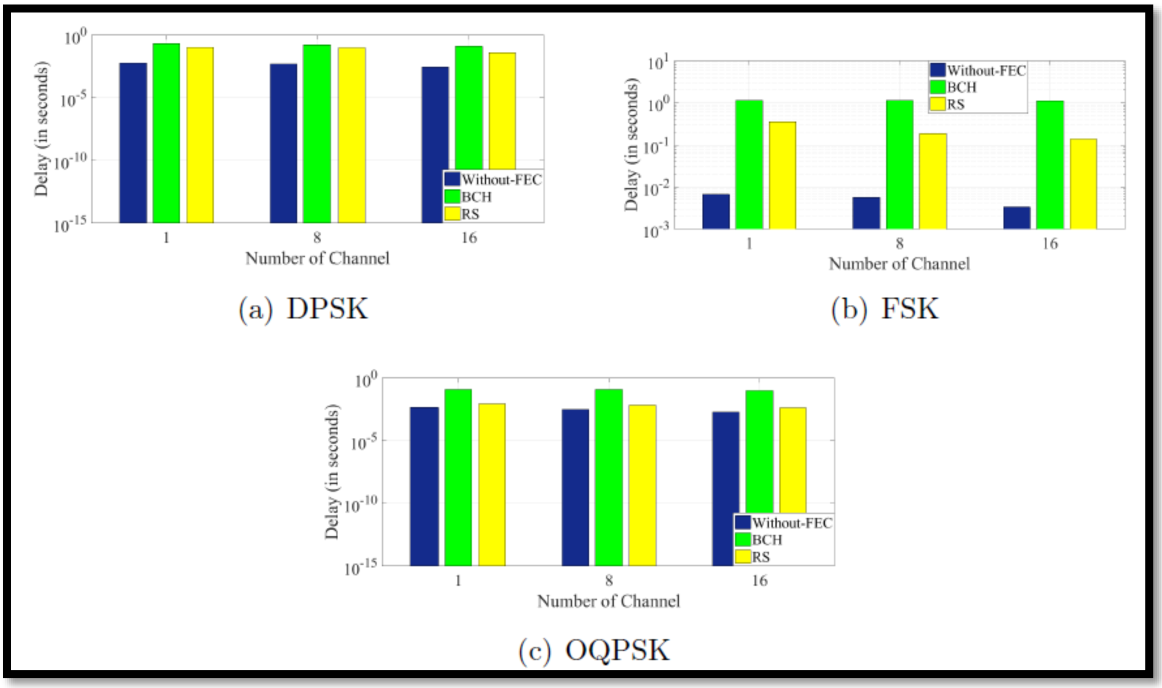
Figure 7.5 shows the BER performance of the AEC, static RS, and without- FEC. We see that the BER of AEC is lower than that of static RS and without-FEC for all the threshold values. We also observe that as the threshold increases from 0 to 0.25, the BER of the AEC also increases. The reason for this is that when the threshold is 0.25, the number of erroneous packets increased since the new RS code is not assigned until the PERwindow is not equal to or larger than 0.25. Furthermore, we also notice that, as the number of channels increases, the BER performance of all schemes increases. It is observed that the best BER result is obtained when using AEC at threshold 0 and channel 16 because AEC immediately changes the RS code, according to the look-up table shown in Table 7.3, when the bit error occurs.

Figure 7.2: Ber vs. number of channel for log-normal shadowing channel (using dpsk, fsk, and oqpsk) without-fec, rs, and bch codes in 500kv los substation smart grid environment



(a) DPSK (b) FSK (c) OQPSK

Figure 7.3: Delay vs. number of channel for log-normal shadowing channel (using dpsk, fsk, and oqpsk) without-fec, rs, and bch codes in 500kv los substation smart grid environment



(a) DPSK (b) FSK (c) OQPSK

Figure 7.4: Throughput vs. number of channel for log-normal shadowing channel (using dpsk, fsk, and oqpsk) without-fec, rs, and bch codes in 500kv los substation smart grid environment

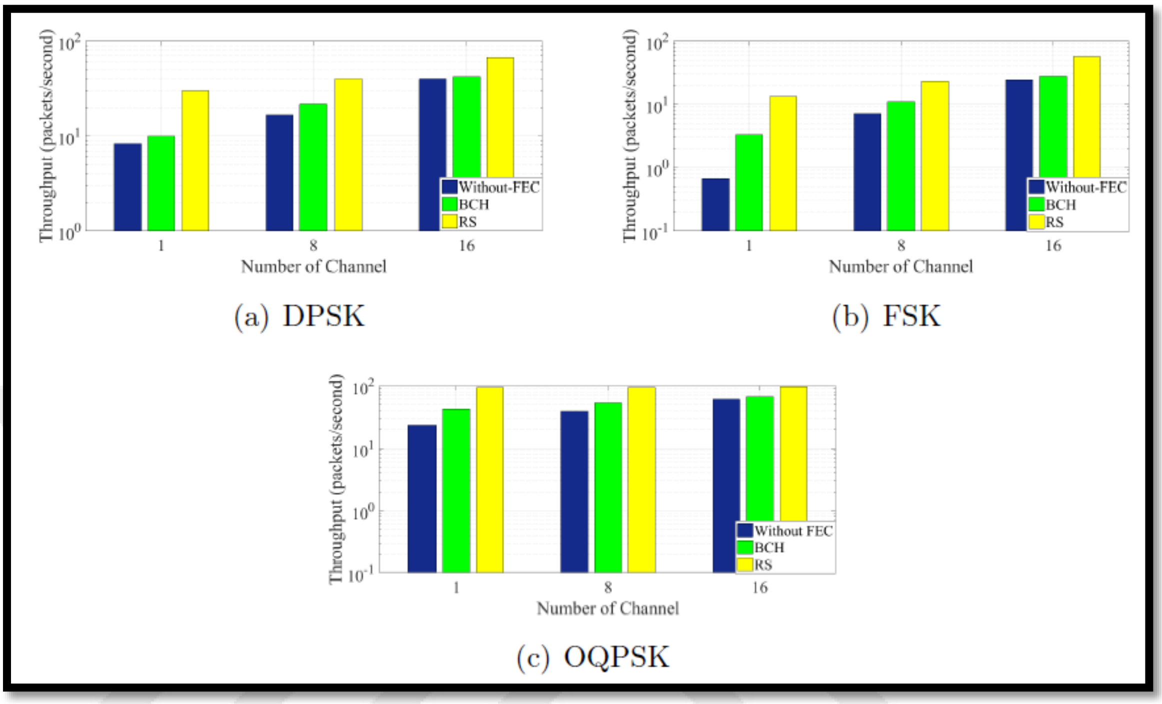


Figure 7.5: Comparison of ber of the static rs, without-fec, and aec as the number of channels increases at different thresholds of aec

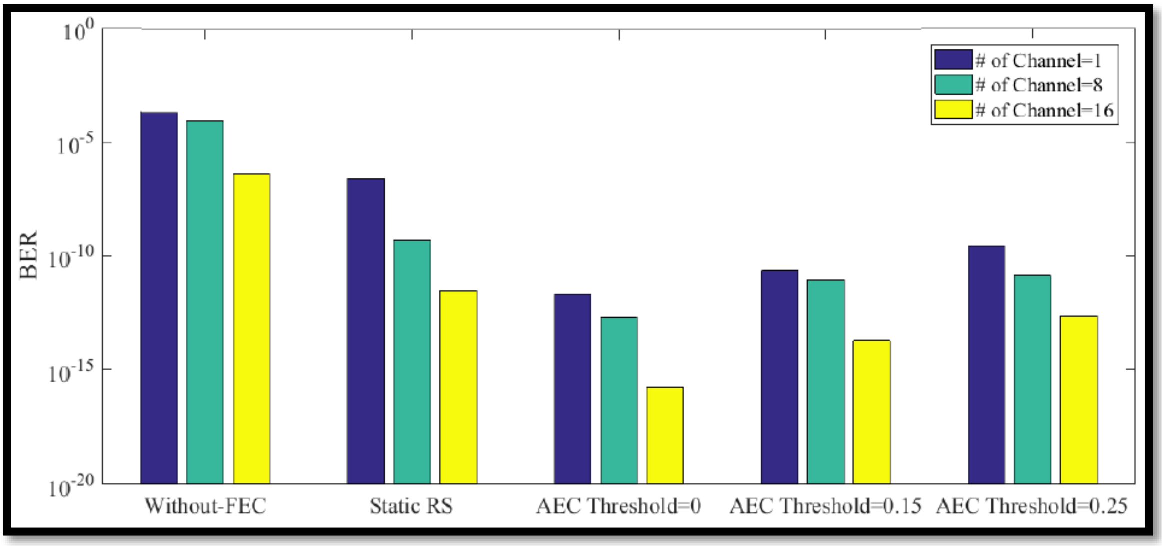


Figure 7.6 shows delay results of without-FEC, static RS, and AEC for three different switching thresholds. According to the results, without-FEC always provides the lowest delay among the schemes since it makes no error correction and detection during transmission. We also observe that as the number of channels increases from 1 to 16, delay of all schemes decreases as multiple channels provide parallel transmission that reduces packet delivery time. Furthermore, the results show that AEC provides lower delay than the static RS schema for all switching threshold values because AEC changes the RS codes according to channel conditions so as to prevent sending unnecessary redundant bits. In this way, AEC causes lower overhead than the static RS schema. In addition, as the switching threshold value increases from 0 to 0.25, the delay of AEC decreases. This is because higher values of switching thresholds indicates a less conservative reaction to channel conditions, where lower codes that have fewer redundant bits are used often, and less transmission is required to transmit the same amount of data bits compared to the codes that provide higher reliability with lower threshold values.

Figure 7.6: Comparison of delay of the static rs, without-fec, and aec as the number of channels increases at different thresholds of aec

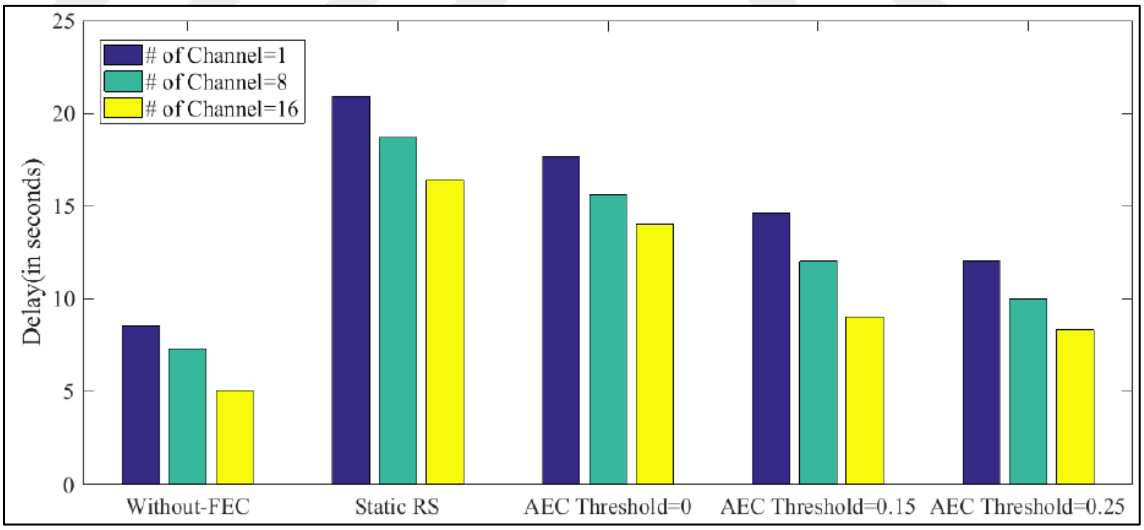


Table 7.6: Code rates of rs codes

RS codes	**Code rate**
RS(39,35)	0.897
RS(45,35)	0.778

RS(51,35)	0.686
RS(57,35)	0.614
RS(63,35)	0.556

Figure 7.7: Comparison of throughput of the static rs, without-fec, and aec as the number of channels increases at different thresholds of aec

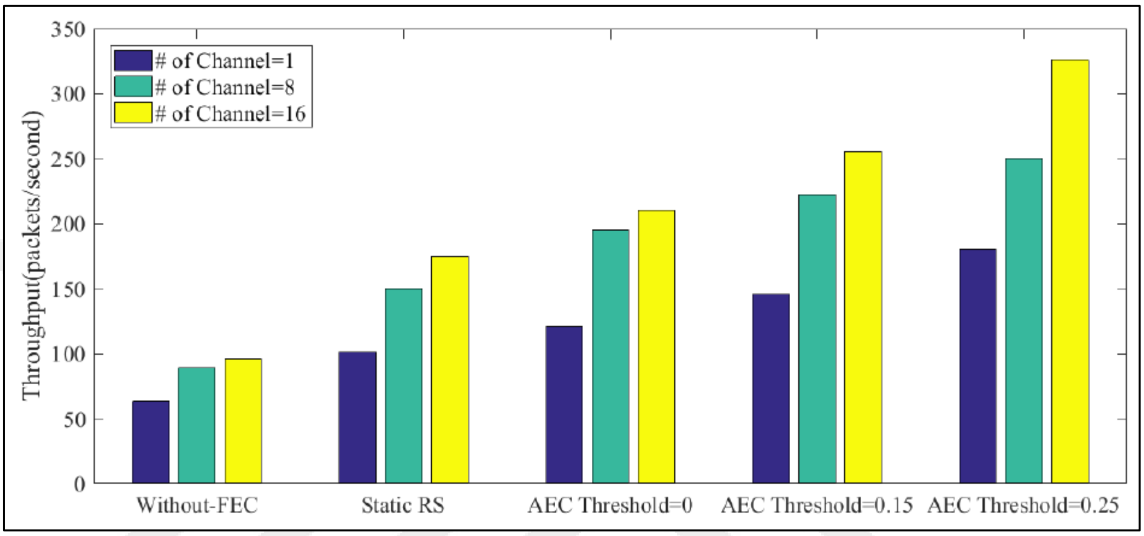


Figure 7.7 shows the throughput performance of all performed schemes. We observe that when the number of channel increases from 1 to 16, throughput performance of all schemes increases as multi-channel scheduling overcomes the impact of interference and achieves simultaneous transmission over multiple channels. We also observe that throughput performance of AEC is better than without-FEC and static RS as it is better than without-FEC because without-FEC makes no error detection and correction algorithm, and therefore, many packets drop during transmission. Static RS also cannot catch the performance of AEC for all switching threshold values since AEC always changes the RS codes according to channel conditions. Therefore, AEC does not use unnecessary redundant bits that increase the delay of transmission (delay and throughput are inversely proportional to each other). Furthermore, we also investigated the impact of the switching threshold on delay performance of AEC scheme. We observe that as the threshold increases from 0 to 0.25, throughput increases and the highest throughput is obtained when threshold is 0.25 at channel 16 because when the threshold increases, AEC uses the RS codes that provide higher code rates (# of data bits / # of code word bits). For

instance, code rate of RS(39,35) is higher than the code rate of RS(45,35). Code rates of our RS codes are shown in Table 7.6. Moreover, AEC with a 0.25 threshold value uses the weaker codes more frequently than the AEC with 0 threshold and 0.15 threshold as it makes fewer jumps to the stronger codes. Weaker codes have higher code rates and send fewer redundant bits which decrease the delay. As a result, AEC with a 0.25 threshold has a higher throughput than the other schemes and other AEC threshold values.

7.5 DISCUSSON OF RESULTS

Field tests show that the smart grid has harsh environmental conditions such as noise, interference, and fading. Using an error detection and correction code can solve all of these problems by reducing bit errors during transmission. Selecting an efficient ECC is important for WSN-based smart grid applications. In this respect, in this study, delay, throughput, and the BER performance of RS code, BCH code, and without-FEC in a 500kV LoS substation smart grid environment were first compared using different modulation schemes. Simulations were also performed to evaluate the impact of the number of channels on delay, throughput, and BER. The performance evaluations were done to determine quantitatively how much communication delay, BER, and throughput of the network change when the number of channels increases. Then, a new AEC method was proposed for WSN-based smart grid applications. This scheme firstly assigned the RS codes according to distance between the node and its parent, and then used a look-up table in order to determine the jump values of RS codes. This look-up table was constructed in a heuristic way by measuring the BER ranges of each RS code for different numbers of channels. The impact of multi-channels on the BERrange of RS codes was also analyzed. Wireless channel conditions in a 500kVLoS substation smart grid environment can vary greatly. Therefore, changing the RS code according to the current BER value by using the heuristic look-up table is not suitable for these variable mediums. In this respect, a threshold mechanism was used according to the history of recent transmitted packets using ACKs packets. Different threshold values were used in order to observe how the threshold change affected the performance of our algorithm. Furthermore, the impact of multi-channels on the performance of AEC was also analyzed. The results showed that when multi-channels were used, the performance of all schemes improved. Based on the simulations, it was observed that the performance of AEC differs in terms of throughput, BER, and delay in different threshold values. Therefore, before making a decision for network design in a 500kV substation smart grid environment, the requirements of WSN-based smart grid applications must be considered to improve the network performance. If the application requires less BER, AEC can be used with 0 threshold value. However, if the application needs high throughput, AEC should be used with 0.25 threshold value. This study is the first study that proposes a new FEC schema and makes performance comparison with other error detection and correction codes for smart grid applications.

8. CONCLUSION

This thesis focus on the solutions to data transmission problems that arise with the progression of WSNs in various harsh smart grid environments from monitoring applications with low data-rate to more complex delay-sensitive applications, which require timely and efficient delivery of huge amount of data. It identifies the difficulties such as radio frequency interference, multi-path, fading, node contentions, and noise to transmit data in various smart grid environments. Accordingly, several solutions are proposed to cope with these difficulties by using multiple channels together with routing trees, link-quality-aware routing as well as the priority and channel-aware multi-channel sheduling strategies, QoS-aware medium access control techniques, and error correction techniques. The contributions of the thesis are summarized in the following section.

8.1 CONTRIBUTION REVISITED

a. Contribution 1: Multi-Channel Scheduling and Tree-Based Routing

The impact of multi-channel communication and the selection of efficient routing topologies on the performance of wireless sensors networks in different smart grid spectrum environments is explored to enhance the network capacity. The network performance is evaluated by using a receiver-based channel selection method and using different routing trees, including routing trees constructed considering the link qualities, CMSTs, capacitated minimum hop spanning tree considering link qualities and MHSTs. Specifically, CMST trees were presented to minimize latency with perfect link qualities in (Incel and et al. (2012)), but, their performance was not investigated for WSNs operating in smart grid environments with varying link qualities. Therefore, the impact of different routing topologies on the network performance in such environments is evaluated. The routing topologies are formed by considering the link qualities that provides to prevent bad-quality links and enhance network performance.

The performance of routing topologies, which are constructed with considering PRR, is also evaluated. Furthermore, the CMST and PRR-based routing topologies are combined in order to investigate the possible capacity improvements. Besides, the impact of retransmissions on the network performance both in terms of latency and capacity is also presented by considering the lost packets due to unreliable links in smart grid environments.

The simulation results show that CMST with PRR routing tree is found to perform better than others when the number of channels increases. This is because it minimizes the schedule length by constructing balanced trees according to each node's PRR value that must exceed certain threshold to build reliable paths. Throughput of all tree types are measured by applying multiple channels in smart grid environments and their performance is compared with each other. CMST with PRR shows the best performance because it delivers the same amount of packets in a shorter interval compared to other routing trees. On the other hand, other trees construct paths without taking into consideration PRR values or balanced subtrees and therefore, their performance is lower than CMST with PRR routing tree algorithm. Impact of the number of nodes is also investigated to assess the performance of different routing trees with changing density. CMST with PRR routing tree performs better in delay and throughput performance than the other routing tree algorithms. Despite in some cases, CMST and CMST with PRR routing tree algorithms have similar results, in general, CMST with PRR performs better than CMST. This is because it constructs the paths also considering the PRR values of the links which is not implemented by CMST. Impact of the number of retransmissions is considered to evaluate its effect on throughput and delay performance of different routing tree algorithms in smart grid environments. Number of retransmissions increases the reliability of the network, however, it decreases the throughput of the routing algorithms because it increases the delay by making multiple transmissions, as expected. Therefore, it must be applied carefully according to application's requirements in smart grid environments. Simulations show that none of the evaluated routing tree algorithms perform very well when the number of retransmissions has been increased. Therefore, before applying retransmission, application requirements and network capabilities should be considered together to improve the overall network performance. However, if retransmissions has been applied for the application, according to simulations CMST with PRR routing tree can be preferred because its throughput and delay performance is better than other routing algorithms with balanced subtrees and PRR threshold.

b. Contribution 2: Channel-Aware Routing and Priority-Aware Multi-Channel Scheduling

In this thesis, two novel algorithms, which are LQ-CMST algorithm as well as the priority and PCA-MC scheduling algorithm, have been proposed for smart grid applications. Besides, the effect of different modulation and encoding schemes on the performance of the proposed algorithms has been presented under harsh smart grid channel conditions.

The performance evaluations are presented according to smart grid application scenarios by employing multi-channel scheduling. In the first scenario, there are three packet types, RT, NRT or BE traffic; in the second scenario, all traffic has been treated in a best effort manner and all packets are transmitted without any prioritization; in the third scenario, performance evaluations have been conducted under low and high traffic loads. Delay is used as a performance metric to evaluate all these performance results.

Comparative performance evaluations through extensive simulations show that the LQ-CMST routing algorithm decreases the average latency of all traffic classes,i.e., the RT, NRT and BE traffics, compared to the MHST routing algorithm. This is because it considers real channel conditions and link-quality variations, while constructing the data paths. Although the LQ-CMST algorithm leads to lower communication delay compared to the MHST algorithm, both the routing algorithms have the same service differentiation mechanism that guarantees that high priority channels, carrying the RT traffic, are preferred compared to the lower priority channels, carrying NRT and BE flows. The performance of the routing algorithms under different traffic loads show that LQ-CMST and MHST algorithms still provide delay requirements of the RT class, since it has the highest priority. Hence, communication delay of the NRT and BE packets increases. However, such increases are not important, since they do not include time-critical packets. The performance results also demonstrates that the communication delay increases with large numbers of contenders. This is because when large numbers of nodes want to access to the network and if there is only one common channel, network bottleneck occurs. The impact of multi-channel scheduling on delay performance of routing algorithms is also shown. Communication delay of all classes decreases when the number of channels increases,since packets are scheduled on more channels and therefore, schedule length decreases. The effect of PCA-MAC multi-channel scheduling algorithm on the average communication delay, when low and high traffic loads are applied with increasing number of channels is also analyzed. The performance evaluations show that when the proposed routing algorithms follow delay-aware scheduling, the average latency of the RT packets decreases significantly. It is also important to note that the delay performance of the LQ-CMST algorithm is better than the MHST algorithm with and without delay-aware scheduling, since it considers link qualities while constructing routing paths in the network. Furthermore, the effect of modulation and encoding schemes on the delay performance of the proposed algorithms is also analyzed. The performance evaluations show that the O-QPSK shows the best result for both routing algorithms. After the O-QPSK, the FSK provides the second best result and lastly the ASK presents the third best result. Overall performance evaluations show that LQ-CMST with the PCA-MC algorithm, which consider link quality while constructing routing paths, provides lower delay both low and high traffic loads. This scheme is significantly superior to MHST with the PCA-MC scheme.

c. Contribution 3: QoS-Aware MAC Protocols Utilizing Sectored Antenna

Two protocols that aim to address prioritization, delay, and reliability-aware data transmission for smart grid communication networks is introduced. The proposed protocols make service differentiation (prioritization) between the traffic classes based on their requirements in order to achieve better performance. The first approach, the QODA-MAC protocol, uses omnidirectional antennas for neighbor discovery. The QODA-MAC gets neighbor information and makes scheduling according to the traffic types such as best effort, non-real time, and real time. The second approach, named QFSA-MAC protocol, utilizes directional antennas, as opposed to QODA-MAC, to discover the neighbors by concentrating the transmission power towards a certain direction. In QFSA-MAC, the use of the directional antenna increases the spatial reuse of the wireless channel that provides simultaneous communication between the nodes without interference. In this way, it can connect the nodes far away from each other and decreases the number of hops from source node to sink node when compared with omnidirectional antennas. Similar to QODA-MAC, QFSA-MAC makes the scheduling by making service differentiation and uses the same routing protocol, which is CMST with PRR, for forwarding packets towards the sink node.

Prioritized and unprioritized modes, which provide switching from one mode operation to another according to the application requirements, are used by both QODA-MAC and QFSA-MAC. Although many studies have been proposed to meet the QoS requirements of smart grid applications (Al-Anbagi and et al. (2014), Sun and et al. (2010), Singh and Tepe (2009)), QODA-MAC and QFSA-MAC are the first QoS-aware MAC protocols that consider service differentiation of different traffic classes by considering the impact of antenna for smart grid communication networks.

The QOADA-MAC and QFSA-MAC is analyzed with comprehensive simulations for different traffic classes in terms of best effort traffic, non-real time traffic and best effort traffic. Performance of QODA-MAC and QFSA-MAC compared with each other for smart grid communication network. Simulation results show that the prioritized QFSA-MAC protocol achieves better performance than either unprioritized QFSA-MAC or all modes of the QODA-MAC protocol. Compared with prioritized QODA-MAC protocol, which utilizes the omnidirectional antenna, prioritized QFSA-MAC protocol can effectively allocate the limited wireless channel resources of RT traffic, which is the reason why the performance of RT packet is better, but NRT and BE packets are worse than unprioritized QFSA-MAC protocol. Compared with the prioritized and unprioritized QODA-MAC protocol, unprioritized QFSA-MAC protocol realized better throughput, delay, and energy performance. As a result of the simulations, prioritized QFSA-MAC protocol achieves QoS provisioning for time-critical smart grid applications. This is because the the QFSA-MAC protocol takes the advantage of sectored antennas. Sectored antennas strengthens the receiver power and reduces variance of fading rate. Furthermore, sectored antennas also extend the range for reaching far-away nodes, and their power requirements are less than the omnidirectional antennas in covering the same range. Because of these benefits of sectored antennas, the number of transmitted packets increases with low delay and less energy in the QFSA-MAC protocol.In this way, the QFSA-MAC protocol overcomes several challenges such as application-specific QoS requirements and variable channel capacity that influence the design of WSNs. Furthermore, the QFSA-MAC protocol yields many open research issues with accurate delay modeling and suitable utility functions.

d. Contribution 4: Comprehensive Analysis of Hamming Code

A comprehensive analysis of the Hamming code integrated with the modulations including BPSK, DPSK, FSK, and OQPSK is done in WSN-based smart grid communication networks. Specifically, the Hamming code is preferred for WSNs in smart grid environments to minimize the BER and to maximize the throughput. LQ-CMST is used as a routing protocol and multi-channel scheduling is used to schedule nodes in randomly deployed network. Thus, impact of LQ-CMST and multi-channel scheduling on the performance of Hamming code are also analyzed for WSNs in smart grid environments.

Comparative performance evaluations of the Hamming code and without FEC algorithm have been done according to different modulation schemes in 500kV substation smart grid environment. Performance metrics including bit error rate, throughput, and delay are used in simulations. Simulation results reveal that the Hamming code with OQPSK modulation outperforms the without FEC, which is combined with different modulation schemes, in smart grid communication network because of its low BER and high throughput performance. However, delay performance of Hamming code is worse than the delay performance of the without FEC. This is because Hamming code adds parity bits, which causes extra overhead, to correct the error and Hamming encoding and decoding also cause additional communication delays. Results also show that increasing the number of channels also improves the performance of Hamming code for all types of modulation schemes. Furthermore, Hamming code with OQPSK modulation has been also comprehensively investigated in terms of output power and packet size which leads to a deeper understanding of the impact of physical layer parameters on BER, throughput, and delay performance of smart grid communication. When the output power increases, performance of Hamming code improves. This is because high output power increases the reliability of the network by decreasing number of packet losses as expected. On the other hand, the same result cannot be obtained with the increasing of packet size. High packet size affects adversely the delay and BER performance of Hamming code combined with OQPSK modulation. Therefore, although throughput increases until the packet size reaches 100 bytes, it decreases slowly when the packet size exceeds the 100 bytes. For this reason, packet size must be chosen carefully according to applications' requirements in 500kV LOS substation smart grid environment.

e. Contribution 4: A New Efficient Error Control Algorithm

An extensive analysis of the two forward error correction methods including BCH and RS codes with various modulation methods such as FSK, OQPSK, and DPSK is done in a 500kV LoS substation smart grid environment. As a result of this comparison, a new AEC protocol is proposed. AEC uses RS codes with OQPSK modulation and adaptively changes error correction code based on the switching criterion that is defined according to the number of acknowledgments of P previously transmitted packets that is received inside a window. The packet error rate of these packets was measured and compared with the predefined threshold to determine whether to switch to a weaker or stronger RS code. A suitable RS code was chosen based on a look-up table. This table was constructed using a heuristic method. The aim of AEC is to maintain the reliability required by the smart grid application, while balancing the tradeoff between network overhead and reliability. The LQ-CMST routing algorithm and the multi-channel scheduling algorithm are used for data transmission over the log-normal shadowing channel. Therefore, the performance of compared coding techniques and AEC are also evaluated when multiple channels are used during transmission.

Firstly, performance comparison of BCH and RS codes combined with different modulation schemes are analyzed and compared for the first time in a WSN-based smart grid communication network. Performance evaluations show that they can efficiently improve network performance in terms of throughput and BER. Results also reveal that RS code combined with OQPSK modulation provides the best result. Secondly, AEC is analyzed in terms of the delay, BER, and throughput. AEC is also compared with static RS and without-FEC mechanisms. The simulation results show that the BER of AEC is lower than that of static RS and without-FEC for all the threshold values. We also observe that as the threshold increases from 0 to 0.25, the BER of the AEC also increases. The reason for this is that when the threshold is 0.25, the number of erroneous packets increased since the new RS code is not assigned until the PER_{window} is not equal to or larger than 0.25. Furthermore, we also notice that, as the number of channels increases, the BER performance of all schemes increases. It is observed that the best BER result is obtained when using AEC at threshold 0 and channel 16 because AEC immediately changes the RS code, according to the look-up table shown in Table 7.3, when the bit error occurs. The performance evaluations also show that delay results of without-FEC, static RS, and AEC for three different switching thresholds. According to the results, without-FEC always provides the lowest delay among the schemes since it makes no error correction and detection during transmission. We also observe that as the number of channels increases from 1 to 16, delay of all schemes decreases as multiple channels provide parallel transmission that reduces packet delivery time. Furthermore, the results show that AEC provides lower delay than the static RS schema for all switching threshold values because AEC changes the RS codes according to channel conditions so as to prevent sending unnecessary redundant bits. In this way, AEC causes lower overhead than the static RS schema. In addition, as the switching threshold value increases from 0 to 0.25, the delay of AEC decreases. This is because higher values of switching thresholds indicates a less conservative reaction to channel conditions, where lower codes that have fewer redundant bits are used often, and less transmission is required to transmit the same amount of data bits compared to the codes that provide higher reliability with lower threshold values. Finally, the throughput performance of all performed schemes are measured. We observe that when the number of channel increases from 1 to 16, throughput performance of all schemes increases as multi-channel scheduling overcomes the impact of interference and achieves simultaneous transmission over multiple channels. We also observe that throughput performance of AEC is better than without-FEC and static RS as it is better than without-FEC because without-FEC makes no error detection and correction algorithm, and therefore, many packets drop during transmission. Static RS also cannot catch the performance of AEC for all switching threshold values since AEC always changes the RS codes according to channel conditions. Therefore, AEC does not use unnecessary redundant bits that increase the delay of transmission. Furthermore, we also investigated the impact of the switching threshold on delay performance of AEC scheme. We observe that as the threshold increases from 0 to 0.25, throughput increases and the highest throughput is obtained when threshold is 0.25 at channel 16 because when the threshold increases, AEC uses the RS codes that provide higher code rates. As a result, AEC with a 0.25 threshold has a higher throughput than the other schemes and other AEC threshold values.

8.2 SUMMARY

As a final mark of the thesis, multi-channel scheduling algorithms, link-quality-aware routing algorithm, priority and channel-aware multi-channel scheduling algorithm, QoS-aware directional and omnidirectional antenna-based medium access control protocols, and new error mitigating technique are studied in order to satisfy QoS requirements of smart grid applications in WSNs. The results imply that the selection of proper protocols from application layer to physical layer is important to provide the QoS requirements of smart grid applications. Therefore, in this thesis, studies are performed from application layer to physical layer. Firstly, link-quality-aware routing protocol combined with the multi-channel scheduling is proposed for WSN-based smart grid applications. The contribution of this study is to investigate the performance of multi-channel communication combined with different routing trees under harsh conditions of smart grid and meet the general application requirements, such as delay, throughput, and reliability. Secondly, priority and channel-aware multi-channel scheduling is presented in order to make scheduling according to applications' traffic types. The purpose of this study is to investigate the performance of multi-channel WSNs for smart grid and to quantify how priority and channel-aware communication will perform under different network traffic loads and the harsh smart grid channel conditions. Thirdly, two novel MAC protocols based on the directional and omnidirectional antennas are proposed to increase the transmission efficiency. The aim of this study that using different types of antennas is to explore the impact of antenna type on meeting the QoS requirements of smart grid applications and use it as a parameter for service differentiation. Fourthly, the performance of Hamming code is verified by using different modulation schemes in smart grid environment. The main contribution of this study is investigating the performance of the Hamming code with different modulation techniques, such as FSK, DPSK, OQPSK, and BPSK, and quantifying how multi-channel communication combined with the LQ-CMST routing protocol affects the performance of Hamming code in terms of throughput, BER, and delay under the harsh conditions of a 500-kV LOS substation smart grid environment. Finally, the performance of BCH and RS codes are evaluated with using different modulations schemes and a new efficient AEC protocol is proposed in order to maintain reliability requirements of WSN-based smart grid applications. The purposes of this study are to identify the impact of some ECCs on sensor networks in a 500kV LoS substation smart grid environment and to propose a new AEC protocol in order to maintain the reliability required by the smart grid application, while balancing the tradeoff between network overhead and reliability. As a result, proposed methods and investigated schemes are beneficial in providing QoS requirements for WSN-based smart grid applications.

8.3 FUTURE RESEARCH DIRECTIONS

The future works are as follows:

a. Time Slotted Channel Hopping (TSCH) mechanism can be adapted to our proposed RBCA-based multi-channel scheduling algorithm. TSCH, which is included in IEEE802.15.4e standard, provides energy efficient and reliable communication with minimizing collision and frequency diversity (Palattella and et al. (2013)). Energy efficiency and reliability can be obtained by using TSCH with the synchronization of nodes via slotframe structure and with channel hopping, respectively. After the synchronization, a schedule is established to define the slots and channel offsets of each nodes for making transmission. For scheduling both centralized and distributed approaches can be considered. A centralized scheduling approach of TSCH can be adapted to our study in the channel and time slot assignment phase. Instead of assigning static channels to the nodes, like in RBCA, TSCH's slotframe structure and the hopping mechanism can be utilized to exploit the frequency diversity and hence to better cope with possible changing interference conditions on different channels.
b. It is planned to integrate our framework with other error correction methods including, ARQ, Hybrid ARQ, etc. In this way, a comprehensive analysis of these error correction methods will be investigated in order to obtain the effect of these methods on the throughput, BER, and delay performance.
c. In future research, the proposed AEC algorithm may be integrated to QFSA-MAC algorithm to evaluate AEC performance when sector antennas are used. The integration of these algorithms may provide to find better throughput, BER, and delay results.
d. Optimization studies to enhance the performance of proposed framework can be considered, which include finding the optimum physical layer parameters, such as

finding optimum modulation scheme or optimum transmission energy. Hence, an investigation of the optimum solutions on new proposed communication algorithms are crucial for meeting the QoS requirements of smart grid applications.

e. Our proposed link quality-aware multi-channel scheduling algorithm can be integrated with weighted fair scheduling schemes to provide fairness in different smart grid application scenarios. In this way, fairness may be provided while meeting QoS requirements of smart grid applications, such as low delay or high throughput.

REFERENCES

Books

Cesana, M., & Fratta, L. (Eds.). 2006. *Wireless systems and network architectures in next generation internet*. Vigoni, Italy: Springer-Verlag.

Dimitriou, T., & Kalis, A., 2004. Efficient delivery of information in sensor networks using smart antennas. *Algorithmic aspects of wireless sensor networks. ALGOSENSORS 2004. Lecture Notes in Computer Science*. 3121, pp. 109-122, In: Nikoletseas S.E., Rolim J.D.P. (Eds.). Berlin, Heidelberg: Springer-Verlag.

Hamming, R. W., 1980. *Coding and theory*. Prentice-Hall.

Hurni P. & Braun T., 2010. Maxmac: a maximally traffic-adaptive mac protocol for wireless sensor networks. *Wireless sensor networks*. Berlin, Heidelberg: Springer-Verlag, pp. 289-305.

Leeson, M. S., & Patel, S., 2015. Energy efficiency of coding schemes for underwater wireless sensor networks. *In technological breakthroughs in modern wireless sensor applications*. pp. 27-55, Sharif, H. R., & Kavian, Y. S. (Eds.). USA: IGI Global.

Moon, T. K., 2005. *Error correction coding: mathematical methods and algorithms*. Wiley-Interscience.

Wicker, S. B., 1995. *Error control systems for digital communication and storage*. Englewood Cliffs: Prentice hall.

Zhang S., & Datta A., 2005. A directional-antenna based mac protocol for wireless sensor networks. *Computational science and its applications –iccsa 2005*. pp. 551-586, In: Gervasi O. et al. (Eds.). Berlin, Heidelberg: Springer-Verlag.

Periodicals

Ahmed, A. A., & Fisal, N., 2008. A real-time routing protocol with load distribution in wireless sensor networks. *Computer Communications*. **31** (14), pp. 3190-3203.

Akande, D. O., Ojo, F. K., & Abolade, R. O., 2014. Performance of rs and bch codes over correlated rayleigh fading channel using qam modulation technique. *Journal of Information and Engineering Applications*. **4** (9), pp. 88-94.

Akkaya, K., & Younis, M., 2005. Energy and QoS aware routing in wireless sensor networks. *Cluster computing*. **8** (2-3), pp. 179-188.

Akyildiz, I. F., Melodia, T., & Chowdury, K. R., 2007. Wireless multimedia sensor networks: A survey. *IEEE Wireless Communications*. **14** (6), pp. 32-39.

Al-Anbagi, I., Erol-Kantarci, M., & Mouftah, H. T., 2014. Priority-and delay-aware medium access for wireless sensor networks in the smart grid. *IEEE Systems Journal*. **8** (2), pp. 608-618.

Alrajeh, N. A., Marwat, U., Shams, B., & Shah, S. S. H., 2015. Error correcting codes in wireless sensor networks: an energy perspective. *Applied Mathematics & Information Sciences*. **9** (2), pp. 809-818.

Al-suhail, G. A., Louis, K., W., & Abdallah, T., Y., 2012. Energy efficiency analysis of adaptive error correction in wireless sensor networks. *International Journal of Computer Science Issues*, **9** (4), pp. 79-84.

Arkin, E. M., Guttmann-Beck, N., & Hassin, R., 2012. The (k, k)-capacitated spanning tree problem. *Discrete Optimization*. **9** (4), pp. 258-266.

Balakrishnan, G., Yang, M., Jiang, Y., & Kim, Y., 2007. Performance analysis of error control codes for wireless sensor networks. *In Information Technology, 2007. ITNG'07*. 2-4 April 2007 Las Vegas, NV, USA: Fourth International Conference on. IEEE, pp. 876-879.

Bari, A., Jiang, J., Saad, W., & Jaekel, A., 2014. Challenges in the smart grid applications: an overview. *International Journal of Distributed Sensor Networks*. **2014**, pp. 1-11.

Brar, G., Blough, D. M., & Santi, P., 2006. Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks. *In Proceedings of the 12th annual international conference on Mobile computing and networking.* 23-29 September 2006 Los Angeles, CA, USA: ACM, pp. 2-13.

Bicen, A. O., Akan, O. B., & Gungor, V. C., 2012. Spectrum-aware and cognitive sensor networks for smart grid applications. *IEEE Communications Magazine*. **50** (5), pp. 1-8.

Bjelica, M., & Pejovic, M. S., 2017. Communications protocol for power management in smart homes. *Turkish Journal of Electrical Engineering & Computer Sciences*. **25** (2), pp. 1554-1562.

Bononi, L., Donatiello, L., & Furini, M., 2009. Real-time traffic in ad-hoc sensor networks. *In Communications, 2009. ICC'09*. 14-18 June 2009 Dresden, Germany: IEEE International Conference on, pp. 1-5.

Borms, J., Steenhaut, K., & Lemmens, B., 2010. Low-overhead dynamic multi-channel MAC for wireless sensor networks. *In EWSN*. 17-19 February 2010 Coimbra, Portugal: 7th European Conference, pp. 81-96.

Capone, A., Martignon, F., & Fratta, L., 2008. Directional MAC and routing schemes for power controlled wireless mesh networks with adaptive antennas. *Ad Hoc Networks.* **6** (6), pp. 936-952.

Chen, T. S., Tsai, H. W., & Chu, C. P., 2010. Adjustable convergecast tree protocol for wireless sensor networks. *Computer Communications*. **33** (5), pp. 559-570.

Cho, J., Lee, J., Kwon, T., & Choi, Y., 2006. Directional antenna at sink (DAaS) to prolong network lifetime in wireless sensor networks. *In Wireless Conference.* 2-5 April 2006 Athens, Greece: VDE, pp. 1-5.

Deng, R., Yang, Z., Chow, M. Y., & Chen, J., 2015. A survey on demand response in smart grids: Mathematical models and approaches. *IEEE Transactions on Industrial Informatics*. **11** (3), pp. 570-582.

Depuru, S. S. S. R., Wang, L., & Devabhaktuni, V., 2011. Smart meters for power grid: Challenges, issues, advantages and status. *Renewable and sustainable energy reviews*. **15** (6), pp. 2736-2742.

Dunlop, J., & Cortes, J., 2007. Impact of directional antennas in wireless sensor networks. *In Mobile Adhoc and Sensor Systems, 2007. MASS 2007*. 8-11 October 2007 Pisa, Italy: IEEE, pp. 1-6.

El-Nahal, F. I., & Salha, M. A., 2013. Comparison between OQPSK and DPSK Bidirectional Radio over Fiber Transmission Systems. *Universal Journal of Electrical and Electronic Engineering*. **1** (4), pp. 129-133.

Erol-Kantarci, M., & Mouftah, H. T., 2011. Wireless multimedia sensor and actor networks for the next generation power grid. *Ad Hoc Networks*. **9** (4), pp. 542-551.

Erol-Kantarci, M., & Mouftah, H. T., 2011. Wireless sensor networks for cost-efficient residential energy management in the smart grid. *IEEE Transactions on Smart Grid*. **2** (2), pp. 314-325.

Fadel, E., Gungor, V. C., Nassef, L., Akkari, N., Malik, M. A., Almasri, S., & Akyildiz, I. F., 2015. A survey on wireless sensor networks for smart grid. *Computer Communications*. **71**, pp. 22-33.

Fan, Z., Kulkarni, P., Gormus, S., Efthymiou, C., Kalogridis, G., Sooriyabandara, M., Zhu, Z., Lambotharan, S., & Chin, W. H., 2013. Smart grid communications: Overview of research challenges, solutions, and standardization activities. *IEEE Communications Surveys & Tutorials*. **15** (1), pp. 21-38.

Fang, X., Misra, S., Xue, G., & Yang, D., 2012. Smart grid - The new and improved power grid: A survey. *IEEE communications surveys & tutorials*. **14** (4), pp. 944-980.

Felemban, E., Vural, S., Murawski, R., Ekici, E., Lee, K., Moon, Y., & Park, S., 2010. Samac: A cross-layer communication protocol for sensor networks with sectored antennas. *IEEE Transactions on Mobile Computing*. **9** (8), pp. 1072-1088.

Felemban, E., Lee, C. G., & Ekici, E., 2006. MMSPEED: multipath Multi-SPEED protocol for QoS guarantee of reliability and timeliness in wireless sensor networks. *IEEE transactions on mobile computing*. **5** (6), pp. 738-754.

Florens, C., Franceschetti, M., & McEliece, R. J., 2004. Lower bounds on data collection time in sensory networks. *IEEE Journal on selected Areas in Communications*. **22** (6), pp. 1110-1120.

Florens, C., & McEliece, R., 2003. Packets distribution algorithms for sensor networks. *In INFOCOM 2003*. 30 March - 3 April 2003 San Francisco, CA, USA: Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. IEEE Societies, pp. 1063-1072.

Fu, B., & Ampadu, P., 2009. On hamming product codes with type-II hybrid ARQ for on-chip interconnects. *IEEE Transactions on Circuits and Systems I: Regular Papers*. **56** (9), pp. 2042-2054.

Gandham, S., Zhang, Y., & Huang, Q., 2008. Distributed time-optimal scheduling for convergecast in wireless sensor networks. *Computer Networks*. **52** (3), pp. 610-629.

Gelenbe, E., & Ngai, E. C. H., 2008. Adaptive qos routing for significant events in wireless sensor networks. *In Mobile Ad Hoc and Sensor Systems, 2008. MASS 2008*. 29 September-2 October 2008 Atlanta, GA, USA: 5th IEEE International Conference on, pp. 410-415.

Ghosh, A., Incel, O. D., Kumar, V. A., & Krishnamachari, B., 2009. Multi-channel scheduling algorithms for fast aggregated convergecast in sensor networks. *In Mobile Adhoc and Sensor Systems, 2009. MASS'09*. 12-15 October 2009 Macau, China, China: IEEE 6th International Conference on, pp. 363-372.

Grönkvist, J., & Hansson, A., 2001. Comparison between graph-based and interference-based STDMA scheduling. *In Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing.* 4-5 October 2001 Long Beach, CA, USA: ACM, pp. 255-258. ACM.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P., 2013. A survey on smart grid potential applications and communication requirements. *IEEE Transactions on Industrial Informatics*. **9** (1), pp. 28-42.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P., 2012. Smart grid and smart homes: Key players and pilot projects. *IEEE Industrial Electronics Magazine*. **6** (4), pp. 18-34.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P., 2011. Smart grid technologies: Communication technologies and standards. *IEEE transactions on Industrial informatics*. **7** (4), pp. 529-539.

Gungor, V. C., Lu, B., & Hancke, G. P., 2010. Opportunities and challenges of wireless sensor networks in smart grid. *IEEE transactions on industrial electronics*. **57** (10), pp. 3557-3564.

Gupta, P., & Kumar, P. R., 2000. The capacity of wireless networks. *IEEE Transactions on information theory*. **46** (2), pp. 388-404.

He, L., Yang, Z., Pan, J., Cai, L., Xu, J., & Gu, Y. J., 2014. Evaluating service disciplines for on-demand mobile data collectionin sensor networks. *IEEE Transactions on mobile computing*. **13** (4), pp. 797-810.

He, L., Pan, J., & Xu, J., 2013. Data Collection Latency in Wireless Sensor Networks with Multiple Mobile Elements. *Adhoc & Sensor Wireless Networks*, **18** (1/2), pp. 109-129.

He, L., Pan, J., & Xu, J., 2013. A progressive approach to reducing data collection latency in wireless sensor networks with mobile elements. *IEEE Transactions on Mobile Computing*. **12** (7), pp. 1308-1320.

He, T., Stankovic, J. A., Lu, C., & Abdelzaher, T., 2003. SPEED: A stateless protocol for real-time communication in sensor networks. *In Distributed Computing Systems*. 19-22 May 2003 Providence, Rhode Island, USA, USA: Proceedings. 23rd International Conference on. IEEE, pp. 46-55.

Howard, S. L., Schlegel, C., & Iniewski, K., 2006. Error control coding in low-power wireless sensor networks: When is ECC energy-efficient? *EURASIP Journal on Wireless Communications and Networking*. **2006** (2), pp. 29-29.

Huang, J., & Bi, J., 2016. A proportional fairness scheduling for wireless sensor networks. Personal and Ubiquitous Computing. 20 (5), pp. 695-703.

Incel, O. D., Ghosh, A., Krishnamachari, B., & Chintalapudi, K., 2012. Fast data collection in tree-based wireless sensor networks. *IEEE Transactions on Mobile computing*. **11** (1), pp. 86-99.

Incel, O. D., Van Hoesel, L., Jansen, P., & Havinga, P., 2011. MC-LMAC: A multi-channel MAC protocol for wireless sensor networks. *Ad Hoc Networks*. **9** (1), pp. 73-94.

Incel, O. D., 2011. A survey on multi-channel communication in wireless sensor networks. *Computer Networks*. **55** (13), pp. 3081-3099.

Islam, M. R., 2010. Error correction codes in wireless sensor network: An energy aware approach. International Journal of Computer and Information Engineering. 4 (1), pp. 59-64.

Janjic, A., Savic, S., Velimirovic, L., & Nikolic, V., 2015. Renewable energy integration in smart grids-multicriteria assessment using the fuzzy analytical hierarchy process. *Turkish Journal of Electrical Engineering & Computer Sciences*. **23** (6), pp. 1896-1912.

Kilic, N., & Gungor, V. C., 2013. Analysis of low power wireless links in smart grid environments. *Computer Networks*. **57** (5), pp. 1192-1203.

Kim, M. S., Kim, S. R., Kim, J., & Yoo, Y., 2011. Design and implementation of MAC protocol for SmartGrid HAN environment. *In Computer and Information Technology (CIT)*, 31 August-2 September 2011 Pafos, Cyprus: 2011 IEEE 11th International Conference on, pp. 212-217.

Kim, Y., Shin, H., & Cha, H., 2008. Y-mac: An energy-efficient multi-channel mac protocol for dense wireless sensor networks. *In Proceedings of the 7th international conference on Information processing in sensor networks.* 22-24 April 2008 Washington, DC, USA: IEEE Computer Society, pp. 53-63.

Ko, Y. B., Shankarkumar, V., & Vaidya, N. H., 2000. Medium access control protocols using directional antennas in ad hoc networks. *In INFOCOM 2000*. 26-30 March 2000 Tel Aviv, Israel: Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE, pp. 13-21.

Kolar, V., Tilak, S., & Abu-Ghazaleh, N. B., 2004. Avoiding head of line blocking in directional antenna [MAC protocol]. *In 29th IEEE International Conference on Local Computer Networks.* 16-18 November 2004 Tampa, FL, USA, USA: IEEE, pp. 385-392.

Korakis, T., Jakllari, G., & Tassiulas, L., 2003. A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks. *MobiHoc '03 Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing.* June 01 - 03 2003 Annapolis, Maryland, USA: ACM, pp. 98-107.

Korrapati, V., Prasad, M. V. D., Reddy, D. V., & Tej, G. A., 2013. A Study on performance evaluation of reed solomon codes through an awgn channel model for an efficient communication system. *International Journal of Engineering Trends and Technology (IJETT).* **4** (4), pp. 1038-1041.

Kumar, S., & Sharma, S., 2010. Error Probability of Different Modulation Schemes for OFDM based WLAN standard IEEE 802.11 a. *International Journal of Engineering (IJE)*. **4** (4), pp. 262-267.

Kumar, U., Gupta, H., & Das S. R., 2006. A topology control approach to using directional antennas in wireless mesh networks. *Communications, 2006. ICC '06.* 11-15 June 2006 Istanbul, Turkey: IEEE International Conference on, pp. 4083-4088.

Lee, S., & Younis, M., 2009. QoS-aware relay node placement in a segmented wireless sensor network. *In Communications, 2009. ICC'09*. 14-18 June 2009 Dresden, Germany: IEEE International Conference on, pp. 1-5.

Liang, X., Chen, M., Xiao, Y., Balasingham, I., & Leung, V. C., 2010. MRL-CC: a novel cooperative communication protocol for QoS provisioning in wireless sensor networks. *International Journal of Sensor Networks*. **8** (2), pp. 98-108.

Li, H., & Zhang,W., 2010. Qos routing in smart grid. *In: IEEE Global Telecommunications Conference (GLOBECOM 2010)*. 7-9 December 2010 Miami,Florida,USA: IEEE, pp. 1–6.

Malhotra, B., Nikolaidis, I., & Nascimento, M. A., 2011. Aggregation convergecast scheduling in wireless sensor networks. *Wireless Networks*. **17** (2), pp. 319-335.

Malode, M. V., & Patil, D. B., 2010. PAPR reduction using modified selective mapping technique. *International Journal of Advanced Networking and Applications*. **2** (02), pp. 626-630.

Manes, G., Fantacci, R., Chiti, F., Ciabatti, M., Collodi, G., Di Palma, D., Nelli, I., & Manes, A., 2008. Energy efficient MAC protocols for wireless sensor networks endowed with directive antennas: a cross-layer solution. *In Radio and Wireless Symposium*. 22-24 January 2008 Orlando, FL, USA: IEEE, pp. 239-242.

Manes, G., Fantacci, R., Chiti, F., Ciabatti, M., Collodi, G., Di Palma, D., Nelli, I., & Manes, A., 2007. Efficient MAC protocols for wireless sensor networks endowed with directive antennas: a cross layer solution. *EURASIP Journal on Wireless Communications and Networking*. **2007** (9), pp. 1-9.

Manzoor, B., Javaid, N., Rehman, O., Bouk, S. H., Ahmed, S. H., Park, S. H., & Kim, D., 2013. Energy aware error control in cooperative communication in wireless sensor networks. *In ACM SIGAPP Applied Computing Review*. 1-4 October 2013 Montreal, Quebec, Canada: ACM, pp. 254-260.

Monowar, M. M., Rahman, M. O., Pathan, A. S. K., & Hong, C. S., 2008. Congestion control protocol for wireless sensor networks handling prioritized heterogeneous traffic. *In Proceedings of the 5th Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services*. 21-25 July 2008 Dublin, Ireland: Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering (ICST), pp. 1-17.

Moscibroda, T., 2007. The worst-case capacity of wireless sensor networks. *In Proceedings of the 6th international conference on Information processing in sensor networks*. 25-27 April 2007 Cambridge, Massachusetts, USA: ACM New York, NY, pp. 1-10.

Mstafa, R. J., & Elleithy, K. M., 2014. A highly secure video steganography using Hamming code (7, 4*). IEEE Long Island Systems, Applications and Technology (LISAT) Conference 2014*. 2 May 2014 Farmingdale, NY, USA: IEEE, pp. 1-6.

Okeke, C., & Eng, M., 2015. A comparative study between hamming code and reed-solomon code in byte error detection and correction. International Journal for Research in Applied Science & Engineering Technology (IJRASET). 3 (12), pp. 34-39.

Palattella, M. R., Accettura, N., Grieco, L. A., Boggia, G., Dohler, M., & Engel, T., 2013. On optimal scheduling in duty-cycled industrial IoT applications using IEEE802. 15.4 e TSCH. *IEEE Sensors Journal*. **13** (10), pp. 3655-3666.

Palattella, M. R., Accettura, N., Vilajosana, X., Watteyne, T., Grieco, L. A., Boggia, G., & Dohler, M., 2013. Standardized protocol stack for the internet of (important) things. *IEEE communications surveys & tutorials*. **15** (3), pp. 1389-1406.

Panicker, N. V., & Sukesh, A. K., 2014. BER Performance Evaluation of Different Digital Modulation Schemes for Biomedical Signal Transceivers under AWGN and Fading Channel Conditions. *International Journal of Engineering and Advanced Technology (IJEAT)*. **3** (5), pp. 212-215.

Pham, T. N., Tsai T. Y., & Wu, N., 2017. An algorithm for the selection of eefective error correction coding in wireless networks based on a lookup table structure. *International Journal of Communication Systems.* **30** (17), pp. 1-14.

Ramanathan, R., Redi, J., Santivanez, C., Wiggins, D., & Polit, S., 2005. Ad hoc networking with directional antennas: a complete system solution. *IEEE Journal on selected areas in communications.* **23** (3), pp. 496-506.

Razzaque, M. A., Alam, M. M., Mamun-Or-Rashid, M., & Hong, C. S., 2008. Multi-constrained QoS geographic routing for heterogeneous traffic in sensor networks. *IEICE Transactions on communications*. **91** (8), pp. 2589-2601.

Rego, C., & Mathew, F., 2011. A filter-and-fan algorithm for the capacitated minimum spanning tree problem. *Computers & Industrial Engineering*. **60** (2), pp. 187-194.

Rezaee, A. A., Yaghmaee, M. H., & Rahmani, A. M., 2014. Optimized congestion management protocol for healthcare wireless sensor networks. *Wireless personal communications.* **75** (1), 11-34.

Rhee, I., Warrier, A., Aia, M., Min, J., & Sichitiu, M. L., 2008. Z-MAC: a hybrid MAC for wireless sensor networks. *IEEE/ACM Transactions on Networking (TON).* **16** (3), pp. 511-524.

Salajegheh, M., Soroush, H., & Kalis, A., 2007. HYMAC: Hybrid TDMA/FDMA medium access control protocol for wireless sensor networks. *In Personal, Indoor and Mobile Radio Communications*. 3-4 September 2007 Athens, Greece: IEEE 18th International Symposium on, pp. 1-5.

Shah, G. A., Gungor, V. C., & Akan, O. B., 2013. A cross-layer QoS-aware communication framework in cognitive radio sensor networks for smart grid applications. *IEEE Transactions on Industrial Informatics*. **9** (3), pp. 1477-1485.

Siddique, M. A. R., & Kamruzzaman, J., 2010. Performance analysis of PCF based WLANs with imperfect channel and failure retries. *In Global Telecommunications Conference (GLOBECOM 2010)*, 6-10 Dec. 2010 Miami, FL, USA: IEEE, pp. 1-6.

Singh, B. K., & Tepe, K. E., 2009. Feedback based real-time MAC (RT-MAC) protocol for wireless sensor networks. *In Global Telecommunications Conference, 2009. GLOBECOM 2009*. 30 November-4 December 2009 Honolulu, HI, USA: IEEE, pp. 1-6.

Sun, W., Yuan, X., Wang, J., Han, D., & Zhang, C., 2010. Quality of service networking for smart grid distribution monitoring. *In Smart Grid Communications (SmartGridComm).* 4-6 Oct. 2010 Gaithersburg, MD, USA: 2010 First IEEE International Conference on, pp. 373-378.

Tsai, M. F., Chilamkurti, N., Shieh C. K., & Vinel A., 2011. Mac-level forward error correction mechanism for minimum error recovery overhead and retransmission. *Mathematical and computer modelling.* **53** (11-12), pp. 2067-2077.

Turan, M. T., & Gökalp, E., 2016. Relay coordination analysis and protection solutions for smart grid distribution systems. T*urkish Journal of Electrical Engineering & Computer Sciences*. **24** (2), pp. 474-482.

Ullo, S. L., Vaccaro, A., & Velotto, G., 2010. Performance analysis of IEEE 802.15. 4 based sensor networks for smart grids communications. *Journal of Electrical Engineering: Theory and Application*. **1** (3), pp. 129-134.

Usman, A., & Shami, S. H., 2013. Evolution of communication technologies for smart grid applications. *Renewable and Sustainable Energy Reviews*. **19**, pp. 191-199.

Van Dam, T., & Langendoen, K., 2003. An adaptive energy-efficient MAC protocol for wireless sensor networks. *In Proceedings of the 1st international conference on Embedded networked sensor systems*. November 05 – 07 2003 Los Angeles, California, USA: ACM, pp. 171-180.

Villaverde, B. C., Rea, S., & Pesch, D., 2012. InRout–A QoS aware route selection algorithm for industrial wireless sensor networks. *Ad Hoc Networks*. **10** (3), pp. 458-478.

Vineet, V., Harish, P., Patidar, S., & Narayanan, P. J., 2009. Fast minimum spanning tree for large graphs on the GPU. I*n Proceedings of the Conference on High*

Performance Graphics 2009. 1-3 August 2009 New Orleans, Louisiana: ACM, pp. 167-171.

Vuran, M. C., & Akyildiz, I. F., 2009. Error control in wireless sensor networks: a cross layer analysis. *IEEE/ACM Transactions on Networking (TON).* **17** (4), pp. 1186-1199.

Wu, Y., Stankovic, J. A., He, T., & Lin, S., 2008. Realistic and efficient multi-channel communications in wireless sensor networks. *In INFOCOM 2008*. 13-18 April 2008 Phoenix, AZ, USA: The 27th Conference on Computer Communications. IEEE, pp. 1193-1201.

Yaghmaee, M. H., Yousefi, Z., Zabihi, M., & Alishahi, S., 2013. Quality of service guarantee in smart grid infrastructure communication using traffic classification. *In 22nd International Conference and Exhibition on Electricity Distribution, (CIRED 2013).* 10-13 June 213 Stockholm, Sweden: IET, pp. 1-4.

Yahya, B., & Ben-Othman, J., 2010. Energy efficient and QoS aware medium access control for wireless sensor networks. *Concurrency and Computation: Practice and Experience*. **22** (10), pp. 1252-1266.

Yan, Y., Qian, Y., Sharif, H., & Tipper, D., 2013. A survey on smart grid communication infrastructures: Motivations, requirements and challenges. *IEEE communications surveys & tutorials*. **15** (1), pp. 5-20.

Yang, J., & Ulukus, S., 2010. Delay minimization with a general pentagon rate region. *In Information Theory Proceedings (ISIT)*, 13-18 June 2010 Austin, TX, USA: 2010 IEEE International Symposium on, pp. 1808-1812.

Yang, J., & Ulukus, S., 2009. Delay minimization in multiple access channels. *In Information Theory, 2009. ISIT 2009.* 28 June-3 July 2009 Seoul, South Korea: IEEE International Symposium on, pp. 2366-2370.

Ye, W., Heidemann, J., & Estrin, D., 2002. An energy-efficient MAC protocol for wireless sensor networks. *In INFOCOM 2002*. 23-27 June 2002 New York, NY, USA, USA: Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings, pp. 1567-1576.

Yigit, M., Gungor, V.C., & Boluk, P., 2018. Performance analysis of amming code for wsn-based smart grid applications. *Turkish Journal of Electrcial Engineering & Computer Sciences.* **26** (1), pp. 125-137.

Yigit, M., Durmaz Incel, O., Baktir, S., & Gungor, V. C., 2017. QoS-Aware MAC protocols utilizing sectored antenna for wireless sensor networks-based smart grid applications. *International Journal of Communication Systems*. **30** (7), pp. 1-24.

Yigit, M., Gungor, V. C., Fadel, E., Nassef, L., Akkari, N., & Akyildiz, I. F., 2016. Channel-aware routing and priority-aware multi-channel scheduling for WSN-based smart grid applications. *Journal of Network and Computer Applications*. **71**, pp. 50-58.

Yigit, M., Durmaz Incel, O., & Gungor, V. C., 2014. On the interdependency between multi-channel scheduling and tree-based routing for WSNs in smart grid environments. *Computer Networks*. **65**, pp. 1-20.

Yigitel, M. A., Incel, O. D., & Ersoy, C., 2011. Design and implementation of a qos-aware mac protocol for wireless multimedia sensor networks. *Computer Communications.* **34** (16), pp. 1991-2001.

Yigitel, M. A., Incel, O. D., & Ersoy, C., 2011. QoS-aware mac protocols for wireless sensor networks: a survey. *Computer Networks*. **55** (8), pp. 1982-2004.

Yu, K., Barac, F., Gidlund, M., & Akerberg, J., 2012. Adaptive forward error correction for best effort wireless sensor networks. *In Communications (ICC), 2012 IEEE International Conference on.* pp. 7104-7109.

Zeng, Q., Li, H., & Peng, D., 2012. Frequency-hopping based communication network with multi-level qoss in smart grid: code and performance analysis. *IEEE Transaction on Smart Grid*. **3** (4), pp. 1841-1852.

Zhang, J., & Jia, X., 2009. Capacity analysis of wireless mesh networks with omni or directional antennas. *In INFOCOM 2009.* 19-25 April 2009 Rio de Janeiro, Brazil: IEEE, pp. 2881-2885.

Zhou, G., Huang, C., Yan, T., He, T., Stankovic, J. A., & Abdelzaher, T. F., 2006. MMSN: multi-frequency media access control for wireless sensor networks. *In Infocom*. 23-29 April 2006 Barcelona, Spain: 25th IEEE International Conference on Computer Communications, pp. 1-13.

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Publications :

—— Journals ——

- **Melike Yigit, Ozlem Durmaz Incel, and Vehbi Cagri Gungor**, 2014. On the interdependency between multi-channel scheduling and tree-based routing for WSNs in smart grid environments. *Computer Networks*. **65**, pp. 1-20.
- **Melike Yigit, Vehbi Cagri Gungor, Gurkan Tuna, Maria Rangoussi, and Etimad Fadel**, 2014. Power line communication technologies for smart grid applications: A review of advances and challenges. *Computer Networks*. **70**, pp. 366-383.
- **Melike Yigit, Vehbi Cagri Gungor, and Selcuk Baktir**, 2014. Cloud computing for smart grid applications. *Computer Networks*. **70**, pp. 312-329.

- **Melike Yigit, Bilal Erman Bilgin, and Adem Karahoca**, 2015. Extended topology based recommendation system for unidirectional social networks. *Expert Systems with Applications*. **42** (7), pp. 3653-3661.
- **Melike Yigit, Muhammed Macit, Vehbi Cagri Gungor, Taskin Kocak, and Oguz Ozhan,** 2016. Operator User Management System Based on the TMF615 Standard. *Journal of Network and Systems Management*. **24** (1), pp. 161-188.
- **Melike Yigit, Vehbi Cagri Gungor, Etimad Fadel, Laila Nassef, Nadine Akkari, and Ian F. Akyildiz**, 2016. Channel-aware routing and priority-aware multi-channel scheduling for WSN-based smart grid applications. *Journal of Network and Computer Applications*. **71**, pp. 50-58.
- **Melike Yigit, Ozlem Durmaz Incel, Selcuk Baktir, and Vehbi Cagri Gungor**, 2017. QoS-Aware MAC protocols utilizing sectored antenna for wireless sensor networks-based smart grid applications. *International Journal of Communication Systems*. **30** (7), pp. 1-24.
- **Sinan Kurt, Huseyin Ugur Yildiz, Melike Yigit, Bulent Tavli, and Vehbi Cagri Gungor**, 2017. Packet size optimization in wireless sensor networks for smart grid applications. *IEEE Transactions on Industrial Electronics*. **64** (3), pp. 2392-2401.
- **Melike Yigit, Vehbi Cagri Gungor, and Pinar Boluk**, 2018. Performance Analysis of Hamming Code for WSN-Based Smart Grid Applications, *Turkish Journal of Electrical Engineering & Computer Sciences*. **26** (1), pp. 125-137.
- **Melike Yigit, Huseyin Ugur Yildiz, Sinan Kurt, Bulent Tavli, and Vehbi Cagri Gungor,** 2018. A Survey on Packet Size Optimization for Terrestrial, Underwater, Underground, and Body Area Sensor Networks. *International Journal of Communication Systems,* pp. 35-72.

—— Conferences ——

- **M. Yigit, E. A. Yoney, and V. C. Gungor**, 2013. Performance of mac protocols for wireless sensor networks in harsh smart grid environment. *in Proc. IEEE Int. Black Sea Conference on Communications and Networking (BlackSeaCom)*. pp. 50–53.
- **M. Kapdan, M. S. Aktas, M. S., and M. Yigit**, 2013. Yapısal kod klon analizinde metrik tabanlı teknikler, *Proceedings of the 7th Turkish National Software Engineering Symposium*. pp. 1-19.

- **M. Kapdan, M. Aktas, and M. Yigit**, 2014. On the structural code clone detection problem: a survey and software metric based approach, *In International Conference on Computational Science and Its Applications.* pp. 492-507.
- **M. Yigit, P. Sarisaray Boluk, and V. C. Gungor,** 2018. Adaptive error control for wireless sensor network-based smart grid applications, *Second International Balkan Conference on Communications and Networking*. pp. 1-6.