MULTI-CONSTRAINED MECHANISM FOR INTRA-BODY AREA NETWORK QUALITY-OF-SERVICE AWARE ROUTING IN WIRELESS BODY SENSOR NETWORKS

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DEDICATION

This thesis is dedicated to my beloved family for their endless support, love, encouragement and sacrifices.

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With the name of ALLAH (most gracious and merciful), I am grateful to Him in blessing me with the knowledge, giving me the courage to tackle the problems and always help me in each step of my life.

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ABSTRACT

Wireless Body Sensor Networks (WBSNs) have witnessed tremendous research interests in a wide range of medical and non-medical fields. In the delay-sensitive application scenarios, the critical data packets are highly delay-sensitive which require some Quality-of-Service (QoS) to reach the intended destinations. The categorization of data packets and selection of poor links may have detrimental impacts on overall performance of the network. In WBSN, various biosensors transmit the sensed data towards a destination for further analysis. However, for an efficient data transmission, it is very important to transmit the sensed data towards the base station by satisfying the QoS multi-constrained requirements of the healthcare applications in terms of least end-to-end delay and high reliability, throughput, Packet Delivery Ratio (PDR), and route stability performance. Most of the existing WBSN routing schemes consider traffic prioritization to solve the slot allocation problem. Consequently, the data transmission may face high delays, packet losses, retransmissions, lack of bandwidth, and insufficient buffer space. On the other hand, an end-to-end route is discovered either using a single or composite metric for the data transmission. Thus, it affects the delivery of the critical data through a less privileged manner. Furthermore, a conventional route repair method is considered for the reporting of broken links which does not include surrounding interference. As such, this thesis presents the Multi-constrained mechanism for Intra-Body Area Network QoS aware routing (MIQoS) with Low Latency Traffic Prioritization (LLTP), Optimized Route Discovery (ORD), and Interference Adaptive Route Repair (IARR) schemes for the healthcare application of WBSN with an objective of improving performance in terms of end-to-end delay, route stability, and throughput. The proposed LLTP scheme considers various priority queues with an optimized scheduling mechanism that dynamically identifies and prioritizes the critical data traffic in an emergency situation to enhance the critical data transmission. Consequently, this will avoid unnecessary queuing delay. The ORD scheme incorporates an improved and multi-facet routing metric, Link Quality Metric (LQM) optimizes the route selection by considering link delay, link delivery ratio, and link interference ratio. The IARR scheme identifies the links experiencing transmission issues due to channel interference and makes a coherent decision about route breakage based on the long term link performance to avoid unnecessary route discovery notifications. The simulation results verified the improved performance in terms of reducing the end-to-end delay by 29%, increasing the throughput by 22% and route stability by 26% as compared to the existing routing schemes such as TTRP, PA-AODV and standard AODV. In conclusion, MIQoS proves to be a suitable routing mechanism for a wide range of interesting applications of WBSN that require fast, reliable and multi-hop communication in heavily loaded network traffic scenarios.

ABSTRAK

Rangkaian Pengesan Badan Tanpa Wayar (WBSNs) telah menarik perhatian luas dalam penyelidikan pelbagai bidang perubatan dan bukan perubatan. Dalam senario aplikasi *delay-sensitive*, paket data kritikal sangat *delay-sensitive* hingga memerlukan tahap Kualiti Perkhidmatan (QoS) untuk sampai ke destinasi yang dikehendaki. Kategori paket data dan pemilihan pautan yang lemah mungkin memberi kesan buruk terhadap prestasi keseluruhan rangkaian. Dalam WBSN, pelbagai pengesan bio menghantar data yang dikesan ke destinasi untuk dianalisis selanjutnya. Walau bagaimanapun, untuk penghantaran data yang cekap, sangat penting untuk menghantar data yang dikesan kepada stesen pangkalan dengan memenuhi keperluan pelbagai kekangan QoS dalam aplikasi penjagaan kesihatan dari segi paling kurang kelewatan sehala, dan tinggi dari segi kebolehpercayaan, kadar penghantaran data, Paket Nisbah Penghantaran (PDR), dan prestasi kestabilan laluan. Kebanyakan skim laluan WBSN sedia ada memilih keutamaan trafik untuk menyelesaikan masalah peruntukan slot. Akibatnya, penghantaran data mungkin menghadapi kelewatan yang tinggi, kehilangan paket, penghantaran semula, kekurangan jalur lebar, dan ruang penampan yang tidak mencukupi. Sebaliknya, laluan sehala ditemui menggunakan sama ada metrik tunggal atau komposit untuk penghantaran data. Justeru, ia memberi kesan kepada penghantaran data kritikal yang dibuat melalui cara yang kurang berkesan. Tambahan pula, cara konvensional dalam pembaikan laluan digunakan untuk melaporkan pautan yang rosak yang tidak melibatkan gangguan sekeliling. Tesis ini mengemukakan Mekanisme Penghalaan berdasarkan QoS Intra-BAN Berbilang-Kekangan (MIQoS) dengan skim Keutamaan Trafik Pendaman Rendah (LLTP), Penemuan Laluan Teroptimum (ORD), dan Pembaikan Laluan Gangguan Mudah Suai (IARR) untuk aplikasi penjagaan kesihatan WBSN dengan objektif untuk meningkatkan prestasi dari segi kelewatan sehala, kestabilan laluan, dan kadar penghantaran data. Skim LLTP yang dicadangkan menganggap pelbagai keutamaan giliran dengan mekanisme penjadualan teroptimum yang secara dinamis mengenal pasti dan mengutamakan laluan data kritikal dalam keadaan kecemasan untuk meningkatkan penghantaran data kritikal. Oleh itu, ini akan mengelakkan kelewatan giliran yang tidak perlu. Skim ORD menggabungkan laluan metrik pelbagai ciri yang lebih baik, Metrik Kualiti Pautan (LQM) mengoptimumkan pemilihan laluan dengan mempertimbangkan kelewatan pautan, nisbah penghantaran pautan, dan nisbah gangguan pautan. Skim IARR mengenal pasti pautan yang mengalami isu penghantaran akibat daripada gangguan saluran dan membuat keputusan yang koheren tentang kerosakan laluan berdasarkan prestasi pautan jangka panjang bagi mengelakkan pemberitahuan penemuan laluan yang tidak perlu. Keputusan simulasi mengesahkan prestasi meningkat dari segi pengurangan kelewatan sehala sebanyak 29%, peningkatan daya pemprosesan sebanyak 22% dan kestabilan laluan sebanyak 26% berbanding dengan skim laluan sedia ada seperti TTRP, PA-AODV dan AODV yang standard. Kesimpulannya, MIQoS terbukti sebagai mekanisme laluan yang sesuai untuk rangkaian pelbagai aplikasi WBSN yang menarik yang memerlukan komunikasi yang pantas, boleh dipercayai, dan multi-hop dalam senario rangkaian trafik yang sesak.

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	**ii**
	DEDICATION	**iii**
	ACKNOWLEDGEMENT	**iv**
	ABSTRACT	**v**
	ABSTRAK	**vi**
	TABLE OF CONTENTS	**vii**
	LIST OF TABLES	**xi**
	LIST OF FIGURES	**xii**
	LIST OF ABBREVIATIONS	**xiv**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Overview	1
1.2	Problem Background	4
	1.2.1 Traffic Prioritization for Critical Data Transmission	5
	1.2.2 Use of Non-Optimal Parameters for Route Discovery/Selection	6
	1.2.3 Conventional Route Maintenance for Critical Data Transmission	10
1.3	Problem Statement	11
1.4	Research Questions	12
1.5	Research Goal	13
1.6	Research Objectives	13
1.7	Research Contribution	14
1.8	Scope of the Research	15
1.9	Significance of Study	15
1.10	Research Outline	15

CHAPTER 2 LITERATURE REVIEW 17
2.1 Introduction 17
2.2 Overview of the WBSN 17
2.2.1 Communication Layers of the WBSN 20
2.2.2 Types of the WBSN 20
2.2.3 Applications of the WBSN 21
2.3 Routing Protocol 24
2.3.1 Routing Issues and Challenges 25
2.4 Existing Routing Protocols 29
2.4.1 Unoptimized Traffic Prioritization Schemes 29
2.4.2 Unreliable Route Discovery Schemes 35
2.4.2.1 Thermal-aware Routing Protocols 35
2.4.2.2 QoS-aware Routing Protocols 40
2.4.2.3 Link Quality-aware Routing Protocols 46
2.4.3 Unstable Route Maintenance Schemes 54
2.5 Findings 58
2.6 Summary 59

CHAPTER 3 RESEARCH METHODOLOGY 61
3.1 Introduction 61
3.2 Operational Framework 62
3.3 Research Design and Procedure 63
3.3.1 Low Latency Traffic Prioritization (LLTP) Scheme 63
3.3.2 Optimized Route Discovery (ORD) Scheme 66
3.3.3 Interference Adaptive Route Repair (IARR) Scheme 68
3.4 Simulation Framework 69
3.5 Network Model and Simulation Setup 72
3.6 Performance Evaluation 74
3.7 Assumptions and Limitations 76
3.8 Summary 76

CHAPTER 4	**LOW LATENCY TRAFFIC PRIORITIZATION SCHEME**	**77**
4.1	Introduction	77
4.2	Overview of the LLTP Scheme	77
4.3	Design of the LLTP Scheme	78
	4.3.1 Packet Categorization Phase	79
	4.3.2 Queue Formation and Queue Factor Evaluation Phase	81
	4.3.3 Packet Queuing Phase	82
	4.3.4 Timeout Policy Configuration Phase	83
4.4	Experimental Setup of the LLTP Scheme	86
4.5	Performance Evaluation of the LLTP Scheme	88
	4.5.1 Throughput	88
	4.5.2 Packet Delivery Ratio	90
	4.5.3 Average Queuing Delay	91
4.6	Summary	92
CHAPTER 5	**OPTIMIZED ROUTE DISCOVERY SCHEME**	**95**
5.1	Introduction	95
5.2	Overview of the ORD Scheme	95
5.3	Design of the ORD scheme	96
	5.3.1 Initialization Phase	97
	5.3.2 Multi-constrained QoS-aware Routing Phase	99
5.4	Experimental Setup of the ORD Scheme	102
5.5	Performance Evaluation of the ORD Scheme	103
	5.5.1 Throughput	105
	5.5.2 Average End-to-End Delay	106
	5.5.3 Packet Drop Ratio	107
	5.5.4 Normalized Routing Load	108
5.6	Summary	110
CHAPTER 6	**INTERFERENCE ADAPTIVE ROUTE REPAIR SCHEME**	**111**
6.1	Introduction	111

	6.2	Overview of the IARR Scheme	111
	6.3	Design of the IARR Scheme	112
		6.3.1 Link Assessment Phase	114
		6.3.2 Route Breakage Decision Phase	115
	6.4	Experimental Setup of the IARR Scheme	117
	6.5	Performance Evaluation of the IARR Scheme	117
		6.5.1 Average End-to-End Delay	118
		6.5.2 Normalized Routing Load	119
		6.5.3 Throughput	120
		6.5.4 Route Lifetime	121
	6.6	Summary	122
CHAPTER 7		**CONCLUSION**	**125**
	7.1	Overview	125
	7.2	Research Achievements	125
		7.2.1 Low Latency Traffic Prioritization Scheme	126
		7.2.2 Optimized Route Discovery Scheme	126
		7.2.3 Interference Adaptive Route Repair Scheme	127
	7.3	Limitations of the MIQoS	128
	7.4	Directions for Future Works	128
REFERENCES			**131**
LIST OF PUBLICATIONS			149

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	WBSN Projects in the Medical Field	22
Table 2.2	WBSN Projects in the Non-medical Field	24
Table 2.3	Recent MAC-based Traffic Prioritization Schemes	32
Table 2.4	Recent Network-based Traffic Prioritization Schemes	34
Table 2.5	Existing Thermal-aware Routing Protocols	41
Table 2.6	Existing QoS-aware Routing Protocols	46
Table 2.7	Existing Link Quality-aware Routing Protocols	53
Table 2.8	Existing Route Maintenance Schemes	56
Table 3.1	Overall Research Plan	65
Table 3.2	Simulation Framework	71
Table 3.3	Simulation Parameters	74
Table 3.4	Performance Evaluation Metrics	75
Table 4.1	Packet Prioritization based on the Defined Threshold Values	81
Table 4.2	Queue Allocation Rules based on the Proposed SPS Method	83

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Structure of the Literature Review	18
Figure 2.2	Basic WBAN	19
Figure 2.3	Layers of Wireless Communication in WBSN	21
Figure 2.4	Inter-network Interference	52
Figure 3.1	Operational Framework	62
Figure 3.2	Research Framework	64
Figure 3.3	The Block Diagram of the LLTP Scheme	67
Figure 3.4	The Block Diagram of the ORD Scheme	68
Figure 3.5	The Block Diagram of the IARR Scheme	70
Figure 3.6	The structural design of NS-2	72
Figure 3.7	Network model of the Proposed WBSN	73
Figure 4.1	Flowchart of the Proposed LLTP Scheme	80
Figure 4.2	Data packet structure	81
Figure 4.3	Network Scenario of the Proposed WBAN	87
Figure 4.4	Throughput at Different Data Rates	90
Figure 4.5	Packet Delivery Ratio at Different Data Rates	91
Figure 4.6	Average Queuing Delay at Different Data Rates	92
Figure 5.1	Flowchart of the ORD scheme	97
Figure 5.2	Route Discovery Mechanism of the (a) AODV and (b) ORD Scheme	100
Figure 5.3	Substantial Variations in the Delay Performance over Time	104
Figure 5.4	Substantial Variations in the Throughput Performance over Time	104
Figure 5.5	Throughput at Different Data Rates	106
Figure 5.6	Average End-to-end Delay at Different Data Rates	107

Figure 5.7	Packet Drop Ratio at Different Data Rates	108
Figure 5.8	Normalized Routing Load at Different Data Rates	109
Figure 6.1	Route Maintenance Procedure of the IARR Scheme	113
Figure 6.2	Flowchart of the IARR Scheme	114
Figure 6.3	Average End-to-end Delay at Different Data Rates	119
Figure 6.4	Normalized Routing Load at Different Data Rates	120
Figure 6.5	Throughput at Different Data Rates	121
Figure 6.6	Route Lifetime at Different Data Rates	122

LIST OF ABBREVIATIONS

AODV	-	Ad hoc On-demand Distance Vector
ALTR	-	Adaptive Least Temperature Rise
API	-	Application Programming Interface
AC	-	Alarm Control
AS	-	Adjacent hop Selection
ACK	-	Acknowledgment
AHL	-	Allowed Hello Loss-rate
BSU	-	Body Sensor Unit
BCU	-	Body Control Unit
BANC	-	Body Area Network Coordinator
BE	-	Back-off Exponent
CAP		Contention Access Period
CBR	-	Constant Bit Rate
CCA	-	Clear Channel Assessment
CD	-	Command Data
CE	-	Consumer Electronic
CMU	-	Central Monitoring Unit
CM	-	Central Mote
CoR-MAC	-	Contention over Reservation Medium Access Control
CSMA/CA	-	Carrier Sense Multiple Access with Collision Avoidance
Co-LAEEBA	-	Cooperative-Link Aware and Energy Efficient Body Area network
CFP	-	Contention Free Period
CCI	-	Channel Contention Interference
CRF	-	Count of Route Failures
DQBAN	-	Distributed Queuing Body Area Network
DTQ	-	Data Transmission Queue
DP-PCC	-	Data Privacy based Pearson Correlation Coefficient
DTN	-	Delay Tolerant Network
DMQoS	-	Data-centric Multi Objectives QoS-aware routing
DSP	-	Delay Sensitive Packets
DES	-	Discrete Event Simulation

DT	-	Data Transmission
DTSs	-	Data Transmit Slots
EMG	-	Electromyography
ECG	-	Electrocardiogram
EEG	-	Electro-encephalograph
Extra-BAN	-	Extra-Body Area Network
ETX	-	Expected Transmission Count
ETT	-	Expected Transmission Time
ELBPQA	-	Energy Efficient and Load Balanced Priority Queue Algorithm
ENSA-BAN	-	Energy-efficient Next hop Selection Algorithm for multi-hop Body Area Network
E-OCER	-	Extended-Optimized Cost Effective and Energy Efficient Routing protocol
ELR-W	-	Energy-aware Link efficient Routing protocol for WBANs
EPR	-	Energy aware Peering Routing
ERM	-	Enhanced Route Maintenance
ETSs	-	Emergency data Transmit Slots
ETPA	-	Energy efficient Thermal and Power Aware routing protocol
EWMA	-	Exponential Weighted Moving Average
FIFO	-	First In First Out
FDTD	-	Finite Difference Time Domain
FSM	-	Finite State Machine
FTDMA	-	Flexible Time Division Multiple Access
F-LQE	-	Fuzzy Link Quality Estimator
GA	-	Genetic Algorithm
HRPs	-	Hybrid Routing Protocols
HPR	-	Hotspot Preventing Routing
H-LQE	-	Hardware Link Quality Estimators
HI	-	Hello Interval
Intra-BAN	-	Intra-Body Area Network
Inter-BAN	-	Inter-Body Area Network
IAA	-	Interference Avoidance Algorithm
IMHMS	-	Intelligent Mobile Health Monitoring System
IFS	-	Inter Frame Space
IRP	-	Interference aware Routing Protocol

LOCALMOR	-	Localized Multi-Objective Routing
LAEEBA	-	Link Aware and Energy Efficient Body Area network
LQM	-	Link Quality Metric
LD	-	Link Delay
LDR	-	Link Delivery Ratio
LQEs	-	Link Quality Estimators
LQI	-	Link Quality Indicator
LTTP	-	Low Latency Traffic Prioritization
LIR	-	Link Interference Ratio
LoS	-	Line of Sight
LTR	-	Least Temperature Routing
LTRT	-	Least Total Route Temperature
LLF	-	Link Likelihood Factor
MAC	-	Medium Access Control
MIQoS	-	Multi-constrained mechanism for Intra-Body Area Network Quality-of-Service aware routing in Wireless Body Sensor Networks
MAR-PC	-	Multiple Access with Reserve and Priority Control
M-ATTEMPT	-	Mobility-supporting Adaptive Threshold-based Thermal-aware Energy-efficient Multi-hop ProTocol
MMA	-	Min-Max Approach
MDC	-	Medical Display Coordinator
MCS	-	Monte-Carlo Simulation
MANET	-	Mobile Ad-hoc Network
NLoS	-	None Line of Sight
NAM	-	Network AniMator
NSNM	-	Network Simulators with Node Model
NENM	-	Network Emulators with Node Models
NS	-	Network Simulator
NSC	-	Nursing Station Coordinator
OCER	-	Optimized Cost Effective and Energy Efficient Routing
OMAR	-	Opportunistic and Mobility Aware Routing
OBSFR	-	On Body Routing algorithm
OP	-	Opportunistic routing Protocol
OMAR	-	Opportunistic and Mobility Aware Routing
OP	-	Ordinary Packets

ORD	-	Optimized Route Discovery
OTCL	-	Object-oriented Tool Command Language
PSR	-	Prediction based Secure and Reliable
PRR	-	Packet Reception Ratio
PVA	-	Pocket Velocity Approach
PAP	-	Path Assignment Protocol
PRPLC	-	Probabilistic packet routing protocol
PA-AODV	-	Priority Aware Adhoc On-demand Distance Vector
PTR	-	Priority-based Temperature-aware Routing
PRPs	-	Proactive Routing Protocols
PDA	-	Personal Display Assistant
PDR	-	Packet Delivery Ratio
PA-MAC	-	Priority-based Adaptive Medium Access Control
QoS	-	Quality-of-Service
QPRD	-	QoS-aware Peering Routing for Delay-sensitive data
QPRR	-	QoS-aware Peering Routing for Reliability-sensitive data
RT	-	Routine Traffic
RTS	-	Request To Send
Rack	-	Receive acknowledge
RNPT	-	Required Number of Packet Transmissions
RSSI	-	Received Signal Strength Indicator
RSP	-	Reliability Sensitive Packets
RSF	-	Routing Service Framework
RL-QRP	-	Reinforcement Learning based Routing Protocol with QoS Support
RRPs	-	Reactive Routing Protocols
RAIN	-	Routing Algorithm for Network of Homogeneous and ID-Less Bio Medical Sensor Nodes
RTM-RP	-	Relay based Thermal-aware and Mobility support Routing Protocol
RAP	-	Random Access Period
RB-TDMA	-	Relay Buffer Time Division Multiple Access
RD-TDMA	-	Relay Data Time Division Multiple Access
RBNT	-	Route Breakage Notification Threshold
RMPR	-	Reliable Multi-Path Routing algorithm
SINR	-	Signal to Interference Noise Ratio

S-LQE	-	Software-Link Quality Estimators
SNR	-	Signal to Noise Ratio
SAR	-	Specific Absorption Rate
SHA	-	Shortest Hop Algorithm
SSSP	-	Single Source Shortest Path
TARA	-	Thermal Aware Routing Algorithm
TAP-MAC	-	Traffic- Adaptive Priority-based Medium Access Control
TraySL-MAC	-	Traffic priority-aware adaptive SLot allocation based Medium Access Control
TraPy-MAC	-	Traffic Priority-aware adaptive slot allocation for Medium Access Control
TP-CAT	-	Traffic Priority-based Channel Access Technique
TSHR	-	Thermal-aware Shortest Hop Routing
TMQoS	-	Thermal-aware Multi-constrained intra-body QoS
TLQoS	-	Thermal-aware Localized QoS
M-ATTEMPT	-	Thermal-aware Energy efficient Multi-hop ProTocol
TDMA	-	Time Division Multiple Access
TTRP	-	Trust and Thermal-aware Routing Protocol
TDS	-	Trace-Driven Simulation
UDP	-	User Datagram Protocol
UWSN	-	Underwater Wireless Sensor Network
VANET	-	Vehicular Ad-hoc Networks
V-MAC	-	Virtual Medium Access Control
WBSN	-	Wireless Body Sensor Network
WSN	-	Wireless Sensor Network
WUSN	-	Wireless Underground Sensor Network
WMEWMA	-	Window Mean with Exponentially Weighted Moving Average
WLAN	-	Wireless Local Area Network
WPAN	-	Wireless Personal Area Network

CHAPTER 1

INTRODUCTION

1.1 Overview

In the past few years, wireless networks have gained extraordinary appreciation in various fields of life from home to small businesses, hospitals, and military use. The main reason behind its popularity is, it is cheaper and easy to set-up. It helps users to simultaneously join and share the resources in a network without annoying wires and connectors. Moreover, a user can move within its local coverage area without losing the network connection. The most demanding wireless networks are Wireless Sensor Network (WSN), Wireless Underground Ssensor Network (WUSN), Mobile Ad-hoc Network (MANET), Vehicular Ad-hoc Network (VANET), and Wireless Body Sensor Network (WBSN).

The WBSN is a promising technology because of its broad utilization in the medicine and non-medicine domain. The several tiny, intelligent and heterogeneous biosensors (implanted or attached) are incorporated to form a WBSN. Typically, the WBSN provides a biosensor-to-biosensor communication session. The main function of these biosensors is to sense the physical data (biomedical data readings, for instance, Electromyography (EMG), blood sugar, Electrocardiogram (ECG), temperature, and Electro-encephalograph (EEG)) and transmit it to its final destination (base station/Personal Display Assistant (PDA)) for further analysis (Sangwan and Bhattacharya, 2015; Itani *et al.*, 2016; Qu *et al.*, 2019).

The WBSN has some advantages over other wireless networks such as the biosensor nodes of WBSN are lightly weighted, robust and accurate. It gives advantages to medical and non-medical applications by continuously monitoring the physical data (improves the quality of life). It provides wireless interconnection between various biosensors (in or on the human body). It allows a specific way of controlling the complex behaviour of biosensors by a single monitoring device (Ullah *et al.*, 2012; Bangash *et al.*, 2014; Movassaghi *et al.*, 2014a; Elhadj *et al.*, 2016).

The overall communication of WBSN is based on three layers such as Intra-Body Area Network (Intra-BAN), Inter-Body Area Network (Inter-BAN), and Extra-Body Area Network (Extra-BAN) (Ahmed *et al.*, 2019b). Intra-BAN deals with the communication between biosensors and the master node (sink node) of the WBSN. The biosensors are either implanted inside or attached to the human body and are responsible for sending sensed data of the patient to the sink node (Negra *et al.*, 2016). Inter-BAN deals with the communication between the master node and personal devices such as laptops and mobile phones. While the extra-BAN deals with the communication between the personal devices and the outside world via Internet.

However, the biosensor’s communication can be a single-hop or multi-hop. In single-hop communication, a source node can directly communicate with the destination node by using a direct route (Javaid *et al.*, 2013). There is no need for a routing protocol because all biosensor nodes are one hop away from the sink node. While in multi-hop communication; a source node can communicate with the destination node by using multiple routes, it means the sensed data will travel through one or more intermediate nodes before reaching the master node (Abidi *et al.*, 2017). In comparison to a single-hop, multi-hop communication is widely used to protect the human body by excessive heat radiations from the batteries of the biosensor nodes. Moreover, the data traffic load issue arises when the heavy transmission takes place between various biosensor nodes. The single-hop transmission is applicable when there is no traffic overhead while in multi-hop, many intermediate relay nodes are deployed to minimize the network interference effects and power consumption (Ali *et al.,* 2015).

Due to the simultaneous communication among various biosensors, there is a possibility of getting various critical issues like network interference and congestion. In WBSN, there are two most common types of network interference that takes place within or with other wireless networks such as intra-network and inter-network interference. Intra-network interference considers a single WBSN among different sensor nodes while the inter-network interference takes place between multiple WBSNs (named as mutual interference) or among WBSNs and other wireless technologies. However, congestion issues arise when the incoming traffic load exceeds the capacity of the transmission link, buffer overflows, packet collision and channel contention (Tickoo and Gambhir, 2015; Ibrahim *et al.*, 2019; Ullah *et al.*, 2019). There are two most common types of congestion such as node-level congestion and link-level congestion. The node-level congestion occurs when buffer/queue overflows while the link-level congestion occurs when many active sensor nodes use the same channel simultaneously, packet collision and channel contention/network interference. Consequently, it impacts the Quality-of-Service (QoS) in terms of packet loss, end-to-end delay, Packet Delivery Ratio (PDR) and affects the critical data to be delivered in a less privileged manner. To enhance the PDR and throughput of the network, it is very important to avoid both types of congestion as much as possible.

However, the wireless networks have significantly different circumstances than the wired networks, because of using air as a physical medium for communication. Air is an unbounded medium with no protection from other signals so, the nodes in a wireless network has low bandwidth and high interference. As opposed to a wired network they have a shared medium for transmission; therefore, they also face the contention from other nodes. Although, with the evolvement of real-time applications, users demand some quality from the wireless networks. Providing quality to users is a challenge for wireless networks due to its constraints. While in WBSN, the physical data requires a different kind of QoS due to the heterogeneous nature of biosensors to transmit without data loss and delay (Cai *et al.*, 2019).

Furthermore, the QoS-aware routing scheme not only discovers a route from source to destination but also satisfies the QoS requirements in heavily loaded wireless networks. The data priority, data security, link reliability, low transmission delay, high delivery ratio, energy efficiency, and temperature rise are the QoS requirements that need to be considered in WBSN. Recent research proves that researchers have proposed various QoS-aware routing schemes. However, the proposed schemes still pose vulnerabilities in providing data categorization, optimized route discovery and route maintenance and do not offer a cost-effective solution tailored to the stringent constraints of sensor nodes (Ambigavathi and Sridharan, 2015; Anwar *et al.*, 2018; Ambigavathi and Sridharan, 2018; Shanmugapriya and Karthikeyan, 2018; Bhangwar *et al.*, 2019; Jamil *et al.*, 2019). Therefore, there is a significant need to provide QoS support in WBAN that make use of optimized traffic prioritization, route discovery, and route maintenance and overcome the aforementioned limitations.

1.2 Problem Background

In the majority of cases, WBSN is deployed in the delay-sensitive application scenarios where providing QoS is of utmost importance. Emergency and critical data packets must reach to the intended destination without incurring significant delays. The categorization of data packets and selection of poor links may have detrimental impacts on the performance of WBSN and there can be significant variations in throughput, delay, and route stability performance. The following subsections summarize some of the limitations of existing routing schemes in WBSN that laid the foundation for this thesis.

1.2.1 Traffic Prioritization for Critical Data Transmission

The emergence of real-time and delay-sensitive applications designed for WBSN demands to provide data dissemination on time. In an emergency situation, the generated data is critical (carries patient related information) that must be delivered to their intended destinations by fulfilling the multi-constrained demands (reliability, throughput, delay, and route stability) of the healthcare applications. Moreover, congestion occurs in heavy traffic situations when the incoming traffic load exceeds the capacity of the transmission link, buffer overflows, packet collision and channel contention. Consequently, it impacts the QoS in terms of packet loss, end-to-end delay, and PDR. However, most of the routing protocols proposed for WBAN overlook important characteristics of prioritization, in pursuit of WBAN, in their design models (Ambigavathi and Sridharan, 2015; Ayatollahitafti *et al.*, 2016; Kaur and Singh, 2017; Ambigavathi and Sridharan, 2018).

In past literature, there is a variety of priority-aware routing protocols have been proposed for WBSN, especially for the Medium Access Control (MAC) layer (Yu *et al.*, 2016; Bhandari and Moh, 2016; Ullah *et al.*, 2017a; Alam and Hamida, 2017). The presented MAC-based slot allocation schemes prioritize the data frames (super-frames) and solve the problem of slot allocation. The Traffic priority-aware adaptive SLot allocation based MAC (TraySL-MAC) protocol was proposed (Ullah *et al.*, 2017a). In TraySL-MAC protocol, there are three slot allocation algorithms that have been developed such as high threshold vital sign criticality-based adaptive slot allocation, low threshold vital sign criticality-based adaptive slot allocation and reduced contention adaptive slot allocation. A Contention over Reservation MAC (CoR-MAC) protocol was proposed for critical time services in WBSNs (Yu *et al.*, 2016). The CoR-MAC protocol uses the dual booking, for instance, if the reserved time slots are empty then, other nodes can access them through the contention-based reservation to increase the channel usage and decrease the data delay. Moreover, the Priority-based Adaptive MAC (PA-MAC) protocol was proposed to allocate the time slots dynamically according to the traffic priority (Bhandari and Moh, 2016). In PA-MAC protocol, the data traffic is prioritized by priority-guaranteed Carrier Sense Multiple Access with Collision

Avoidance (CSMA/CA) procedure in the Contention Access Period (CAP). The Contention Free Period (CFP) is used to transfer significant numbers of consecutive data packets to the coordinator.

In the light of the abovementioned related works, it can be observed that various priority mechanisms are proposed for the MAC layer. In the MAC standard, there is only one queue within a station and does not provide any service differentiation to the flows that may need some QoS. Moreover, the MAC priority-aware protocols are more focused on the priorities of the super-frames and solve the slot allocation problems. However, the slot allocation strategy is not preferable for emergency data transmission because it reduces the performance of the MAC protocol in terms of minimum duration of super-frame and slots or insufficient slots, retransmission of collided data packets, delay, frequent invocation of beacon interval and high energy consumption (Ullah *et al.*, 2017b). The high number of retransmission and collision degrade the performance, throughput, lifetime of the network and consume a high amount of energy. However, these protocols overlook the optimized traffic prioritization for emergency data transmission, because it increases the data redundancy, queue delay, data loss and decreases the reliability of the network. Consequently, it affects the critical data to be delivered in a less privileged manner. Therefore, an efficient traffic prioritization scheme should be incorporated in routing that addresses the aforementioned issues effectively.

1.2.2 Use of Non-Optimal Parameters for Route Discovery/Selection

The selection of a suitable route is necessary for routing in any network. By using an appropriate route, the sensed data (data packets) can easily be routed from source to destination in a specified time. In past literature, there are many route selection protocols proposed for WBSN (Ayatollahitafti *et al.*, 2016; Smail *et al.*, 2016; Bhangwar *et al.,* 2017; Kaur and Singh, 2017; Bhangwar *et al.*, 2019; Ibrahim *et al.*, 2019). Moreover, these route selection protocols either use a single metric (i.e. temperature/energy consumption/distance) or composite metric (i.e. temperature with hop count/energy with hop count). In WBSNs, biosensors are very limited in terms of energy resource because in most cases, it has an inaccessible power source, or it is very difficult to replace the power source. To counter this limitation there are various energy-aware routing protocols proposed in the past few decades. However, their route selection methods are not optimized, and they are entirely based on temperature, hop count, and cost function.

Many routing protocols consider cost function metric for the route selection. A cost function represents the node's distance from the sink and its remaining energy. It selects the forwarder (parent) node with the least cost function and all adjacent nodes transmit their data towards the forwarder node. Then the forwarder node clusters the collected data and forwards it to the sink node. An Energy-efficient Next hop Selection Algorithm for multi-hop BAN (ENSA-BAN) was proposed to minimize the energy consumption (Ayatollahitafti *et al.*, 2016). The ENSA-BAN selects the adjacent hop node by considering minimum hop count and cost function. The Optimized Cost Effective and Energy Efficient Routing protocol (OCER) and Extended-OCER (E-OCER) protocols were proposed (Kaur and Singh, 2017). In OCER, an optimal route is selected by applying a Genetic Algorithm (GA) on a multi-objective cost function. A node with the least cost function is selected as the forwarder node. While the E-OCER is the extended version of OCER that considers the intercommunication between biosensor nodes by the multi-hop method. The same cost function scheme was used in route selection (Shilpa and Hiremath, 2017).

Some protocols consider the shortest path algorithm for route selection. Kachroo and Bajaj (2015) has used a GA to select the optimized route by taking the shortest path among possible paths. Satyaprasad and Rajasekhararao (2016) proposed the Path Assignment Protocol (PAP) due to some security issues. The PAP was designed to find the distance among the suspicious nodes. In PAP, the selection of the adjacent node discovers the minimum short route. An Opportunistic and Mobility Aware Routing protocol (OMAR) proposed to optimize the routing process by fetching advantages from the short term (short-time, like few seconds) and long term (long-time, like hours) (Hamida *et al.*, 2014). While Ahmed *et al.* (2015b) proposed the Cooperative-Link Aware and Energy Efficient Body Area network (Co-

LAEEBA) which is an improved version of Link Aware and Energy Efficient Body Area network (LAEEBA) protocol based on cooperative routing. In Co-LAEEBA, the shortest-path route algorithm is used to find the cooperative nodes. A minimum hop count route is selected for data transmission.

Several routing protocols proposed for WBSN to overcome the heating or hotspot issue. Their routing metrics are temperature and hop count. Every node selects a minimum hop count route to the sink node. The Mobility supporting Adaptive Threshold-based Thermal-aware Energy-efficient Multi-hop ProTocol (M-ATTEMPT) was proposed (Javaid *et al.*, 2013). The proposed protocol consists of four stages such as initialization, routing, scheduling, and data transmission stage. In the initialization stage, each node telecast a Hello packet. In the routing stage, less hop count routes are chosen from the possible routes. In the scheduling stage, the sink node constructs a Time Division Multiple Access (TDMA) program for every origin node. While in the transmission stage, origin nodes transmit their data to the sink node. Every node selects a minimum hop count route to the sink node. If a parent node gets heated, then the children nodes choose another optimal route. Monowar *et al.* (2014) proposed a Thermal-aware Multi-constrained intra-body QoS (TMQoS) routing protocol to create a routing table which holds many shortest routes. The routing table is updated by the estimation values of node temperature. While Monowar and Bajaber (2015) proposed a Thermal-aware Localized QoS (TLQoS) routing protocol for in-vivo sensor nodes in WBSN. In the TLQoS protocol, a localization method is used for the route selection. Their routing potentials are based on temperature, hop count and a routing loop avoidance method is used to avoid the routing loops.

Kanagachidambaresan and Chitra (2016) proposed the Thermal-Aware: Fail Safe Fault Tolerant (TA-FSFT) algorithm to prevent the damage of internal tissues of the human body. Their routing metrics are temperature and hop count. The Finite State Machine (FSM) is used to model the situation while the Markov model is used to analyze the situation of the patients. The biosensor nodes communicate with the Central Monitoring Unit (CMU) or Central Mote (CM). Then CMU/CM collects the data from each biosensor node and broadcasts to the sink node. Bhangwar *et al.*

(2017) proposed a Trust and Thermal-aware Routing Protocol, named (TTRP) for WBSN. It integrates the security primitive with the thermal-aware routing to avoid hotspot nodes from the selected routes. While another Weighted QoS-based Energy and Thermal-aware Routing Protocol (WETRP) is proposed for WBSNs (Bhangwar *et al.*, 2019). It considers a composite metric for route selection which incorporates link delay, node energy, and temperature.

Furthermore, very few WBSN routing protocols consider ETX and ETT link quality metrics for route selection (Zhou *et al.*, 2011; Liang *et al.*, 2012a; Liang *et al.*, 2014b; Sarra *et al.*, 2014; Gousalya *et al.*, 2016; Javaid *et al.*, 2016; Lai *et al.*, 2017; Shimly *et al.*, 2017; Ye *et al.*, 2018). However, these metrics are not feasible due to their serious limitations in terms of QoS demands. As the ETX has few limitations such as it is not designed for a heterogeneous environment and prefers shorter paths. It considers the loss rate by assuming delivery ratios (of forward and reverse data packets). And it does not consider the interference on the link, bandwidth, and mobility. ETT performs well when there is no interference in the network, however, this is not a realistic situation in dynamic networks. In addition, the network interference problem is investigated in many types of researches (Kim *et al.*, 2013; Zhang *et al.*, 2013; Movassaghi *et al.*, 2014c; Ali *et al.,* 2015; Meharouech *et al.*, 2016; Mile *et al.*, 2018; Shaik *et al.*, 2018; Adhikary *et al.*, 2018) where they have focused on inter-network interference. Recently, a comparative study is presented which considers the classification of network interference and inter-network interference mitigation schemes for ZigBee-WBAN (Shaik *et al.*, 2018).

In the light of the abovementioned related works, it can be observed that the existing routing protocols deal with single or composite metric. Their route selections schemes are not optimized, most of them are based on temperature, energy, hop count, and cost function. In which each biosensor selects a minimum hop count route to transmit the data packets to the sink node. To minimize the network overhead, most of the existing schemes discover routes based on the shortest time interval and shortest distance among biosensor nodes. However, the shortest route or shortest time interval without taking into consideration the suitable link quality metric leads towards the data loss. The selection of unstable/broken link can cause data loss and retransmissions thereby significantly affecting the network performance. Moreover, it is also observed that existing routing protocols do not integrate dynamic network conditions like channel interference in their routing decisions. Consequently, it leads to the selection of routes that do not meet the QoS requirements. The interference on links causes significant variations in the performance of reliability, delay, and throughput. Therefore, an efficient route discovery scheme should be designed with an integrated set of requirements (such as link delay, link delivery ratio, and link quality/channel interference) for optimized route selection in Intra-BAN communication.

1.2.3 Conventional Route Maintenance for Critical Data Transmission

Typically, the multi-hop routing protocols depend on intermediate nodes for forwarding the data packets and reporting the route breakages. Although in most of the situations, the reported notifications of the link failure are not valid due to wireless interference/noise and channel contention. Temporary congestion causes false link failure notification for transient route breakage (Ahmed *et al.*, 2016). Moreover, the frequent failure notification of the transmission link unnecessarily declares unstable/broken route and consumes more energy of biosensors; additionally, the relay node drops data packets which cause delay or loss of critical data packets. The high frequency of link failure notifications results in the high number of route discoveries and route instability (Ahmed *et al.*, 2018). Route instability is one of the hindering factors that dramatically impact the performance of multi-hop wireless networks. The route stability is a very important concept in route maintenance and the stability period is defined as "the time of network operation till the first node die. The time after the death of the first node is termed as an unstable period" (Javaid *et al.*, 2015).

As described in the previous subsection 1.2.2, the existing literature on WBSN only considers various metrics i.e. cost function, long and short-term link behavior for link configuration/selection. However, an improved route maintenance mechanism for reporting route breakages is overlooked. The frequent failure of the transmission link undermined the route stability, consumes more energy of biosensors, high overload in terms of new route discoveries and more packet drops which cause a huge loss to the delivery of critical data packets. Therefore, an efficient route maintenance scheme should be designed that makes a dynamic decision regarding route breakage status (either permanent breakage or transient) based on monitored congestion level and frequency of link failure.

1.3 Problem Statement

This thesis addresses the problems faced by existing routing protocols which limit the overall throughput, delay, and route stability performance. The healthcare applications of WBSN demands on the dissemination of data, reliably and on time. The critical data packets are highly delay-sensitive that must reach the intended destination through high priority routes (have a low end-to-end delay and intra-network interference ratio and high PDR). A great number of the existing routing schemes focus on the slot allocation problem and very few routing schemes consider queuing techniques for data categorization. However, these protocols overlook the optimized traffic prioritization for critical data transmission, because it increases the data redundancy, queue delay, data loss and decreases the reliability of the network. Consequently, it affects the critical data to be delivered in a less privileged manner.

Furthermore, most routing schemes focus on selecting end-to-end route either using single or composite metric whereas overlook optimized route selection by keeping in view important design characteristics of WBSN. Moreover, most of the existing routing protocols incorporate ETX or ETT metric for link quality which is not feasible for WBSN due to their limitations and does not integrate channel interference in their routing decisions. Consequently, it leads towards the selection of routes that do not meet the QoS requirements. The interference on links causes significant variations in the performance of reliability, delay, and throughput.

Besides, most of multi-hop routing protocols employ route maintenance for reporting route breakage. However, these conventional route breakage reporting methods cannot distinguish temporary or permanent transmission disruption. Consequently, give rise to high route maintenance calls thereby undermine throughput, delay, and route stability.

1.4 Research Questions

Based on the discussion in section 1.3, the research questions can be formulated as follows:

i. How to prioritize critical data packets in the Intra-BAN network that can be delivered within the time constraints?

    a) How to assign various threshold values to the sensed data readings for an efficient traffic prioritization?

    b) How to en-queue and dequeue data packets from a specified queue to avoid node-level congestion, queue overflow and packet loss?

    c) How to minimize the queuing delay? and improve the overall performance of the WBSN?

ii. How to select an optimized end-to-end route in the Intra-BAN network by considering the characteristics of WBSN, especially QoS requirements?

    a) What parameters should be considered in route selection metric?

    b) How to minimize the link delay and drop ratio for critical data transmission?

    c) How to minimize the channel interference to avoid inconsistent transmission?

iii. How to minimize the frequency of link failure notifications in the Intra-BAN network and make a more actual decision regarding the status of the link?

   a) How to estimate the channel interference before declaring the route breakage decision?

   b) How to assess the transmission link in terms of actual status and link quality?

   c) How to improve route reliability in terms of route stability?

1.5 Research Goal

This thesis aims to develop a Multi-constrained mechanism for Intra-Body Area Network Quality-of-Service aware routing (MIQoS) with an optimized traffic prioritization, route discovery, and route maintenance schemes for healthcare application of WBSN with an objective to improve performance in terms of average end-to-end delay, route stability, and throughput.

1.6 Research Objectives

The objectives of this thesis are designed in the perspective of the research questions mentioned in section 1.4. The key objectives of this thesis are:

i. To develop a low latency traffic prioritization scheme in the Intra-BAN network that dynamically identifies and prioritizes the critical data traffic in an emergency situation.
ii. To develop an optimized route discovery scheme in the Intra-BAN network. This incorporates an improved and multi-facet routing metric (Link Quality

Metric (LQM)) that optimizes the route selection by considering multi-constraints (link delay, link delivery ratio, and link interference ratio).

iii. To develop an improved route maintenance scheme in the Intra-BAN network that avoids unnecessary route discovery notifications.

1.7 Research Contribution

The main contribution of this thesis is MIQoS for WBSN, which is an incorporated outcome of following three schemes:

i. The Low Latency Traffic Prioritization (LLTP) scheme considers various priority queues with an optimized scheduling mechanism to identify the data traffic to enhance the critical data transmission (reliability), avoids the node-level congestion and queuing delay. The performance of the LLTP scheme is evaluated in terms of the average queuing delay, PDR, and throughput.

ii. The Optimized Route Discovery (ORD) scheme incorporates an improved and multi-facet routing metric that optimizes the route selection by considering multi-constraints. The performance of the ORD scheme is evaluated in terms of the average end-to-end delay, packet drop ratio, normalized routing load, and throughput.

iii. The Interference Adaptive Route Repair (IARR) scheme identifies the links experiencing transmission issues due to channel interference and makes a coherent decision about route breakage based on long term link performance to avoid false route breakages. The performance of the IARR scheme is evaluated in terms of the average end-to-end delay, normalized routing load, route lifetime, and throughput.

1.8 Scope of the Research

The scope of this thesis is as follows:

i. The single Intra-BAN and Intra-network interference are focused in this thesis. While the Inter-BAN and Extra-BAN communications are not included in this thesis.
ii. The main focus of this thesis is the communication instead of sensing issues.
iii. All the communication between various nodes is wireless and follows IEEE 802.15.4 MAC standard.
iv. Inter-network interference, energy consumption, temperature, security, and mobility issues are not considered in this thesis.

1.9 Significance of Study

This thesis focuses on developing a MIQoS which is capable of routing data packets within a realistic network scenario i.e. healthcare. It is also applicable in non-healthcare application scenarios (i.e. sports/gaming, transportation, security and surveillance, training and education, emergency, and social welfare). The MIQoS is suitable for a wide range of interesting services that require fast, reliable and multi-hop communication. Moreover, it can also be considered as a possible option in heavily loaded network traffic scenarios where high route instability significantly disrupts the data transmission.

1.10 Research Outline

The rest of this thesis is organized as follows:

Chapter 2 reviews the literature of this thesis. This includes the fundamental information about WBSN such as its architecture, communication layers, types, potential applications and routing protocols (routing issues, challenges, and presented routing protocols). In this chapter, the different stages of routing protocols have been highlighted with a discussion of existing schemes.

Chapter 3 presents the research methodology of this thesis. This includes the proposed framework and simulation setup. The operational and research framework detail the proposed phases of the MIQoS such as LLTP, ORD, and IARR. The Network Simulator (NS)-2 simulation framework is considered to achieve the defined research objectives. The various assumptions and limitations are also considered in the simulation setup of this thesis.

Chapter 4 demonstrates the design and development of the proposed traffic prioritization scheme (LLTP). It addresses the problem of traffic prioritization for critical data transmission. Furthermore, the simulation results are evaluated to observe the efficiency of this scheme.

Chapter 5 presents the design and development of the proposed route discovery scheme (ORD). It addresses the problem of route discovery especially, discovering a route with the high delivery ratio, low intra-network interference, and end-to-end delay. Moreover, the simulation results are also depicted in this chapter.

Chapter 6 details the design and development of the proposed route maintenance scheme (IARR). It addresses the problem of route maintenance to avoid unnecessary route discoveries. Moreover, the efficiency of the proposed scheme is analyzed in this chapter.

Finally, chapter 7 concludes the thesis work by summarizing the research achievements and suggests the future directions of this thesis.

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1. **Zuhra, F. T.**, Bakar, K. B. A., Arain, A. A., & Tunio, M. A. (2017). Routing protocols in wireless body sensor networks: A comprehensive survey. *Journal of Network and Computer Applications,* 99, 73-97 (**Q1, Impact Factor = 3.5**).
2. **Zuhra, F. T.,** Bakar, K. B. A., Arain, A. A., (2019). LLTP-QoS: Low Latency Traffic Prioritization and QoS-aware routing in Wireless Body Sensor Networks. *IEEE Access,* 7, 152777-152787 (**Q1, Impact Factor 4.0**).
3. **Zuhra, F. T.,** Bakar, K. B. A., Ahmed, A., Khan, U. A., & Bhangwar, A. R. (2020). MIQoS-RP: Multi-Constraint Intra-BAN, QoS-Aware Routing Protocol for Wireless Body Sensor Networks. *IEEE Access,* 8, 99880-99888 **(Q1, Impact Factor 4.0)**.
4. Ahmed, A., Ashraf, U., **Tunio, F.**, Bakar, K. A., & AL-Zahrani, M. S. (2018). Stealth Jamming Attack in WSNs: Effects and Countermeasure. *IEEE Sensors Journal*, 18(17), 7106-7113 **(Q1, Impact Factor 3.0**).