A PRIORITY-BASED ENERGY EFFICIENT MULTI-HOP ROUTING PROTOCOL WITH CONGESTION CONTROL FOR WIRELESS BODY AREA NETWORK

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DEDICATION

To my beloved late sonMuhammad Bin Anwarwho left us during the journey of my Ph.D. studies. May Almighty ALLAH SWT be pleased with him and grant him the highest level in Jannah (Ameen).

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ABSTRACT

Wireless Body Area Networks (WBANs) are advanced and integrated monitoring networks for healthcare applications. In these networks, different types of Biomedical Sensor Nodes (BSNs) are used to monitor physiological parameters of the human body. The BSNs have limited resources such as energy, memory and computation power. These limited resources make the network challenging especially in terms of energy consumption. Efficient routing schemes are required to save the energy during communication processes. Additionally, the BSNs generate sensitive and non-sensitive data packets, which need to be routed according to their priority. In order to address these problems, a priority-based Energy Efficient Multi-hop Routing protocol with congestion control (3EMR) for wireless body area network was developed that comprises of three different schemes. First, an Optimal Next-hop Selection (ONS) scheme was developed based on the cost function of routing parameters to dynamically select best next-hop for forwarding data packets. Second, a Priority Based Routing (PBR) scheme was developed to forward data packets according to data priority, which is based on sensitivity of the data with regards to patience's life. Third, a Congestion Avoidance and Mitigation (CAM) scheme was developed to save energy consumption and packet loss due to congestion by considering packet flow adjustment and congestion zone avoidance based strategy. It improvement is benchmarked against related solutions, and they are Healthcare-aware Optimized Congestion Avoidance (HOCA), Differentiated Rate control for Congestion (DRC), Priority based Cross Layer Routing (PCLR), Even Energy-consumption and Backside Routing (EEBR), and Energy Efficient Routing (EER) scheme. The simulation results demonstrated that the 3EMR scheme achieved significant improvement in terms of increased network lifetime by 31.4%, increased throughput by 33.2%, reduced packet loss 30.9%, increased packet delivery ratio by 21.1% and reduced energy consumption 26.8%. Thus, the proposed routing scheme has proven to be an energy efficient solution for data communication in wireless body area networks.

ABSTRAK

Rangkaian Kawasan Badan Tanpa Wayar (WBAN) adalah rangkaian pemantauan yang terintegrasi dan bersepadu untuk aplikasi penjagaan kesihatan. Dalam rangkaian ini, pelbagai jenis Nod Sensor Biomedikal (BSN) digunakan untuk memantau parameter fisiologi tubuh manusia. BSN mempunyai sumber yang terhad seperti tenaga, memori dan kuasa pengiraan dan sumber-sumber ini menjadi rangkaian mencabar terutamanya dari segi penggunaan tenaga. Di samping itu, mekanisme penghalaan yang cekap diperlukan untuk menjimatkan tenaga semasa proses komunikas. Di samping itu, BSNs menghasilkan paket data yang sensitif dan tidak sensitif, yang perlu disalurkan mengikut keutamaan mereka. Untuk menangani masalah ini, *a priority-based Energy Efficient Multi-hop Routing protocol with congestion control* (3EMR) yang terdiri dari tiga mekanisme yang berbeza telah dibangunkan. Pertama, mekanisme *Optimum Next-hop Selection* (ONS) dibangunkan berdasarkan fungsi kos parameter peralihan untuk secara dinamik memilih hop seterusnya yang terbaik untuk menghantar paket data. Kedua, mekanisme *Routing Based P*r*iori*t*y* (PBR) dibangunkan untuk menghantar paket data mengikut keutamaan data berdasarkan sensitiviti data berkenaan dengan kehidupan pesakit. Akhirnya, mekanisme Pengelakan dan Mitigasi Congestion (CAM) telah dibangunkan untuk menjimatkan penggunaan tenaga dan kehilangan paket disebabkan oleh kesesakan dengan mempertimbangkan strategi pelarasan aliran paket dan strategi berasaskan zon kesesakan. Penambahbaikan ini diukur berdasarkan penyelesaian yang berkaitan termasuk *Healthcare-aware Optimized Congestion Avoidance* (HOCA), Kawalan Kadar Berbeza untuk Congestion (DRC), *Priority based Routing Layer Routing* (PCLR), *Even Energy-consumption and Backside Routing* (EEBR), dan Tenaga Cekap Mekanisme penghalaan (EER). Hasil simulasi menunjukkan bahawa skim 3EMR telah mencapai peningkatan yang ketara dari segi jangka hayat rangkaian yang meningkat sebanyak 31.4%, peningkatan daya tampung sebanyak 33.2%, menurunkan paket sebanyak 30.9%, meningkatkan nisbah penghantaran paket sebanyak 21.1% dan mengurangkan penggunaan tenaga sebanyak 26.8%. Oleh itu, skim laluan yang baru dibangunkan telah membuktikan bahawa ia adalah penyelesaian cekap tenaga untuk komunikasi data dalam rangkaian kawasan badan tanpa wayar.

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3EMR	-	A priority-based Energy Efficient Multi-hop Routing
ADC	-	Analog to Digital Converters
AEC	-	Average Energy Consumption
AID-N	-	Advanced health and Disaster aid Network
AMR	-	Adaptive Multi-hop tree-based Routing
AP	-	Access Point
ARCS	-	Adaptive Rate Control Scheme
BNC	-	Body Node Coordinator
BSNs	-	Biomedical Sensor Nodes
CAM	-	Congestion Avoidance and Mitigation
CBR	-	Constant Bit Rate
CF	-	Cost Function
C-Flag	-	Congestion Flag
COCM	-	Class Based Optimized Congestion Management
CSMA/CA	-	Carrier-Sense Multiple Access with Collision Avoidance
C-Zone	-	Congestion Zone
DMQoS	-	Data-centric Multi-objective QoS
DRC	-	Differentiated Rate control for Congestion
ECBR	-	Even-energy Consumption and Backside Routing
ECG	-	ElectroCardioGraphy
EEBR	-	Even Energy-consumption and Backside Routing
EED	-	End-to-end delay
EEG	-	ElectroEncephaloGraphy
EER	-	Energy Efficient Routing
EERS	-	Energy Efficient Routing Scheme
EMG	-	ElectroMyoGraphy
GPS	-	Global Positioning System
HBC	-	Human Body Communication
HIT	-	Hybrid Indirect Transmission
HOCA	-	Healthcare aware Optimized Congestion Avoidance Scheme
HPs	-	Hello Packets
ICTs	-	Information Communication Technology
ISM	-	Industrial Scientific Medical

LACAS	-	Learning Automata based Congestion Avoidance Scheme
LCCP	-	Learning based Congestion Control Protocol
LOCALMOR	-	Localized Multi-objective Routing
MAC	-	Medium Access Control
M-ATTEMPT	-	Mobility Adaptive Threshold based Thermal aware Energy efficient Multi-hop Protocol
MLACAS	-	Mobility Automata Based Congestion Avoidance Scheme
NB	-	Narrowband
NCCP	-	Novel Congestion Control Protocol
NC-Zone	-	Non-Congestion Zone
ND	-	Non-sensitive Data
ND-Queue	-	Non-sensitive Data Queue
NN	-	Neighbor Nodes
NS 2	-	Network Simulator Two
NT	-	Neighbor Table
ONS	-	Optimal Next-hop Selection
OTcL	-	Object-oriented Tool Command Language
PBCC	-	Priority Based Congestion Control
PBR	-	Priority Based Routing
PCLR	-	Priority based Cross Layer Routing
PCMP	-	Prioritization-based Congestion Mitigation Protocol
PDA	-	Personal Digital Assistant
PDR	-	Packet Delivery Ratio
PERA	-	Priority-based Energy-efficient Routing Algorithm
PHY	-	Physical
PSOS	-	Packet Size Optimization Scheme
PSR	-	Packet Sending Rate
PTP	-	Packet Timeout Period
QO	-	Queue Occupancy
QOR	-	Queue Occupancy Rate
QPRD	-	Queue based Priority Routing for Data
RCF	-	Rate Control Factor
RCS	-	Rate Control Scheme
RE-ATTEMPT	-	Reliability Enhanced-Adaptive Threshold based Thermal-unaware Energy-Efficient Multi-hop Protocol
RSP	-	Route Selection Probability

SD	-	Sensitive Data
SD-Queue	-	Sensitive Data Queue
TDMA	-	Time-Division multiple access
TICOSS	-	Time zone Coordinator Sleep Scheduling
TMQoS	-	Thermal-aware Multi-constrained QoS-aware
TTD	-	Time To Deliver
UWB	-	Ultra WideBand
WBAN	-	Wireless Body Area Network
WHMS	-	Wearable Health Monitoring Systems
WSNs	-	Wireless Sensor Networks

LIST OF SYMBOLS

E_{Res}	-	Residual energy
$E_{\text{Cons }(N_\text{i})}$	-	Energy consumption of a node N_i
E_{Rx}	-	Energy consumption of receiving node
$E_{Rx-elect}$	-	Energy consumption by the radio operations for the purpose of reception
E_{Tx}	-	Energy consumption of transmitting node
$E_{Tx-elect}$	-	Energy consumption by the radio operations for the purpose of transmission
E_{amp}	-	Energy consumption for amplification
LE	-	Link efficiency
$PD_{(C-NFV\leftrightarrow DVN)}$	-	Present Distance
P_{Drop} and P_{Sent}	-	Packet drop and Packet sent
$PSR(max)_j$	-	Maximum Packet Sending Rate of node *j*
PSR_i	-	Packet Sending Rate of node *i*
$P_{delivered}$	-	Packets successfully delivered
P_{sent}	-	Number of packets sent by the source
$QMax_j$	-	Maximum queue size
QOR_j	-	Queue occupancy rate of node *J*
QO_j	-	Queue occupancy of node *J*
$TT_{i\ldots\text{BNC}}$	-	transmission time required to deliver a packet received from node i to BNC
$T_{delivered}$	-	Time when packet is received at BNC
T_{sent}	-	Time when packet is sent by the source
$Tx_{Success}$	-	Number of packets completely transmitted over a link
Tx_{Total}	-	Number of attempts for transmission of data packets
HC	-	Hop-count
Pn	-	Number of packets sent
X, Y	-	Coordinate positions
d	-	Euclidean distance
i, j	-	Nodes
k	-	Number of bits

n	-	Number of nodes in the network
α	-	Weight factors for residual energy
β	-	Weight factors for link efficiency
γ	-	Weight factors for hop-count
δ	-	Weight factors for distance

CHAPTER 1

INTRODUCTION

1.1 Overview

Advancement in Information and Communication Technologies (ICTs) led to the invention of Wireless Sensor Networks (WSNs) which are capable of gathering information from the surrounding environment and sending the gathered information to the base station. The WSNs are used in many applications to improve and facilitate human lifestyle such as, environmental monitoring, intelligent transportation system, smart cities, home automation, sports and entertainment (Oliveira and Rodrigues, 2011). Further enhancement in WSNs introduced a prominent application in healthcare known as Wireless Body Area Network (WBAN) that is an automated system to monitor the health of patients remotely (Rezaee *et al.*, 2013)**.**

The WBANs consist of small and intelligent Biomedical Sensor Nodes (BSNs) which are used to monitor different physiological parameters of patients. These BSNs are categorized into two types according to their application and deployment. The first type is known as wearable sensors, which can be attached to the patient's body and can be used to monitor blood pressure, heartbeat and Electrocardiography (ECG) pulse. The second type is known as implantable sensors, which can be inserted or implanted inside the patient's body to monitor the functionality of various organs such as endoscopy and pacemaker. The BSNs collect the physiological information of patients and send them to the external monitoring station for further processing (Hamida *et al.*, 2015). Medical staff reviews the received information to predict future condition or analyze current situation of the patient. WBAN offers innovative, integrated and personalized medical applications to proactively manage the well-being of patients by early detection and treatment indications (Fengou *et al.*, 2013). The WBAN is an automated system, which provides portable, helpful and low cost solutions.

WBAN is formally defined by the Institute of Electrical and Electronics Engineers as IEEE 802.15.4 which is a communication standard designed for low power devices. According to this standard, the WBAN nodes are connected through wireless communication channel. Meanwhile, another IEEE 802.15.6 standard protocol has been developed recently. However, very few research works have been implemented considering the IEEE 802.15.6 protocol. Thus, all the benchmarking schemes considered in this thesis employed the IEEE 802. 15. 6. All the BSNs send their sensory data to Body Node Coordinator (BNC) through multi-hop star topology. The BNC after receiving data from BSNs transmits it to medical server through Internet. The BNC can be a Personal Digital Assistant (PDA) or mobile device. The BNC acts as a gateway for all BSNs. Figure 1.1 shows architecture of WBAN communication.

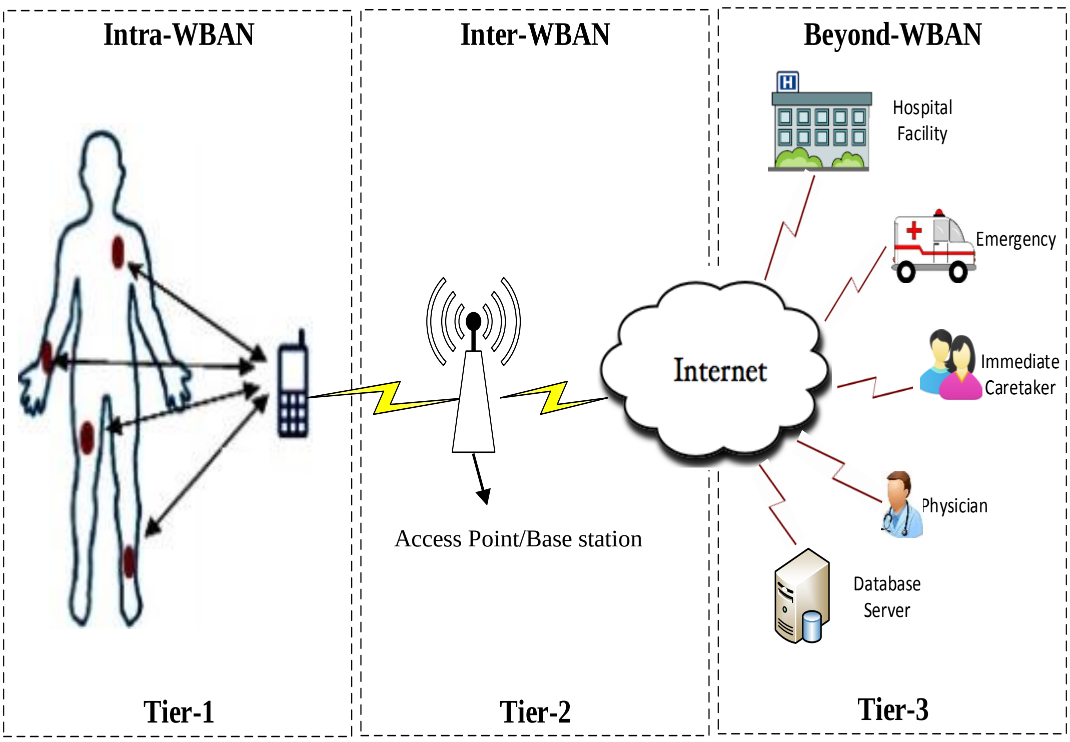

Figure 1.1 WBAN Communication Architecture

The WBANs communication is broadly divided into three tiers: Tier 1 is known as intra-WBAN communication, where BSNs monitor and send physiological parameters of human body to BNC. Tier 2 is known as inter-WBAN, which consists of a base station or access points and acts as a gateway to connect intra-WBAN to outside WBAN. The Tier 3 is known as beyond-WBAN communication which comprises medical server and/or medical staff who analyze and process the received data for further actions (Chakraborty *et al.*, 2013). The frequent monitoring system through the BSNs reduce the risk of fainting, heart attack, and life blindness. Through WBANs application, elderly people can get the benefits of staying home rather than hospital. This automated monitoring system prevents sudden emergency situations such as sudden death syndrome, brain hemorrhage and paralysis (Aminian and Naji, 2013).

However, the WBANs have certain limitations. The BSNs are powered by small batteries, which have limited storage capacity. Efficient energy consumption is a major challenge in WBANs (Anagnostopoulos *et al.*, 2014; Kaur and Singh, 2017; Maskooki *et al.*, 2011). In most cases, recharging and replacing the batteries are not feasible. Therefore, energy is a scarce resource and has to be managed wisely to prolong the network lifetime. Energy efficiency can be achieved by addressing and managing various issues in WBANs such as best possible route selection for data delivery, congestion control and load balancing among the BSNs in the network. The existing research studies in this domain have only partially addressed these issues. Nevertheless, this research work aims to improve the energy efficiency in WBANs by addressing the aforesaid issues while keeping in view the limitations of BSNs.

1.2 Background and Motivation

Due to the rise in elderly population and healthcare cost, most researchers focused on inventing low cost and automated healthcare solutions. Generally, the old people suffer from various chronic and fatal health issues, therefore, they require continuous medical care. Most of these patients have to stay in hospitals or under constant supervision of medical professionals, otherwise their lives may be at risk

(Cetin *et al.*, 2015). The researches revealed that most of the health issues can be controlled if identified at early stages (World Health Organization, 2016).The aforementioned phenomenon triggered a need towards development of proactive and affordable healthcare systems for unattended health monitoring. In order to address these challenges, the researchers introduced Wireless Body Area Network (WBAN), which is a promising technology in health care to constantly monitor the health of patients (Cavallari *et al.*, 2014a; Ullah *et al.*, 2012a).

The BSNs in WBAN are equipped with limited resources in terms of memory, computational power and battery life (Popovici *et al.*, 2013). Due to the short battery lifetime of BSN, the energy consumption is a major problem in WBAN (Lai *et al.*, 2013; Ullah *et al.*, 2017). The energy is one of the important requirements for network lifetime in WBAN. If any BSN runs out of battery and is unable to transmit physiological signals, it will be life threatening to the patient. Therefore, these BSNs should last longer. Data communication is the most resource hungry process in WBAN. Almost 80% of the sensors energy in WBANs are utilized by data communication process (Ishtaique ul Huque *et al.*, 2013; Lee and Annavaram, 2012). The energy efficiency of BSNs can be improved in WBANs by addressing the problems discussed as follows.

1.2.1 Ineffective Next-Hop Selection in Multi-Hop Routing

Due to the resource limitations and short communication range of BSNs, direct communication between BSNs and BNC is not suitable (Puccinelli and Haenggi, 2015). The direct communication causes transmissions delay because of the dispersion of nodes between the BSN and the BNC. The higher the distance between nodes, the lower the communication strength, which lead to retransmission and more energy efficiency (Monowar *et al.,* 2014). The nodes have to transmit data with high power, which leads to temperature rise that affects the human body tissues. However, multi-hop communication is appropriate for WBANs (Ahmed *et al.*, 2017). In multi-hop communication, the BSNs send data to their neighboring nodes instead of directly sending to the BNC (Yuce, 2010). Nonetheless, in multi-hop communication, the selection of next-hop as a forwarder node is critical while designing routing schemes. The existing routing schemes in WBANs presented several tradeoffs for designing of next-hop selection criteria in multi-hop routing. Javaid *et al.* (2013a) presented adaptive thermal aware energy efficient routing scheme named M-ATTEMPT, which exploits number of hop-counts to decide the route for data delivery. This approach determines the shortest path but do not factor in the crucial information of remaining energy of the BSNs. This leads in shortening the lifespan of the BSNs. Monowar *et al.* (2014) proposed Thermal-aware Multi-constrained Intra-body QoS Routing scheme targeted to maintain the temperature of BSNs in WBANs. This protocol uses multi-hop routing and selects the next-hop based on temperature of the BSN and number of hop-counts to the BNC. Similar to the M-ATTEMPT, the information of residual energy not taken into consideration for selecting the next-hop, which leads to unequal distribution of energy utilization in the network thus, the problem of energy consumption can still arise.

Ha (2016) introduced an even energy consumption and backside routing designed to cover the backside area of human body. This scheme exploits a cost function for selecting the next-hop based on residual energy and number of hop-counts to the BNC. Similarly, Khan *et al.* (2018) presented energy efficient routing scheme which recommends direct communication for critical data and multi-hop communication for normal data. In the case of multi-hop communication, the next-hop is selected based on residual energy of the BSNs and distance to the BNC. However, the information of residual energy, number of hop-counts and/or Euclidean distance support to determine the next-hop based on shorter path instead of the node with best quality in the path. The node with best quality is based on efficiency of the link. The link efficiency has direct impact transmission delay. The route with low link efficiency may lead to packet loss and retransmission attempts, which consume high energy. Hence, the link efficiency needs to be taken into account for designing an energy efficient routing scheme.

1.2.2 Imprecise Priority-based Next-Hop Selection for Sensitive and Non-Sensitive Data Packets

As stated earlier, the BSNs in WBANs monitor different kind of vital signs such as temperature, blood pressure and heart rate. Each sensory data packet contains some value of the specific vital sign. These vital signs have specified normal range like in case of heart rate the normal range is 51-119 beats/min (Fletcher *et al.*, 2013; Guazzi *et al.*, 2016; Sailunaza *et al.*, 2016). Based on the range, the data packets in WBAN can be classified into two basic categories; Non-sensitive Data (ND) and Sensitive Data (SD) packets. The packets containing value of vital signs within normal range referred to as ND packets whereas, the packets contains value beyond the normal range referred to as SD packets (Khan *et al.*, 2012; Rezaee *et al.*, 2014). The SD packets need to be delivered to BNC with minimum delay and packet loss (Ben Elhadj *et al.*, 2016; Gambhir *et al.,* 2015).

Many researchers provide solutions for priority based routing of ND and SD packets.Djenouri and Balasingham (2009a) were the first to introduce four different categories of WBAN data packets. These categories are critical data, delay-constrained data, reliability-constrained data and non-constrained data packets. Furthermore, it uses two kinds of sinks: primary and secondary, for each patient. Each data packet is forwarded towards both sinks, which results in high traffic congestion and thus increasing the data delivery delay and packet loss ratio.Razzaque *et al.* (2011a) proposed a Data centric Multi objective QoS aware routing scheme (DMQoS) for WBAN. This scheme prioritizes data packets and forwards them through the respective queues one after the other according to their priority. Lower priority queue can send packets after the higher queue finished sending. The routing decision is taken by using location based on number of hop-counts. However, considering the importance of sensitive data, this proposed scheme does not consider the time required to deliver the sensitive data, which might lead to late delivery of sensitive packet or packet loss. Time To Deliver (TTD) is the time required to deliver a packet from source to destination that is, BNC. TTD has direct impact in delivery of SD packets. Selecting a routing path having TTD less than the packet timeout period (packet expiry period) ensures successful delivery of SD packets.

Rezaee *et al.* (2014) proposed Healthcare aware Optimized Congestion Avoidance (HOCA) scheme for WBAN. This scheme is designed for two objectives including congestion control and priority based routing. In this scheme, each BSN maintains two different routing tables. The routing table for SD data traffic stores only one path which is the best among the available paths. Whereas, the routing table for ND packets has many paths but other than the best one. In this way, only SD are forwarded to the best routing path whereas, ND packets are forwarded to non-best paths. Therefore, ND packets experience large number of packet loss. Further, the routing paths are selected based on the energy of the BSNs and number of hop-counts to the BNC. However, TTD is not considered to select the optimal route for SD packets which leads to number of SD packet loss. Later, Ben Elhadj *et al.* (2016) proposed Priority based Cross Layer Routing (PCLR) scheme for WBANs. They prioritized data packets into three different classes and introduced separate slots for each type of packet. The routing decision is made on the basis of residual energy and number of available TDMA slots. However, TTD is not considered to ensure successful delivery of SD packets. Hence, this scheme experience a number of SD packet loss.

In routing schemes, data packets need to be classified and prioritized to forward them according to the priority. However, priority based routing have different Quality of Service (QoS) requirements. Due to its lower priority, ND packets can tolerate some delay or packet loss. However, SD packets require on time delivery with minimized packet loss. Thus, routing process needs to consider some more criteria to ensure on time delivery of SD packets, which is TTD. Whereas other parameters such as residual energy, link efficiency, hop-counts and Euclidean distance ensures the energy efficiency while selecting the next-hop

1.2.3 Imbalance Data Packets Routing Leading to Congestion

WBAN uses multi-hop communication to transmit data where BSNs have the responsibility to send their own generated data as well as forward the data received from other sensor nodes to BNC. The BSNs have limited storage capacity and queue size (Rezaee *et al.*, 2014). If there exists that several BSNs send their data simultaneously, an extensive amount of data reach the BSNs which are located near to the BNC. The storage queue becomes overloaded and starts dropping data which results in congestion. The congestion causes continuous packet drops and retransmission attempts in the network which depletes energy of BSNs quickly resulting in failure of their services. In additions, the BSNs generate ND and SD packets that have different requirements. The SD packets have high priority requires on time delivery with minimum packet loss. Whereas ND packets have low priority and can bear some delay or packet loss. When congestion occurs, it starts dropping the data packets arbitrarily that is, the SD packets may be dropped while ND packets are delivered. This indiscrimination of dropping data packets can be life threatening in WBAN applications. Therefore, it is essential to avoid congestion in WBANs. However, in the case of inevitable congestion, it should be mitigated. A good routing mechanism is one that supports both schemes, i.e. congestion avoidance and congestion mitigation.

A number of studies have proposed congestion control algorithms for WBANs such as Baek *et al.* (2009), Yaghmaee Moghaddam and Adjeroh (2010), Bahalgardi *et al.* (2012) and Rezaee *et al.* (2013). These studies focused either to avoid or mitigate congestion in WBAN. However, both congestion avoidance and mitigation schemes are not taken into consideration to handle sensitive and non-sensitive data. Only Rezaee *et al.* (2014) proposed a congestion avoidance and mitigation algorithm, known as Healthcare Aware Optimized Congestion Avoidance and control algorithm (HOCA). In this algorithm, the congestion is avoided using a multi-path routing. If congestion could not be avoided, it is mitigated using a congestion mitigation algorithm. However, during congestion mitigation process in this algorithm, only SD packets get chance to be forwarded whereas, ND packets not get forwarded until congestion is mitigated. In this way, the ND data experience delay due to long time waiting. Later, Gambhir *et al.* (2015) and Richard Jaramillo (2016) proposed congestion mitigation schemes but these schemes controls congestion after it occurs in the network. They did not provide any congestion avoidance scheme, which in anticipation can avoid congestion to occur in the network. Hence, there is a need of designing a composite congestion avoidance and mitigation scheme, which simultaneously handles sensitive and non-sensitive data traffic in the network.

1.3 Problem Statement

The wireless communication in WBANs is a most resource-hungry process especially in terms of energy consumption. However, energy efficiency can be achieved by making the communication process efficient. Routing schemes plays important role in this regard by deciding optimal path for data delivery. The existing routing schemes in WBANs uses residual energy, number of hop-counts or distance to the BNC to decide the data delivery route. These parameters are not sufficient to guarantee packet delivery with minimum packet loss and delay, which may occur due to lack of link quality evaluation. In addition, BSNs sense life critical data of the patients. Some of the data packets may belong to SD, which have higher priority to delivery with minimum possible packet loss, whereas other belongs to ND and can tolerate some delay and packet loss. These ND and SD packets need to be routed according to their priority. Moreover, continuous and simultaneous data transmission by BSNs causes congestion in WBANs. The congestion leads to random packets drop that is, the SD packets may be dropped while ND are delivered. This can affect efficient delivery of SD packets, which may leads to life threat to the patient. In the existing schemes, both congestion avoidance and congestion mitigation schemes are not taken into consideration to handle SD and ND packets.

1.4 Research Questions

Based on the previously mentioned discussion, the following research questions were derived.

i. What are the most suitable parameters for selecting the best next-hop Node for data packet forwarding that has minimum energy consumption?

ii. Why prioritization of data packet necessary for ensuring delivery of packets with minimum delay and packet loss while considering less energy consumption?

iii. How to avoid and mitigate congestion in data delivery to reduce energy dissipation due to congestion?

1.5 Research Goal

The main aim of this research is to design and develop a priority-based energy efficient multi-hop routing protocol with congestion control for wireless body area network by improving the network lifetime of WBANs, optimal next-hop selection in the network, controlling congestion and evenly utilizing the energy of all BSNs in the network. Based on the research questions, the following objectives were derived.

1.5.1 Research Objectives

The objectives of the research are as follows:

i. To improve the energy efficiency by optimal next-hop selection in multi-hop routing in WBANs.

ii. To design a priority based routing scheme to deliver SD and ND packets according to their requirements.

iii. To improve routing scheme considering congestion avoidance and mitigation to reduce energy dissipation.

1.6 Research Scope

The scope of this research are as follows:

i. This study focuses on intra-WBAN (tier-1) communication, and not focused on the communication outside the intra-WBAN.

ii. All BSNs are placed on a single human body and connected to a BNC through wireless link.

iii. IEEE 802.15.4 Medium Access Control (MAC) standard is used for communication, because the recently produced 802.15.6 protocol has not been used by the baseline studies, which are considered in this study.

iv. The focus of this research is on communication, instead of sensing.

1.7 Research Contribution

The proposed routing scheme offer more efficient solutions to prolong the network lifetime of WBANs. The BSNs are used to monitor life critical information of patient, therefore they need to be active for a long time. The proposed routing scheme apply the optimal next-hop selection strategy, priority based route selection and congestion control scheme in WBANs. The proposed next-hop selection scheme provides a way to balance out and minimize the energy consumption of all BSNs in WBANs. The priority based routing scheme selects the next-hop for sensitive and non-sensitive data packets according to their priority. Moreover, the congestion control scheme further adds up in network lifetime by reduction of energy consumption due to packets drops and retransmissions. The proposed solutions would help recent healthcare intelligent monitoring systems and address the energy deficiency issues.

1.8 Structure of the Thesis

After having presented a comprehensive overview in Chapter 1, the five remaining chapters are organized as follows.

In Chapter 2, an extensive review of related literature on energy consumption in WBANs is presented as a critical exploration of the recent routing schemes for WBANs. The data communication in WBANs is introduced by discussing various energy efficient transmission schemes to address the energy consumption issue in the area.

In Chapter 3, the research methodology and design & development phases of the proposed schemes are discussed to achieve the research objectives. It discusses the problem formulation based on the literature review. The simulation setup parameters are also presented along with the performance evaluation criteria for the proposed scheme.

Chapter 4 presents the design and development of a priority-based Energy Efficient Multi-hop Routing (3EMR) protocol with congestion control for wireless body area network. This chapter consists of three schemes named as Optimal Next-hop Selection (ONS) scheme, Priority Based Routing (PBR) scheme and Congestion Avoidance and Mitigation (CAM) scheme. This chapter also presents the various algorithms and flow charts proposed to achieve the objectives of these schemes.

Chapter 5 presents the performance evaluation and analysis of the simulation based experimental results of the all three schemes. The results are analyzed and discussed in details and further compared with the existing state-of-the art schemes.

Chapter 6 concludes this work, summarizes the research achievements and suggests directions for future work.

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LIST OF PUBLICATIONS

1. **Muhammad Anwar,** Abdul Hanan Abdullah, Kashif Naseer Qureshi, Abdul Hakeem Majid, "**Wireless Body Area Networks for Healthcare Applications: An Overview**", TELKOMNIKA, 2017 **(Indexed by Scopus)**

2. **Muhammad Anwar,** Abdul Hanan Abdullah, Farhan Masud, Fasee Ullah, "**CAMP: Congestion Avoidance and Mitigation Protocol for Wireless Body Area Networks**", International Journal of Integrated Engineering, 2018 **(Indexed by Scopus) (Accepted)**

3. **Muhammad Anwar,** Abdul Hanan Abdullah, Ayman Altameem, Kashif Naseer Qureshi, Farhan Masud, Muhammad Faheem, Yue Cao, Rupak Kharel, "**Green Computing for Wireless Body Area Networks: Energy Efficient Link Aware Routing Approach**", Sensors, 2018 **(Indexed by ISI, IF=2.47) (Revision Submitted)**