PRIORITIZATION-BASED ADAPTIVE EMERGENCY TRAFFIC MEDIUM ACCESS CONTROL PROTOCOL FOR WIRELESS BODY AREA NETWORKS

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To my beloved father Mufti Khalid Masud, mother, wife and children.

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ABSTRACT

Wireless Body Area Networks (WBANs) provide continuous monitoring of a patient by using heterogeneous Bio-Medical Sensor Nodes (BMSNs). WBANs pose unique constraints due to contention-based prioritized channel access, sporadic emergency traffic handling and emergency-based traffic adaptivity. In the existing medium access control protocols, the available contention-based prioritized channel access is incomplete due to the repetitions in backoff period ranges. The emergency traffic is considered based on traffic generation rate as well as sporadic emergency traffic that is not handled at multiple BMSNs during contention. In an emergency situation, non-emergency traffic is ignored, traffic is not adjusted dynamically with balanced throughput and energy consumption, and the energy of non-emergency traffic BMSNs is not preserved. In this research, prioritization-based adaptive emergency traffic Medium Access Control (MAC) protocol was designed to consider contention-based prioritized channel access for heterogenous BMSNs along with sporadic emergency traffic handling and dynamic adjustment of traffic in sporadic emergency situation. Firstly, a Traffic Class Prioritization based slotted-CSMA/CA (TCP-CSMA/CA) scheme was developed to provide contention-based prioritized channel access by removing repetitions in backoff period ranges. Secondly, an emergency Traffic Class Provisioning based slotted-CSMA/CA (ETCP-CSMA/CA) scheme was presented to deliver the sporadic emergency traffic instantaneously that occurs either at a single BMSN or multiple BMSNs, with minimum delay and packet loss without ignoring non-emergency traffic. Finally, an emergency-based Traffic Adaptive slotted-CSMA/CA (ETA-CSMA/CA) scheme provided dynamic adjustment of traffic to accommodate the variations in heterogeneous traffic rates along with energy preservation of non-emergency traffic BMSNs, creating a balance between throughput and energy in the sporadic emergency situation. Performance comparison was conducted by simulation using NS-2 and the results revealed that the proposed schemes were better than ATLAS, PLA-MAC, eMC-MAC and PG-MAC protocols. The least improved performances were in terms of packet delivery delay 10%, throughput 14%, packet delivery ratio 21%, packet loss ratio 28% and energy consumption 37%. In conclusion, the prioritization-based adaptive emergency traffic MAC protocol outperformed the existing protocols.

ABSTRAK

Rangkaian Kawasan Badan Tanpa Wayar (WBAN) menyediakan pemantauan berterusan pesakit dengan menggunakan Nod Sensor Bio-Medical Nodes (BMSNs). WBAN menimbulkan kekangan yang unik disebabkan oleh akses saluran keutamaan berasaskan perbalahan, pengendalian lalu lintas kecemasan yang sporadis dan penyesuaian lalu lintas berasaskan kecemasan. Dalam protokol kawalan akses sederhana yang sedia ada, akses saluran keutamaan berasaskan perbalahan yang ada tidak lengkap kerana pengulangan dalam julat tempoh backoff. Lalu lintas kecemasan itu dipertimbangkan berdasarkan kadar penjanaan lalu lintas, dan lalu lintas kecemasan yang sporadis tidak dikendalikan oleh BMSN semasa pertikaian. Dalam situasi kecemasan, lalu lintas bukan kecemasan diabaikan, lalu lintas tidak diselaraskan secara dinamik dengan penggunaan seimbang dan penggunaan tenaga, dan tenaga BMSN trafik bukan kecemasan tidak dipelihara. Dalam kajian ini, protokol pengendalian Akses Kawalan Sejagat (MAC) yang berdasarkan prioriti berasaskan pengaturcaraan direka untuk mempertimbangkan akses saluran keutamaan berasaskan perbalahan bagi BMSN yang bersifat heterogenous bersamaan dengan pengendalian lalu lintas kecemasan yang sporadis dan penyelarasan dinamik lalu lintas dalam situasi kecemasan sporadis. Pertama, skim Slotted-CSMA / CA (TCP-CSMA / CA) yang berasaskan Kelas Trafik telah dibangunkan untuk menyediakan akses saluran keutamaan berasaskan perbalahan dengan mengeluarkan pengulangan dalam julat tempoh backoff. Kedua, skim Slotted-CSMA / CA (ETCP-CSMA / CA) berdasarkan Pelaksanaan Kelas Lalu Lintas Kecemasan telah dibentangkan untuk menyampaikan lalu lintas kecemasan yang sporadis dengan segera yang berlaku sama ada di BMSN tunggal atau BMSN berganda, dengan kelewatan minimum dan kehilangan paket tanpa mengabaikan trafik tidak kecemasan. Akhir sekali, skim slaid-CSMA / CA (ETA-CSMA / CA) berasaskan kecemasan yang diarahkan untuk kecemasan menyediakan pelarasan trafik dinamik untuk menampung variasi kadar trafik heterogen bersama dengan pemeliharaan tenaga BMSN lalu lintas bukan kecemasan, mewujudkan keseimbangan antara truput dan tenaga dalam keadaan kecemasan sporadis. Perbandingan prestasi dijalankan melalui simulasi menggunakan NS-2 dan hasilnya menunjukkan bahawa skim yang dicadangkan lebih baik daripada protokol ATLAS, PLA-MAC, eMC-MAC dan PG-MAC. Prestasi yang kurang baik adalah dari segi kelewatan penghantaran packet 10%, truput 14%, nisbah pengiriman paket 21%, nisbah packet loss 28% dan penggunaan energi 37%. Kesimpulannya, skim yang dicadangkan diperbaiki daripada protokol sedia ada.

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LIST OF ABBREVIATIONS

AB - Advertisement Beacon
AC - Alarm Control
Ada-MAC - An Adaptive Medium Access Control
AO - Acknowledgement of Opportunity
ATLAS - A Traffic Load Aware Sensor Medium Access Control
BC - Body Coordinator
BMSN - Bio-Medical Sensor Node
BMSN-BP - BMSN for Blood Pressure Monitor
BMSN-HR - BMSN for Heartbeat Rate Monitor
BMSN-RR - BMSN for Respiratory Rate Monitor
BMSN-TM - BMSN for Temperature Monitor
BP - Beacon Period / Blood Pressure
BPR - Backoff Period Range
CA-MAC - Context-Aware Medium Access Control
CAC-MAC - Context-Aware and Channel based Medium Access Control
CAP - Contention Access Period
CCA - Clear Channel Assessment
CCAP - Configurable-CAP
CD - Command Data
CDP - Critical Data Packet
CE - Consumer Electronic
CFP - Contention Free Period
CoR-MAC - Contention over Reservation Medium Access Control
CPs - Critical Packets
CSMA/CA - Carrier Sense Multiple Access/Collision Avoidance
CTC - Critical Traffic Class
CTPA - Contention-based Traffic Priority-Aware Medium Access Control
DDP - Delay-constrained Data Packet
DPs - Delay Packets
DTC - Delay Traffic Class

DTP	-	Data Transmission Period
DTS	-	Data Transmit Slots / Data Transmission Slot
EA	-	Emergency Alert
EAP	-	Exclusive Access Phase
EC	-	Energy Consumption
ECG	-	Electrocardiography
ECP	-	Emergency Contention Period
ED	-	Emergency Data
EDAV-HTR	-	Emergency-based Dynamic Adjustment of Variations in Heterogeneous Traffic Rates
EDP	-	Emergency Data Packet
EE-BMSN	-	Expected Emergency Bio-Medical Sensor Node
EEG	-	Electroencephalography
EEVS	-	Expected Emergency Vital-Signs
EMG	-	Electromyography
eMC-MAC	-	Energy-efficient Multi-constrained Medium Access Control
ER	-	Emergency Resolved
ES	-	Emergency Slot
ETA-CSMA/CA	-	Emergency-based Traffic Adaptive slotted-CSMA/CA
ETC	-	Emergency Traffic Class
ETCP	-	Emergency Traffic Class Provisioning
ETCP-CSMA/CA	-	Emergency Traffic Class Provisioning-based slotted-CSMA/CA
ETCP-HEE-BMSNs	-	Emergency Traffic Class Provisioning for three Expected Emergency BMSNs
ETCP-SEE-BMSN	-	Emergency Traffic Class Provisioning for Single Expected Emergency BMSN
ETCP-TEE-BMSNs	-	Emergency Traffic Class Provisioning for Two Expected Emergency BMSNs
ETCT	-	Emergency Traffic Class Termination
ETDMA	-	Emergency TDMA
ETS	-	Emergency Data Transmit Slot
FCS	-	Frame Check Sequence
FDMA	-	Frequency Division Multiple Access
FFD	-	Fully Function Device
GTS	-	Guaranteed Time Slot
HR	-	Heartbeat Rate

ICU	Intensive Care Unit
IEEE	The Institute of Electrical and Electronics Engineers
LB	Lower Bound
LIFS	Long Inter-Frame Space
LR-WPANs	Low Rate-Wireless Personal Area Network
MAC	Medium Access Control
MCAP	Medical CAP
McMAC	Multi-Constrained QoS Provisioning Medium Access Control
MDTA-MAC	Multi-Dimensional Traffic Adaptive Energy-efficient Medium Access Control
MFR	MAC Footer
MHR	MAC Header
MIFS	Medium Inter-Frame Space
MPDU	MAC Protocol Data Unit
MS	Monitoring Station
NC	Network Coordinator
ND	Normal Data
NDP	Normal Data Packet
NE-MAC	New Medium Access Control
NTC	Normal Traffic Class
NTDMA	Normal TDMA
OCDP	Opportunistic Contention Decision Period
OCFP	Opportunistic Contention Free Period
OCM	Opportunity Contention Message
OCM ACK	OCM Acknowledgement
OPs	Ordinary Packets
OTCL	Object-Oriented Scripting Language
PA-MAC	Priority-based Adaptive Medium Access Control
PD	Periodic Data
PDD	Packet Delivery Delay
PDR	Packet Delivery Ratio
PG-MAC	Priority Guaranteed Medium Access Control
PHY	Physical Layer
PLA-MAC	Traffic Priority and Load Adaptive Medium Access Control
PLR	Packet Loss Ratio

PNP-MAC	-	Preemptive slot allocation and Non-Preemptive transmission Medium Access Control
QoS-MAC	-	Quality of Service Medium Access Control
RAP	-	Random Access Phase
RDP	-	Reliability-constrained Data Packet
RFD	-	Reduced Function Device
RFID	-	Radio Frequency Identification
RMAC	-	RFID-enabled Medium Access Control
RO	-	Request of Opportunity
RPs	-	Reliability Packets
RR	-	Respiratory Rate
RT	-	Routine Traffic
RTC	-	Reliability Traffic Class
SBTE	-	Scheme to Balance Throughput and Energy
SC-EE-BMSNs	-	Selection Criteria for Expected Emergency-BMSNs
SCEP	-	Self Contention Free Period
SHEM-BMSNs	-	Scheme to Handle Emergency at Multiple BMSNs
SIFS	-	Short Inter-Frame Space
SPE-BMSNs-NET	-	Scheme to Preserve Energy of BMSNs with Non-Emergency Traffic
SS-NET-I	-	Save Non-Emergency Traffic from Ignorance
TC	-	Traffic Class
TCP	-	Transmission Control Protocol
TCP-CSMA/CA	-	Traffic Class Prioritization-based slotted-CSMA/CA
TM	-	Traffic Model
TDMA	-	Time Division Multiple Access
UB	-	Upper Bound
UDP	-	User Datagram Protocol
UPs	-	Urgent Packets
UK	-	United Kingdom
USA	-	United States of America
WBAN	-	Wireless Body Area Network
WLAN	-	Wireless Local Area Network

LIST OF SYMBOLS

A - A constant

aNumSuperframeSlots - Number of Superframe Slots

aMaxBE - Maximum Number of Backoff Exponent

BC_ID - Unique ID of Body Coordinator

BE - Backoff Exponent

BLE - Battery Life Extension

BMSN_i - ith BMSN

BMSN_i_ID - BMSN ith ID

BMSN_BP_ID - Unique ID of BMSN_BP

BMSN_HR_ID - Unique ID of BMSN_HR

BMSN_RR_ID - Unique ID of BMSN_RR

BMSN_TM_ID - Unique ID of BMSN_TM

CAP_channel - Store the Status of Channel

CW - Contention Window

D_{type} - Traffic Class Value

eFlagBP - Emergency Flag for Blood Pressure

eFlagHR - Emergency Flag for Heartbeat Rate

eFlagRR - Emergency Flag for Respiratory Rate

eFlagTM - Emergency Flag for Temperature

hdr_lrwpan - Protocol Specific Packet Header

HDR_LRWPAN - Returns the Starting Address of the Packet's Protocol-specific Header

Mac - A Pointer at MAC Layer

*mac->index_* - Returns the Current ID of BMSN at MAC Layer

mac->txtime(packet) - Returns Transmission Time

macAckWaitDuration - Acknowledgement Wait Duration Time

macMinBE - Minimum Number of Backoff Exponent

macMaxCSMABackoffs - Maximum Number of CSMA Backoffs

MHR_timeStamp - Stores Data Packet's Generation Time based on the Virtual Simulation Time

NB - Number of Backoff

NumEMR - Number of Emergency Data Packets Received

NumETS	-	Number of Emergency Transfer Slot
Pkt_CLT	-	Packet Current Lifetime
Pkt_ELT	-	Packet Emergency Lifetime
Pkt_NLT	-	Packet Normal Lifetime
S_i	-	ith Slot
S_j	-	jth Slot
$T_{class\text{-}value}$	-	Traffic Class Value
T_i	-	ith Traffic Class
u_i	-	ith Urgent Packet
u_j	-	jth Urgent Packet
UnitBackoffPeriod	-	Basic Unit of Time Period Used by CSMA/CA
Wph	-	A Pointer at MAC Layer used to Access the Protocol Specific Packet Header

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CHAPTER 1

INTRODUCTION

1.1 Overview

In past, growth of the elderly population in developed countries was higher than developing countries, but now this trend is changing (Chiu *et al.*, 2017). In the near future, the elderly population of the world will suffer from chronic diseases and hence will require continuous monitoring (Movassaghi *et al.*, 2013). Moreover, the hospitalized patients also need various levels of monitoring ranging from multiple times a day to continuous monitoring. The random and continuous health monitoring require additional healthcare cost (Alemdar and Ersoy, 2010). Wireless Body Area Networks (WBANs) provide unsupervised, inconspicuous and real-time continuous health monitoring and hence reduce the healthcare cost (Chen *et al.*, 2013). WBANs are used in various applications, such as sports and fitness, entertainments and rehabilitation systems, medical, personal healthcare, emergency services, consumer electronics, and military systems.

WBAN is a collection of miniature, low processing power, lightweight, and low battery power Bio-Medical Sensor Nodes (BMSNs) that are either placed on the body, or on cloths (wearable) or inside patient's body (implant) (Cao *et al.*, 2009). The heterogeneous BMSNs such as blood pressure, body temperature, respiratory rate monitors, motion sensing, Electrocardiography (ECG), Electroencephalography (EEG), Electromyography (EMG), pH-level monitors, heart rate and others are deployed to monitor the vital-signs information of the patient's body. WBANs use three-tier architecture for communication purpose (Chen *et al.*, 2011; Rashidi and Mihailidis, 2013; Movassaghi *et al.*, 2014) and communicate the vital-signs information of the patient's body to the monitoring station for storage and/or observation purposes, as shown in Figure 1.1.

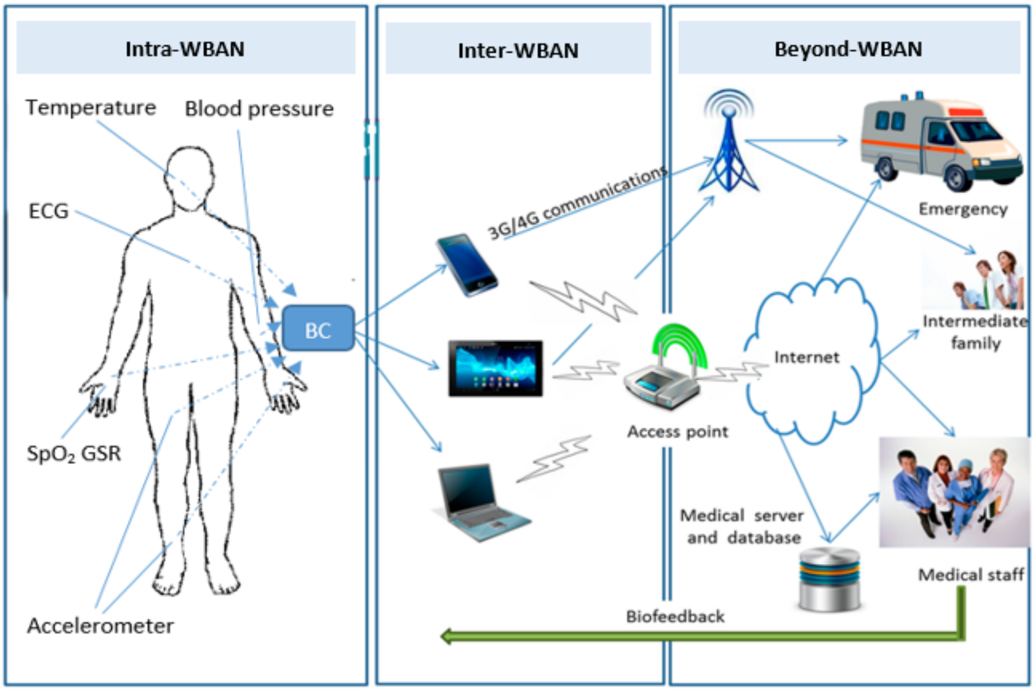

Figure 1.1 Communication architecture of wireless body area networks

The multi-tiers networks result in high reliability, low cost and enhanced coverage as compared to a single-tier network (Nie *et al.*, 2010). The WBAN's communication architecture is discussed as follows.

- **Tier 1 – Intra-WBAN**: It is the local body area network which consists of heterogeneous natured BMSNs that communicate with the local base station known as Body Coordinator (BC) in a range of 2 meters.
- **Tier 2 – Inter-WBAN:** The BC processes the data that is received from different BMSNs, aggregate the data and then forward the received vital-signs information towards Monitoring Station (MS).
- **Tier 3 – Beyond-WBAN:** It is the long-range network where the MS sends the received data to the remote medical centre or another place of interest via the internet, for storage and observational purposes.

A range of BMSNs is used to observe the vital-signs information of the patient's body. Heterogeneous natured BMSNs generate various kinds of data packets containing the vital-signs information. Therefore, the traffic prioritization is necessary during channel access due to the heterogeneous nature of vital-signs information (Yoon *et al.*, 2010; Anjum *et al.*, 2013; Pandit *et al.*, 2015; Rasheed *et al.*, 2017). Some data packets can tolerate the losses but need to be delivered within the specific time-frame whereas some data packets cannot tolerate much losses and need to be delivered within the specific time-frame. There may be some data packets that should be delivered with no or minimal losses but without the limitation of specific time-frame whereas some of the data packets can tolerate the losses and also do not require delivery within the specific time-frame. Hence, traffic prioritization is necessary during channel access due to the heterogeneous nature BMSNs used to monitor vital-signs information.

In WBANs, when the generated data values of heterogeneous natured BMSNs cross the normal readings, then an emergency occurs. An emergency event is a sporadic event by nature that can happen at any time. Emergency traffic has sporadic nature and should be delivered instantaneously (Huq *et al.*, 2012; Monowar *et al.*, 2012). If an emergency event is not handled on a priority basis in medical applications, then it is dangerous for the patient's life. The medical teams have found various cases in which the health of a patient drops instantaneously in an emergency room due to waiting. Therefore, time is very crucial in an emergency situation, and patient's lives cannot be risked due to the delay in emergency rooms (Gao *et al.*, 2007). The emergency traffic identification is among the significant constraints in WBAN (Elhadj *et al.*, 2013; Rajput *et al.*, 2013). Furthermore, the emergency traffic requires the highest priority (Ullah, 2013; Bhandari and Moh, 2016) and sometimes emergency occurs at multiple BMSNs simultaneously (Ullah, 2013). Moreover, in an emergency situation, it is necessary to save non-emergency traffic from ignorance (Muthulakshmi and Shyamala, 2017). Therefore, it is a challenging job to fulfil the aforementioned constraints of the emergency situation.

In WBAN, the patient's body is observed by heterogeneous BMSNs, therefore, the applications consist of heterogeneous traffic rates which become variable in an emergency situation. For example, the BMSNs that are used to observe heartbeat, temperature, and blood pressure have low-rate traffic in the non-emergency situation but generate high rate traffic in case of emergency situation. Therefore, the WBAN applications naturally generate variable traffic-rates. The applications with low-rate traffic require less energy consumption whereas the applications with high-rate emergency traffic demand high throughput. Moreover, the dynamic adjustment of traffic is necessary to create a balance between throughput and energy (Rahman *et al.*, 2011). Thus, the dynamic adjustment of traffic to accommodate the variations in heterogeneous traffic rates, the energy preservation of BMSNs with non-emergency traffic and a balance between throughput and energy is required in the sporadic emergency situations.

1.2 Problem Background

The Medium Access Control (MAC) layer provides the coordination to the BMSNs to access the shared medium. At MAC layer the critical task is to avoid concurrent transmissions and collisions with the increased throughput and packet delivery ratio and the decreased delay, packet loss ratio and energy consumption. The MAC plays a key role in improving the overall performance of the network (Gopalan and Park, 2010). The MAC is the most appropriate layer to deal with packet delivery delay, packet delivery ratio and energy (Barroso *et al.*, 2005; Chiras *et al.*, 2005; Miller and Vaidya, 2005; Zheng *et al.*, 2005; Fang and Dutkiewicz, 2009; Thapa and Shin, 2012; Bradai *et al.*, 2014; Khan *et al.*, 2014; Ramachandran *et al.*, 2014; Ullah and Li, 2015).

WBANs pose unique constraints (such as traffic prioritization, sporadic emergency traffic handling, emergency-based traffic adaptivity, and energy consumption) due to the behaviour of human body, which makes the design of medium access mechanism, a challenging job. It has gained the attention of the research community, and during the last few years, a lot of WBAN MAC protocols have been suggested. The existing MAC protocols for WBANs can be categorized into traffic priority, sporadic emergency traffic, emergency-based traffic adaptive, cross-layered and cluster-based MAC protocols (Rahman *et al.*, 2011; Anjum *et al.*, 2013; Pandit *et al.*, 2015; Rasheed *et al.*, 2017).

The heterogeneous natured BMSNs are used to sense a variety of vital-signs information and generate various types of data packets which require traffic prioritization. Yoon *et al.* (2010) present Preemptive and Non-Preemptive MAC

(PNP-MAC) protocol to provide traffic prioritization for diverse traffic types with preemptive channel allocation and non-preemptive data transmission in the allocated channels. The authors consider five traffic types and distribute these types into three backoff classes that are 0, 1, and 2. All BMSNs use prioritized random backoff and Clear Channel Assessment (CCA) to access the channel in the CAP. They customize standard slotted-Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) scheme of IEEE 802.15.4 by introducing $[0\ To\ 2^{BE}(Class+1)-1]$ as the backoff period range, where Class is the traffic class value. Every BMSN select the random backoff number from the proposed backoff period range.

However, in PNP-MAC, every backoff period range starts from zero which can result in the prior channel access to the low priority BMSN than the high priority BMSN. Moreover, the backoff period range of high priority class is repetitively used as a subpart in the backoff period range of low priority traffic class in each backoff which also can cause non-prioritized channel access. Furthermore, in third, fourth and fifth backoff, [0 – 31] is assigned to traffic class 0, [0 – 63] is assigned to traffic class 1, and [0 –95] is assigned to traffic class 2. Because the assigned backoff period range remains unchanged in their third, fourth and fifth backoff which increases packet collision and a retransmission rate. And in result packet delivery delay is increased. Also, in third, fourth, and fifth backoff, very high backoff period ranges are assigned to traffic class 1 and 2 that are [0 – 63] and [0 – 95] respectively. Therefore, the traffic of BMSNs that belong to traffic class 1 or 2 is highly delayed in third, fourth, and fifth backoff.

Anjum *et al.* (2013) introduce traffic Priority and Load-Aware MAC (PLA-MAC) protocol for WBANs to provide contention-based traffic prioritization with high throughput, low packet delivery delay and less energy consumption. In PLA-MAC, the traffic is categorized into four traffic classes with 0, 1, 2, and 3 as a traffic class value, where 0 represents the highest priority and 3 is the lowest priority. In PLA-MAC, the standard slotted-CSMA/CA scheme of IEEE 802.15.4 is customized by presenting a new backoff period range. All BMSNs perform prioritized random backoff by choosing the random backoff value from the proposed backoff period range $[0\ To\ 2^{T_i+2}-1]$, where T_i represents traffic class value.

However, PLA-MAC uses variable T_i (1, 2, 3, 4) instead of BE (3, 4, 5) in the backoff period range. Therefore, the specific backoff period range assigned to the BMSNs of each traffic class remains unchanged in every backoff which increases the collision rate, packet delivery delay and energy consumption, and decreases the throughput. Further, each backoff period range starts from zero which can cause non-prioritized channel access to all BMSNs. Moreover, the backoff period ranges of high priority traffic classes are repetitively used as a subpart in the backoff period ranges of low priority traffic classes which also result in a high collision. In addition, the upper limit of the backoff period range that is assigned to the BMSNs with ordinary data packets is 63 which is very high backoff value, therefore, also raises the packet delivery delay. Thus, the performance of PLA-MAC is degraded in terms of packet delivery delay, throughput and energy consumption due to the aforementioned shortcomings.

Pandit *et al.* (2015) propose an energy-efficient Multi-constrained MAC (eMC-MAC) to provide emergency traffic handling mechanism with better energy efficiency. In eMC-MAC, the traffic is categorized into five classes each with a specific priority. According to eMC-MAC, emergency traffic is sporadic by nature and must be delivered instantly. In eMC-MAC, the BMSNs either with emergency traffic or with non-emergency traffic use prioritized random backoff to access the channel during contention. Therefore, authors try to save the non-emergency traffic from ignorance. However, in eMC-MAC, the critical and reliability packets get the channel before emergency packets because they use zero as backoff number and emergency packets choose random backoff number from the backoff period range, i.e., [0 – 3]. Also, in each backoff, all backoff period ranges starts from zero, therefore, non-emergency traffic can access the channel before emergency traffic. Furthermore, no mechanism is provided to handle an emergency at more than one BMSNs. Also, a very high backoff period range is assigned to the lowest priority traffic class BMSNs which causes a high packet delivery delay, therefore, in the result, the traffic with the lowest priority is ignored.

Rasheed *et al.* (2017) propose Priority Guaranteed MAC (PG-MAC) to provide emergency traffic management technique with a reduced delay and energy consumption. In PG-MAC, the traffic is categorized in three classes, but the highest priority is given to sporadic emergency traffic. All the BMSNs that belong to three traffic classes contend to access the channel using prioritized random backoff during contention. Therefore, the authors try to save the non-emergency traffic from ignorance. Also, the emergency traffic is selected based on the lowest traffic class value, the highest data generation rate and the generated packet size. The authors also try to handle the emergency traffic at multiple BMSNs. However, the consideration of emergency traffic based on lowest traffic class value and highest traffic generation rate is not the real-time medical approach because the BMSNs with lowest traffic class value and highest traffic generation rate are not considered by doctors in an emergency situation.

A number of emergency-based traffic adaptive MAC protocols have been proposed to address the issue of contention-based dynamic adjustment of traffic in sporadic emergency situations. Rahman *et al.* (2011) propose A Traffic Load Aware Sensor (ATLAS) protocol to adjust the traffic dynamically, to preserve the energy of sensor nodes with non-emergency traffic, and to create a balance between energy and throughput in an emergency situation through traffic load estimation. In ATLAS, various modes of operation in a superframe are provided to adjust the dynamic variations in heterogeneous traffic rates. The traffic load is categorized into four types based on traffic load estimation. The standard slotted-CSMA/CA is used by all the sensor nodes to access the channel in the CAP period.

However, ATLAS does not provide traffic prioritization (Hossain *et al.*, 2014). Also, ATLAS MAC does not provide the opportunity to high priority traffic to access the channel before the low priority traffic and does not consider prioritized backoff class to avoid packet collision (Anjum *et al.*, 2013). Also, it does not consider prioritized channel access for heterogeneous nature BMSNs during contention (Pandit *et al.*, 2015). Moreover, it provides dynamic adjustment of traffic through various modes of operation in superframe using traffic load estimation which causes an extra computational load (Pandit *et al.*, 2015). Additionally, the collision is increased due to the non-prioritized channel access which may become worse in an emergency situation. Because of that all sensor nodes consume high energy, show very low throughput and face a long delay. Thus, ATLAS lacks in energy preservation of non-emergency sensor nodes and creating a balance between throughput and energy.

Furthermore, PLA-MAC (Anjum *et al.*, 2013) also focuses on emergency based traffic load adaptivity with high throughput, low delay and less energy consumption. In PLA-MAC, the traffic is categorized into four classes, and the highest priority is assigned to emergency traffic. In PLA-MAC, the Emergency Data Transfer Slots (ETS) are introduced to transmit emergency traffic, and the number of ETS slots is determined dynamically in each superframe. Although in PLA-MAC, traffic prioritization is provided, if there is no emergency traffic, then ETS slots allocation results in wastage of resources. As a result, PLA-MAC becomes unsuccessful in achieving dynamic adjustment of traffic to accommodate the variations in heterogeneous traffic rates. In addition, in PLA-MAC, the specific backoff period range is assigned to the BMSNs of each traffic class that remains unchanged in every backoff. Therefore, a high traffic load in emergency situation results in a high collision which increases the packet delivery delay and energy consumption and reduces the throughput. Consequently, PLA-MAC becomes weak to preserve the energy of BMSNs with non-emergency traffic and to create a balance between throughput and energy.

Summarizing the aforementioned discussion, it is observed from the previous research works that the existing MAC protocols consider traffic prioritization. Even though some of them use standard slotted-CSMA/CA to provide channel access during contention, and some of them customize the standard slotted-CSMA/CA to give prioritized channel access during contention. But still, there are many limitations in the existing MAC protocols regarding traffic prioritization as explained earlier. Thus, it is necessary to reconsider contention-based prioritized channel access for heterogeneous nature vital-signs information. Similarly, some of the existing MAC protocols also consider the issue of contention-based sporadic emergency traffic handling. But in fact, all of them do not address the issues of sporadic emergency traffic such as emergency traffic identification, emergency traffic handling at single or multiple BMSNs simultaneously, and providing appropriate transmission opportunity to non-emergency traffic. The particular issue which is addressed by them also has many shortcomings as described earlier.

In addition, some of the existing MAC protocols only focus the issue of contention-based sporadic emergency traffic handling but still have many weaknesses as illustrated before. Likewise, some of the current MAC protocols address the issue of contention-based dynamic adjustment of traffic in sporadic emergency situations, but most of them fail to address the issue of energy preservation of non-emergency traffic BMSNs and the issue of creating a balance between throughput and energy. Additionally, even though, the existing MAC protocols either address all the issues or a specific issue of contention-based dynamic adjustment of traffic in sporadic emergency situations. But all of them have a lot of flaws as discussed before. So, it is extremely desirable to introduce mechanisms to resolve the weaknesses of existing MAC protocols.

1.3 Problem Statement

Wireless Body Area Network has a significant role in the domain of healthcare to observe the patient's health and due to its nature; it poses some unique constraints and challenges such as contention-based prioritized channel access for heterogenous natured vital-signs information, contention-based sporadic emergency traffic handling and the contention-based dynamic adjustment of traffic in sporadic emergency situations. These unique constraints and challenges need to be addressed while designing the MAC protocol for WBANs. Most of the existing MAC protocols partially address these issues except PLA-MAC (Anjum *et al.*, 2013).

Most of them use standard slotted-CSMA/CA during contention but still have many limitations regarding traffic prioritization. In particular, the same backoff period range is assigned to each traffic class in every backoff and the backoff period range of third backoff remains unchanged in fourth and fifth backoffs. Also, the backoff period range of first backoff is repetitively used in the backoff period ranges of second, third, fourth, and fifth backoffs. However, such repetitions could cause a high collision which increases the packet delivery delay and energy consumption and decreases the throughput and Packet Delivery Ratio (PDR). Besides, some of them customize the backoff period range of standard slotted-CSMA/CA to provide prioritized channel access. But still have many constraints such as, in each backoff, the backoff period range of high priority traffic class is repetitively used in the backoff period range of low priority traffic class. Therefore, a high priority traffic class BMSN faces a longer delay which is not appropriate in healthcare applications. Furthermore, the assigned backoff period ranges to various traffic classes in first backoff remain unchanged in second, third, fourth, and fifth backoffs. As a result, the packet collision, packet delivery delay and energy consumption are increased, and the throughput and packet delivery ratio are decreased. Also, a very high backoff period range is assigned to low priority traffic classes. In result such traffic classes face a very high packet delivery delay.

Furthermore, some of the existing MAC protocols address the issue of sporadic emergency traffic handling. However, they do not provide any mechanism to handle emergency traffic based on those patient's vital-signs which are considered by the doctors in an emergency situation. Some of them permanently consider a single or a particular group of BMSN(s) that always generate emergency traffic but emergency situation is sporadic and temporary by nature. In emergency situation, the non-prioritized channel access delays the emergency traffic which is not appropriate because it is dangerous for patient's life. Also, most of them provide mechanism to handle an emergency traffic at a single BMSN, but no mechanism is available to handle emergency traffic at multiple BMSNs. However, the BMSNs with emergency traffic also affect the closely related BMSNs. Some of them do not provide appropriate transmission opportunity to non-emergency traffic in an emergency situation whereas some of them address this issue but still lack due to the assignment of very high backoff period range to lowest priority traffic class and non-prioritized channel access.

The existing MAC protocols also attempt to adjust the traffic dynamically. But the dynamic adjustment of traffic through adaptive slot allocation increases the packet drop ratio and energy consumption of non-emergency traffic BMSNs. The non-emergency traffic BMSNs consume high energy due to non-prioritized channel access. Also, it is experimentally observed that the energy is highly consumed and throughput is throttled down due to high-rate emergency traffic but a balance is required between throughput and energy consumption. Because emergency traffic requires high throughput and non-emergency traffic BMSNs require low energy consumption in emergency situation. In emergency situation, some data packets are expired before transmission and communication channel is engaged with the transmission of dead data packets which puts an extra burden over the network but the existing MAC protocols do not provide any mechanism to manage the lifetime of data packets. As a consequence, the performance of the network is decreased in terms of packet delivery delay, throughput and energy consumption.

1.4 Research Goal

This research work aims to develop prioritization-based adaptive emergency traffic medium access control protocol for wireless body area networks. The proposed protocol is deemed to ensure the provision of contention-based prioritized channel access for heterogenous natured vital-signs information with the contention-based sporadic emergency traffic handling and the contention-based dynamic adjustment of traffic in sporadic emergency situation.

1.5 Research Questions

This research work addresses the following research questions:

i. How to provide contention-based prioritized channel access to the heterogeneous natured BMSNs?
ii. How to handle contention-based sporadic emergency traffic at single or multiple BMSN(s) without ignoring non-emergency traffic?
iii. How to create a balance between throughput and energy consumption in sporadic emergency situation?

1.6 Research Objectives

The research objectives are as follows:

i. To design a Traffic Class Prioritization-based slotted-CSMA/CA scheme which assigns a distinct, minimized and prioritized backoff period range to each traffic class in every backoff during channel access in the CAP period that can reduce packet delivery delay, packet loss ratio and energy consumption while it increases throughput and packet delivery ratio.

ii. To design an Emergency Traffic Class Provisioning-based slotted-CSMA/CA scheme which delivers the sporadic emergency traffic instantaneously, that occurs either at a single or multiple BMSN(s) with minimum delay and packet loss without ignoring non-emergency traffic in the CAP period.

iii. To design an Emergency-based Traffic Adaptive slotted-CSMA/CA scheme which provides dynamic adjustment of traffic to accommodate variations in heterogeneous traffic rates along with energy preservation of BMSNs with non-emergency traffic, creating a balance between throughput and energy in the sporadic emergency situation.

1.7 Research Contributions

This research work proposes a MAC protocol which offers a realistic solution that considers several aspects of WBAN. A range of BMSNs is used to monitor the different vital-signs information of the patient's body by classifying the generated data of these vital-signs into Normal Data Packet (NDP), Delay-constrained Data Packet (DDP), Reliability-constrained Data Packet (RDP), Critical Data Packet (CDP), and Emergency Data Packet (EDP) as discussed in Pandit *et al.* (2015). Thus, the following are the research contributions, which are summarized as follows:

i. The proposed Traffic Class Prioritization-based slotted-CSMA/CA scheme assigns a distinct, minimized and prioritized backoff period range to each traffic class in every backoff during channel access in the CAP period. Consequently, packet collision rate, packet delivery delay, packet loss ratio and energy consumption are decreased, while throughput and packet delivery ratio are increased.

ii. The proposed Emergency Traffic Class Provisioning-based slotted-CSMA/CA scheme delivers the sporadic emergency traffic instantaneously occurring either at a single BMSN or multiple BMSNs with minimum delay and packet loss without ignoring non-emergency traffic in the CAP period. As a consequence, energy consumption is decreased while the throughput and packet delivery ratio are increased.

iii. The proposed Emergency-based Traffic Adaptive slotted-CSMA/CA scheme provides dynamic adjustment of traffic to accommodate the variations in heterogeneous traffic rates with the energy preservation of BMSNs with non-emergency traffic and creates a balance between throughput and energy in the sporadic emergency situation.

1.8 Research Scope

The scope of this research work is as follow:

i. This research work focuses on MAC layer for tier–1 (intra-WBANs) of wireless body area networks.

ii. It is based on IEEE 802.15.4.

iii. IEEE standard group also introduced IEEE 802.15.6 standard for WBANs by defining its PHY and MAC layers but due to many constraints (described in Section 2.3.1), it is outside the scope of this research.

iv. All BMSNs are fixed and connected in a star topology under the supervision of an on-body local base station known as BC, which is a Fully Function Device (FFD).

v. The data communication between the BC and MS or server through any network (i.e., Wireless Local Area Network (WLAN), or wired, cellular) is outside the scope of this research.

vi. The data communication among multiple collaborative WBANs is also outside the scope of this research.

vii. The downlink data communication from the BC to the BMSNs is also outside the scope of this research.

1.9 Organization of the Thesis

The rest of this thesis is organized as follows. Chapter 2 presents the literature review of the existing MAC protocols for WBANs. It also identifies the various issues and challenges of MAC protocols for wireless body area networks. Chapter 3 provides the details of the research framework to design the proposed schemes. Chapter 4 presents the design and development of the proposed Traffic Class Prioritization-based slotted-CSMA/CA (TCP-CSMA/CA) with its performance evaluation. Chapter 5 illustrates the design and development of the proposed Emergency Traffic Class Provisioning-based slotted-CSMA/CA (ETCP-CSMA/CA) with comparative results. Chapter 6 presents the design and development of the proposed Emergency-based Traffic Adaptive slotted-CSMA/CA (ETA-CSMA/CA) with its performance evaluation. Finally, Chapter 7 concludes the thesis and provides the possible future directions.

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