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Providing QoS in Autonomous and Neighbor-aware multi-hop Wireless Body Area Networks

Student’s name: Navneet Iyengar

This work and its defense approved by:

Committee chair: Dharma Agrawal, D.Sc.
Committee member: Raj Bhatnagar, Ph.D.
Committee member: Prabir Bhattacharya, Ph.D.
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Navneet Iyengar

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Thesis Advisor and Committee Chair: Dr. Dharma P. Agrawal
Abstract

Continued evolution of Wireless Body Area Networks (WBANs) has made effective monitoring of vital parameters of a person much faster and efficient, thereby providing better personal healthcare. Sensor nodes of a WBAN acquire critical physiological parameters like heartbeat, neural activity, limb motion, muscle movement and fatigue, temperature, etc. that are monitored by a physician. Important factors in the acceptance of WBAN performance are energy efficiency and the Quality of Service (QoS) supported for such critical data that impact human lives.

The sensor nodes of a WBAN are highly constrained in terms of their battery life. Most of the work till date on WBANs uses a star topology which employs single hop communication. This work discusses various factors that affect energy efficiency in a WBAN and establishes the need for a multi-hop tree based topology. It also studies the need for QoS in WBANs and existing support provided by the current Body Area Sensor Network (BASN) Standard.

This thesis tackles the all important challenge of providing QoS in autonomous and neighbor-aware multi-hop WBANs in significant detail spread across multiple chapters. In case of independent, autonomous multi-hop WBANs, the aforementioned issue is resolved by implementing a two layer priority-mapping scheme over a reactive Media Access Control (MAC) layer designed to alter durations of the access phases involved as per QoS requirement. In the case of neighbor-aware WBANs, a framework is defined under which a cooperative inter-WBAN routing scheme is implemented through power based weight assignment and fault detection is carried out by employing Kosaraju’s two-pass algorithm that discovers the strongly connected components in the network deployment graph.
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<th>Description</th>
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<tbody>
<tr>
<td>WBAN</td>
<td>Wireless Body Area Network</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>BASN</td>
<td>Body Area Sensor Network</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
</tr>
<tr>
<td>LQI</td>
<td>Link Quality Indicator</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Collision Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>MAP</td>
<td>Managed Access Phase</td>
</tr>
<tr>
<td>RAP</td>
<td>Random Access Phase</td>
</tr>
<tr>
<td>EAP</td>
<td>Exclusive Access Phase</td>
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<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
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<tr>
<td>WMAN</td>
<td>Wireless Metropolitan Area Network</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>WAN</td>
<td>Wide Area Network</td>
</tr>
<tr>
<td>PLCP</td>
<td>Physical Layer Convergence Protocol</td>
</tr>
<tr>
<td>PPDU</td>
<td>Physical Layer Protocol Data Unit</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
</tr>
</tbody>
</table>
Physical Constants

Speed of Light \( c = 2.997 \, 924 \, 58 \times 10^8 \) ms\(^{-8}\) (exact)
Symbols

\( \alpha \)  Number of packets dropped

\( \beta \)  Number of packets received

\( \mu \)  Ratio of \( \alpha \) to \( \beta \)

\( a \)  Coefficient for linear fitting

\( b \)  Coefficient for linear fitting

\( N \)  Standard deviation considered due to fading
Chapter 1

Introduction

1.1 Wireless Body Area Networks

Development of Wireless Body Area Networks (WBANs) over the years has resulted in faster and efficient health monitoring services, thereby providing enhanced personal healthcare. A WBAN is a network that consists of several sensor nodes that are either attached on the surface or implanted in a human body. A WBAN generally consists of a high energy device that coordinates communication arising from several sensor nodes (SNs) that constitute a WBAN. This device is known as a coordinator node (CN) and can be in the form of a smart phone or a PDA that a person generally carries on him/her in a daily routine. The sensor nodes or devices collect various physiological data that are wirelessly transmitted to the coordinator which acts as a sink in a WBAN topology. The data which is collected by the coordinator is then transmitted to a base station (BS) where it is stored on a database that can be accessed by medical personnel. WBANs have revolutionized the field of healthcare by providing real-time patient data. However, WBANs are not only useful for health monitoring but also have important applications
in the fields of sports, emergency services and entertainment. The following section elucidates on various applications of WBANs and their importance in our lives.

1.1.1 Applications

With increasing focus on real time data monitoring, especially in the health and fitness industry, WBANs have become an intrinsic part of our lifestyle today and are expected to further dominate in the future. It is also expected that the number of WBANs in the future could increase to an extent so as to allow interaction between multiple WBANs in each other’s vicinity. The advantage that WBANs provide is that they allow hassle-free real time patient monitoring. The sensors/devices in a WBAN track various biomarkers that are associated with the organ they are monitoring and hence provide information about its functioning. A person can go about his daily routine without the need to visit a physician in person as the component sensors/devices of a WBAN continuously collect and transmit various physiological parameters of the human body. The physician can then determine the current health status of the patient by understanding about the normalcy/abnormalcy of the physiological parameters like heartbeat, neural activity, limb motion, muscle movement and fatigue, temperature, etc. Aggregated data can also be comprehended to understand if the health of a patient is deteriorating over a period of time or if a particular medicine is being effective. Depending on these parameters, a medical personnel can accordingly decide about the medication and the dosage to be administered [1], [2].

Some of the major diseases that require continuous monitoring are Cardiovascular disorders, Diabetes, Renal failure, Parkinson’s disease, Alzheimer’s disease, Cystic Fibrosis, etc. WBANs can help in timely detection of such diseases and/or also help in ascertaining proper and systematic treatment for curing them. WBANs are also employed for
general fitness monitoring and stamina building.

![Application of WBANs in Health Monitoring](image)

Figure 1.1: Application of WBANs in Health Monitoring [1]

In the field of emergency services and public safety, firefighters and soldiers can be outfitted with a WBAN consisting of devices like Carbon Monoxide sensor, ECG, etc.
to monitor their heart rates and the level of toxicity so as to ensure adequate safety.

Apart from purely medical applications, WBANs are present in other fields such as entertainment in the form of head mounted virtual reality devices, neural interfaces, smart glasses, MP-3 players, virtual gaming interfaces, etc. [1], [2].

Another area of application can be found in the domain of Athlete Training and Sports Medicine. WBANs are used in the form of helmets designed to determine impact so as to avoid brain injury through concussion. They are used to monitor fatigue and endurance levels of athletes and in fine tuning training programmes for stamina building. WBANs are also important in providing effective rehabilitation for injured people.

This brief outline of WBAN applications showcases the usefulness of WBANs in various fields and their immense potential in revolutionizing other areas where they can be of enormous utility. It can be deciphered from these applications that the endeavor behind WBANs is to be beneficial towards improving the quality of human life.

1.1.2 Architecture

Typically, a WBAN contains multiple heterogenous devices. However, most of these devices can be classified broadly into three categories when seen from an architectural perspective of WBANs. They are -

1) **Wireless Sensor Node:** A wireless sensor node in a WBAN can be defined as a device that gathers physiological data on physical stimuli. It then processes the collected data if required and transmits the information wirelessly. A sensor node generally consists of a power unit, memory, processor, wireless transmitter and most importantly sensor hardware that is critical to its functioning. Some typical examples are an EKG
transducer that collects and transmits heart activity readings and a temperature sensor that transmits body temperature data.

2) **Wireless Actuator Node:** A wireless actuator node in a WBAN can be described as a device that acts according to data received from the sensors, personal device or through interaction with the user. The components are usually similar to a wireless sensor node with the exception of a reservoir that holds the medication. An example would be an insulin pump that administers appropriate dosage of insulin to diabetes patients on the basis of instantaneous glucose levels observed in the blood.

3) **Wireless Personal Device:** A wireless personal device gathers all the information that is transmitted by the sensor and actuator nodes. It acts generally in a dual mode of operation- as an aggregator of data that is transmitted by the nodes and also as the coordinator node of the WBAN which coordinates the working of all the sensor and actuator nodes that form a part of a WBAN. In common terminology, it is also referred to as the sink as it collects all the data from the wireless devices in the WBAN. It also informs the user (i.e., medical personnel, patient, etc.) through an external gateway or a display unit, about the data collected. It usually consists of a much larger processor and power unit, wireless transmitter/receiver and memory. A very common coordinator/aggregator device is a smartphone. Some other examples are PDAs like tablets, smartwatch, etc.

WBAN architecture depends on two components of communication - intra-body communication and extra-body communication. The former pertains to the communication on the body between the wireless sensors, actuators and the personal device. The latter controls the communication between the WBAN and an external network. Figure 1.2 depicts an example of intra-body and extra-body communication in a WBAN.
Chapter 1. *Introduction*

Figure 1.2: Extra Body and Intra Body communication in WBANs. [1]

Intra-body communication depends on the kind of network topology being utilized by the WBAN. If the WBAN has been deployed in a topology that utilizes point-to-point communication, then each of the wireless nodes have a communication link between themselves and the personal device. In such a scenario, the nodes transmit data directly to the personal devices in what is also known as single hop communication. Some topologies that employ this type of communication include peer-to-peer and star topologies.

A different type of communication technique is the multi-hop communication paradigm where each of the wireless nodes transmit data to the personal device over multiple hops through neighboring intermediate wireless nodes. Topologies that employ this communication technique include the mesh, hybrid, and tree topologies. A detailed discussion on the different communication techniques and network topologies is provided in Chapter 2 along with their advantages and disadvantages.

Extra body communication takes place between the personal device and internet and also encompasses the communication between the internet and the medical server where the data is stored in a database that can be accessed by medical personnel. Typically intra-body communication range is restricted to a few metres with typical values between 1-2 m. Once extra-body communications come into the picture, a WBAN transforms
into a WPAN which consists of wearable devices and the network environment around the person. The communication range in this scenario is generally around 10 m. As data has to be transmitted over the Internet to the medical servers- WLAN, WMAN and WAN come into the picture and each of these have communication ranges from hundreds of metres to hundreds of kilometres. Each of these networks has its enabling technology. A WPAN uses IEEE 802.15.4 (ZigBee) standard, a WLAN uses IEEE 802.15.11 (Wi-Fi) and a WMAN uses IEEE 802.16 (WiMax) standard. A WAN generally involves setting up satellite and radio links over a large geographical area. Figure 1.3 shows how communication takes place between all the above layers during extra-body data transmission in a WBAN.

As can be understood, the combination of intra-body and extra body communication helps in providing ubiquitous health care monitoring, making WBANs highly effective and useful.
1.1.3 Characteristics

In a broad sense, all the WBANs, regardless of their usage and purposes share the same characteristics in terms of network requirements. Some of these characteristics are listed below:

1. The wireless devices in a WBAN, with the exception of the personal device, i.e., the coordinator, are highly energy constrained. Since most of the devices are small, the battery sizes are small as well and accordingly their lifetimes too. Also, generally, most of the devices cannot be recharged or their batteries cannot be replaced, especially in case of implanted devices.

2. Since there are limited opportunities to recharge or replace the devices, it is required that these devices have a long lifetime and are energy efficient. In order to make this feasible, the computational power and memory at the disposal of these devices is generally limited.

3. The devices usually differ in terms of their requirements of network resources such as bandwidth, power consumption etc.

4. Due to strict guidelines for safety levels with respect to human exposure to electromagnetic radiation [3], WBANs are generally restricted to the maximum operating power of 1 mW.

5. Also, the transmission operating power needs to be low to minimize interference as WBANs operate in a very limited area restricted by the dimensions of the human body.
6. Since the data that is carried by WBANs usually contains physiological data it is imperative for the WBANs to have effective QoS provisioning. High reliability levels and low delay along with minimum network latency are major design requirements of a WBAN.

7. Security is also a major requirement of a WBAN as privacy and confidentiality need to be ensured during transmission of the physiological data.

1.2 Major Design Factors in WBANs

The applications, architecture, and characteristics discussed in the previous sections indicate that WBANs are a specific species of wireless networks that require a unique design methodology of their own. As stated earlier, regardless of purpose and usage, all WBANs share common characteristics and architecture which can help in laying down a common design strategy which can be applicable to a majority of WBANs. This section describes in detail the design requirements and challenges that are involved in creation of an effective WBAN. These include energy efficiency, QoS and reliability, ease of use and security and privacy issues.

1.2.1 Energy Efficiency

The devices in a WBAN are usually small in size, thereby restricting the size of the batteries that power them. Due to smaller battery sizes the energy reserves of these devices are low. In case of medical applications, most of these devices cannot be replenished with newer batteries and their requirement is such that they have to remain functional for multiple years once installed. As a consequence, energy efficiency is a major design factor in creation of a WBAN. It is important to design the WBAN in such a manner
that its power consumption is low and thereby the lifetimes of the sensor nodes can be extended. Network topologies that optimize energy consumption, need to be employed to reduce energy consumption. Energy efficiency can also be improved by employing efficient and optimal architectural designs.

Another energy concern that needs to be kept in mind while designing a WBAN is the Specific Absorption Rate (SAR) of the human body. Communication from devices generates heat that can be absorbed by the surrounding tissues which can be harmful to the human body. The heat absorption into the body should be regulated by limiting the operation of WBANs to power levels that are both optimal and safe [3].

1.2.2 Quality of service

QoS is a very important and an integral part of WBAN design process. QoS in terms of WBANs can be defined as involving resource reservation mechanisms that can guarantee a certain degree of performance to transmissions in the network. Medical applications especially require QoS provisioning as delay and latency along with reliability are important factors that affect the quality of patient monitoring. In some life threatening scenarios, if the data is not received in a timely manner or in a specific order with guarantee, it can result in non-detection of potentially fatal health conditions. Therefore, it is necessary to provide QoS so as to ensure timely and guaranteed delivery of data packets in a WBAN.

1.2.3 Security and Privacy

Health information that is transmitted over WBANs is supposed to be private and confidential. Therefore, the data that is collected and transmitted by the WBAN should
be encrypted by employing cryptographic techniques such as Elliptic Curve Cryptography (ECC) and Advanced Encryption Standard (AES). It is important to ensure that authentication and authorization procedures are utilized at various stages during transmission of data so that it is not vulnerable to intrusion or brute force attacks.

1.2.4 Ease of use

An important factor to be kept in mind while designing a WBAN is usability. A WBAN should be easy to use and deploy. It should be designed in such a manner so as to not hinder any movement of patients during their daily activities. The devices used in a WBAN should be small so that they can be worn on or implanted in the body. The WBAN should be easily reconfigurable and should also possess the ability to be self organizing.

1.3 Thesis Outline

The remainder of this thesis is organized as follows: Chapter 2 establishes the foundation of the work described in this thesis and sheds some light on related work that is relevant to the topic of this thesis. This chapter covers the preliminaries that are key to understanding the work carried out in this thesis. Chapter 3 introduces the proposed scheme for providing QoS in independent autonomous WBANs through a two layer priority mapping algorithm implemented over a reactive MAC layer. This chapter explains in depth the ideas and algorithms that have been employed for realization of the aforementioned scheme through multiple images and flowcharts. Chapter 4 puts forward the implementation details of the proposed scheme and analyses the results arising from the
same. Chapter 5 apprises the reader of the proposed scheme for utilization in neighbor-aware WBANs. Chapter 6 discusses the implementation details and results that are obtained through the proposed scheme. Finally, Chapter 7 concludes this thesis with summary of all findings along with suggestions for future work that could arise out of this thesis.
Chapter 2

Foundation and Related Work

2.1 Motivation

This section elucidates the motivation behind the work carried out in this thesis on the basis of the issues and the requirements of a WBAN as discussed in the previous chapter. As there is ample scope for improvement in the performance of WBANs, there are multiple areas of WBAN functioning on which research focus can be brought upon. This thesis mainly deals with effective QoS provisioning in a WBAN while also maintaining energy efficiency. In case of an autonomous and independent WBAN, these goals are achieved by implementing a two layer priority mapping scheme over a reactive MAC layer. It also provides a framework for providing QoS in neighbor-aware WBANs through co-operative inter-WBAN routing. The following sections establish the need for QoS in both autonomous WBANs and neighbor-aware WBANs and also the need for maintaining a multi-hop communication topology.
2.1.1 Need for QoS in autonomous WBANs

A WBAN is constituted of different types of sensors that collect vital body parameters. An EKG transducer collects and transmits heart activity readings, a temperature sensor transmits body temperature data, an EEG transmits brain activity and an EMG transmits the muscle and limb movements. It is intuitive to understand that heart activity readings are more important than temperature readings and hence can be assigned higher priority from the QoS point of view. Another example that substantiates this view is that, the readings collected by a sweat sensor would be less critical for a physician to monitor than an EEG reading. Moreover, values provided by a temperature sensor are less important when a human being is healthy as compared to those transmitted when he/she is suffering from fever. Therefore, there arises a need to ensure QoS to the data streams with higher priority at all times and even to the data streams with lower priority in the case of an emergency. The main idea is that critical data should not be lost due to interference or fading.

2.1.2 Maintaining Energy Efficiency

It has already been identified [4], [5], [6] that a multi-hop routing strategy is better suited for WBANs as compared to a single-hop star topology to communicate with the coordinator/personal device. This is due to the fact that channel conditions could be poor around human body, resulting in path loss [7]. Therefore, a multi-hop routing strategy is employed that ensures a hop wise transmission that causes energy to be consumed for transmission in a distributed fashion from all nodes in the path to the coordinator. It is also capable of selecting the best path from the transmitting node to the parent by utilization of residual energy based routing algorithms which can also aid
in minimizing the probability of energy-hole while increasing the lifetime of the sensor network.

QoS research in WBANs is not new. However, previous research [8], [9], [10], [11] has focussed mainly on QoS in single-hop star topology network. QoS in case of multi-hop WBANs present a different set of challenges. They are -

1. A typical WBAN consists of a resource rich coordinator and resource starved sensor nodes. Therefore, it is imperative that for a WBAN, most of the computations are carried out at the coordinator.

2. As stated earlier, human body can cause major fading effects to channels around the body [7]. Moreover interference can lead to data loss. Therefore, bandwidth needs to be used properly and an effective QoS scheme should be able to address both these issues.

2.1.3 Neighbor-aware WBANs and QoS requirement

Numerous applications of WBANs along with their cost effectiveness makes them ideally suited for widespread deployment for realization of everyday healthcare needs. It is expected that in the near future, there would be rampant proliferation of WBANs in human life and such a scenario would come with its own challenges with inter-WBAN interference being one of them. With a number of WBANs expected to operate in the vicinity of each other, the problem of inter-WBAN interference gets compounded. A number of works exist in the literature that have tried to deal with this issue.
Kim et al. [12] have tried to solve the problem of inter-WBAN interference by providing a hybrid, asynchronous inter-WBAN interference avoidance solution known as Asynchronous Inter-network Interference (AIAA) that combines CSMA/CA with TDMA. It works by maintaining a table with timing offset values and TDMA transmission schedule related to the WBANs likely to interfere with each other’s working. This table is stored at the gateway of such WBANs and can be looked up to check for and update any conflicting TDMA schedule. Bae et al. [13] have proposed an interference cancellation scheme for ultra wideband (UWB) and multiple-input-multiple-output (MIMO) systems in a WBAN that employs an optimal ordering algorithm along with successive interference cancellation.

A fuzzy logic based intelligent scheduling system has been used by Jamthe et al. [14] for resolving inter-WBAN and intra-WBAN interference. Another solution, PAPU - Pro Active Power Update [15] is a game theory based distributed power control algorithm that mitigates interference by treating each WBAN as a game player in the interference space. These game players exchange information such as transmission power and gain, interference etc. to arrive at a decision on transmission schedules and power levels for transmission.

All the above approaches try to minimize interference as they overlook the possibility of coordinated inter-WBAN communication. They treat interference as an issue as they assume that by default all data from sensor nodes in a WBAN would be transmitted via the coordinator to the base station. However, there could arise emergency situations where the coordinator could be strapped for bandwidth due to sudden or excessive bandwidth demand from sensor nodes. In such a situation, data packets from other sensor nodes would either be transmitted with a delay or might get dropped. Therefore,
there arises a need to find alternative solutions to provide QoS in case of neighbor-
aware WBANs. We provide a framework for carrying out co-operative inter-WBAN
routing which utilizes the infrastructure of neighboring WBANs to provide QoS in such
scenarios.

2.2 Multi-hop Communication in WBANs

It has been observed [16] that WBANs face significant path loss and fading while op-
erating in and along the human body. The wireless signals that are transmitted by the
devices in a WBAN face extensive deterioration in terms of signal strength, data quality,
etc., along the human body. Path loss in-vivo i.e. inside the human body takes place
mainly due to absorption of radio signals by tissues. Therefore, in the case of implanted
devices, the transmissions face severe attenuation which is almost 35 times of the general
attenuation of signals taking place in free space.

Wireless communication among devices on the human body is of two types - line of sight
(LOS) and non-line of sight (NLOS). LOS communications are those where devices are
visible to each other on the same surface. In NLOS communications, the devices are
not visible to each other on the same surface. An example of NLOS communication
specific to WBANs would be a sensor attached to the back trying to communicate
with a pacemaker attached near the chest of the body. In both these communication
models, it has been determined that there is excessive path loss due to electromagnetic
absorption. The path loss and fading is much higher in case of NLOS communication
due to additional penalties incurred as a result of diffraction, as a direct path is non-
existent between the devices. In LOS communication, the following equation [16] gives
the amount of path loss that is incurred in radio transmission along the human tissue
in case of on-body devices -

\[
PL(d) = PL(d_0) + 10 \times n \log_{10} \frac{d}{d_0}
\]  

(2.1)

where \(PL(d)\) is the path loss calculated at distance \(d\) on the basis of \(PL(d_0)\) which is the path loss calculated at reference distance \(d_0\). The path loss coefficient \(n\) depends on the medium causing the path loss which in the instant case is human tissue. The path loss \(PL(d_0)\) calculated at reference distance \(d_0\) can be further expanded on the basis of the following formula -

\[
PL(d_0) = 20 \times \log_{10} \frac{4 \times \pi \times d_0 \times f}{c}
\]  

(2.2)

where \(f\) is the frequency and \(c\) is the speed of light. These equations are then simplified to the following equation for body surface to body surface communication using channel model CM3 at 2.4 GHz [16].

\[
PL(d) = a \times \log_{10}(d) + b + N
\]  

(2.3)

where \(a\) and \(b\) are coefficients for linear fitting, \(d\) is the distance between the sensor nodes and \(N\) is the standard deviation considered due to fading.

These issues make single-hop communications highly expensive in terms of energy consumption which in turn can result in shorter battery lifetime for the devices in the WBAN. Hence, a more effective communication strategy is required to make WBANs energy efficient.

A multi-hop routing strategy is expected to avoid channel fading due to path loss and reduce interference in WBANs [4], [5], [6]. As stated in section 2.1.2, a multi-hop routing topology consumes energy from multiple sensors in a distributed manner, thereby
extending the life time of the WBAN. We use a tree based multi-hop routing strategy which affords the flexibility for adoption of the best path from a sensor node to the coordinator for transmission of data. This determination of the best route depends on the latency, residual energy of the sensor nodes, and the link quality between them. In such a network topology, sensor nodes transmit data packets over several hops to reach the coordinator which basically acts as the root of the tree. Under this topology, a relayed node/child node transmits data to its immediate relaying node/parent node. This data is then transmitted again to its parents and so on, until the packets reach the coordinator. Therefore, the nodes in a tree based multi-hop WBAN topology can be classified as follows:

A. Parent Nodes

Any node that acts as a relaying node in such a network can be called a parent node. The nodes to which it provides its relay services are its immediate successors and can be called as its children. The parent node is responsible for collection of packets from its children and forwarding that data to the coordinator. In such a system, the coordinator acts as the ultimate parent that collects all the data and transmits it to the base station.

B. Non-Parent Nodes

Any node in the network that does not have a successor, can be called as a leaf node or a non-parent node. Such nodes generally have to handle their own data and have greater buffer availability than the parent nodes. Additionally, they are not required to handle any additional traffic.

Figure 2.1 shows a generic tree based sensor deployment, connecting typical relaying/-parent nodes, coordinator and non-parent nodes. As in a tree, the nodes can be divided
Figure 2.1: Tree Structure with Relaying/Parent Nodes and Non-parent nodes.

into various levels depending upon the number of hops required for the data packets to be received by the aggregator. Therefore, the coordinator is always deemed to be at level 0 and the node B is at level 1 and node D at level 2 as shown in Figure 2.1. As can be seen, there are two different types of links between all the nodes in the multi-hop tree topology. The first type of link is the data link. These links are used to transfer data packets from a relayed node to the relaying node or the coordinator. The data packets contain the physiological parameters of a body.

A sensor node transmits the data packet to its immediate parent and waits for an acknowledgement. The acknowledgement is sent by the parent back to the node through the control link which is used to send control packets like acknowledgements or network management packets that define the topology of a network.
As can be seen from Figure 2.1, the data link and the control link flow in opposite directions. Therefore, data packets and control packets maintain the same directions in accordance with their links.

2.3 Existing QoS Support

The current BASN standard IEEE 802.15.6 [17], [18] provides very limited support for QoS. Furthermore, the support that is provided, is suitable for a single hop star topology and the two hop topology in which there is a single relaying node between the coordinator and the relayed node. A relayed node is defined as the node that is transmitting its data and can be either a parent or a non-parent node. A relaying node is the node which provides its relay services to route the data to the coordinator. It can forward data to another relaying node or the coordinator depending on the network topology. The standard defines a High QoS mode that is used for transmission of emergency frames. A User Priority is associated with the frame that assists the network in activating the High QoS mode. In other words, a priority is associated with the data that is transmitted. When the network is in the High QoS mode, emergency frames are transmitted immediately in the Exclusive Access Period (EAP) defined by the hub/coordinator. The EAP is defined in the beacon super frame that is transmitted by the coordinator and is exclusively meant for re-transmissions or emergency transmissions. Table 2.1 shows various User Priority values and the type of frame and traffic that it corresponds to.
Table 2.1: User Priority Mapping [17]

<table>
<thead>
<tr>
<th>Priority</th>
<th>User Priority</th>
<th>Traffic Designation</th>
<th>Frame Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest</td>
<td>0</td>
<td>Background (BK)</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Best Effort (BE)</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Excellent Effort (EE)</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Video (VI)</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Voice (VO)</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Medical Data or network control (BE)</td>
<td>Data or management</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>High-priority medical Data or network control (BE)</td>
<td>Data or management</td>
</tr>
<tr>
<td>Highest</td>
<td>7</td>
<td>Emergency or medical implant event report</td>
<td>Data</td>
</tr>
</tbody>
</table>

The User priority is shared between sensor nodes whenever a connection is established.

This is carried through the Connection Request frame as shown in Figure 2.2. The connection request frame contains an Uplink Request information element (Figure 2.3) which, in turn, contains the Allocation request.

![Figure 2.2: Frame payload format for Connection Request frames. [17]]
The Allocation Request contains the Allocation ID that defines a User Priority which can be established through a three bit sequence as shown in Figure 2.4. Therefore, when the data transmitted from a sensor node is carrying a User Priority of 6 (110) or 7 (111), the EAP is used to transmit it immediately as it is emergency data in accordance with Table 2.1.

Under this scheme, while selecting a relaying node, transmitting node needs to check the quality of links between itself and the relaying node and the relaying node and the hub/coordinator. A relaying node which has its own emergency frames yet to be transmitted can recognize if the relayed node, i.e., its child is sending general or emergency frames. The problem arises when a relaying node in emergency mode determines that it cannot process its own emergency frames. In such a scenario, if the relayed node is transmitting data with a general User Priority, the relaying node denies its relay services to the relayed node. In case, the relayed node is transmitting emergency data, i.e., data with User Priority 6 or higher, the relaying node can decide to provide its relay services depending on factors such as load and the state of its neighboring nodes. In such a case,
a relayed node may need to find an alternative relaying node that can provide its relay services. This can cause unwanted delays in transmission of both emergency and regular data, especially in a multi-hop network topology.

Therefore, we introduce a two-step priority mapping scheme that operates on a reactive MAC layer to provide QoS that addresses these and associated issues in WBANs and is presented in the next chapter.
Chapter 3

QoS scheme for Autonomous Multi-hop WBANs

3.1 Introduction

A WBAN used for health monitoring usually carries critical data that is indispensable in controlling the fate of human lives. Thus, it is important that collected data is transmitted in a reliable and energy efficient manner with low delay. Such networks can benefit from a Quality of Service (QoS) scheme that could support prioritization of data streams and ensure reliable communication in the case of interference or fading in the network that could potentially cause data loss.

Another issue that concerns WBANs is the energy efficiency of the network. WBANs are basically sensor networks deployed on a body that are relatively small in size and sparse in deployment. The deployed sensors have limited energy resources and as these networks operate on the human body they are required to operate at power levels that are not harmful to various physiological functions of the body. This adds to the existing
energy constraints on WBANs. Therefore, it is important that energy efficiency of the network is taken into account while provisioning for QoS.

The work carried out in this thesis introduces a cross-layer solution that addresses both these issues. It proposes a priority based QoS scheme that works on a reactive MAC layer in a tree topology based multi-hop WBAN and analyses performance of the same. The following sections explain in detail the salient features of the proposed scheme which include priority-mapping technique, MAC layer reactivity, time slicing, etc.

3.2 Proposed Scheme

As explained in section 2.3, existing QoS support is limited in cases of native implementation of current BASN standard IEEE 802.15.6 in WBANs. Moreover the support provided is more appropriate for single hop topologies. Therefore there is a need to have efficient QoS schemes that comply with the standard and provide effective QoS provisioning in multi-hop WBANs.

We propose a priority mapping scheme that works over a reactive MAC layer for providing QoS in a multi-hop WBAN. A tree based multi-hop network topology is employed in which each node communicates with its parent node and transmits data packets to maintain energy efficiency and then the proposed scheme is implemented over this topology to provide QoS. The scheme also ensures that most of the energy sapping computations are done by the resource rich coordinator, thereby improving the lifetime of the WBAN. The scheme employs a two layer priority assignment system so as to provide appropriate QoS throughout the lifetime of the network, in any situation- general or emergency. It also utilizes time slicing scheduling to reduce delay in case of general transmissions and
uses the reactive MAC layer to reduce data loss in case of re-transmissions in a WBAN.

Figure 3.1 gives an overview of the proposed QoS scheme. The QoS scheme works largely on the network and MAC layers as it carries out resource allocation through scheduling. The available bandwidth is first assigned to the coordinator to sensor node communications followed by the sensor nodes to coordinator/hub communications and finally
to retransmissions. The arrows between the layers indicate two way communication between the layers which is carried out by the respective service access points.

3.2.1 Priority Mapping

The following are the two layers at which the priority assignment and mapping are carried out.

A. Data based priority assignment

Whenever data is transmitted by a sensor node to the coordinator, a user priority is assigned to it in accordance with Table 2.1. As explained in section 2.3, the user priority is embedded within the frame and is directly related to physiological parameters that the node is collecting and not the sensor node itself. This is carried out by the transmitting node as a part of its functionality, i.e., when a sensor node receives biomedical signals from a body part, on the basis of certain signal strength thresholds, it can automatically determine the importance of the data and transmit a user priority embedded in the data packet. Therefore, a sensor node that is monitoring a person’s insulin levels will transmit data, i.e., sugar level information to the coordinator. This node will transmit data with a lower priority attached to it if the insulin levels are normal in a patient’s body. In case of hyper or hypo glycaemia, the node will transmit data with a higher priority embedded in it, as it is an emergency. This priority value is extracted from the frame and is used by our scheme to determine and trigger prioritized transmission by using the Exclusive Access Period (EAP) in case of an emergency.
### Node Priority Mapping

<table>
<thead>
<tr>
<th>Node Number</th>
<th>Body Part</th>
<th>Assigned Node Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Brain</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Throat</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Heart</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Left Shoulder</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Right Shoulder</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>Left Lung</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>Right Lung</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Abdomen</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>Left Arm</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>Right Arm</td>
<td>13</td>
</tr>
<tr>
<td>11</td>
<td>Groin</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>Left Hip</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>Right Hip</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>Left Hand</td>
<td>18</td>
</tr>
<tr>
<td>15</td>
<td>Right Hand</td>
<td>19</td>
</tr>
<tr>
<td>16</td>
<td>Left Thigh</td>
<td>20</td>
</tr>
<tr>
<td>17</td>
<td>Right Thigh</td>
<td>21</td>
</tr>
<tr>
<td>18</td>
<td>Left Knee</td>
<td>10</td>
</tr>
<tr>
<td>19</td>
<td>Right Knee</td>
<td>11</td>
</tr>
<tr>
<td>20</td>
<td>Left Foot</td>
<td>16</td>
</tr>
<tr>
<td>21</td>
<td>Right Foot</td>
<td>17</td>
</tr>
</tbody>
</table>

### B. Node based priority assignment

In our setup, every sensor node in the network deployment is identified by a one byte NodeID. The proposed scheme assigns a system based priority to each sensor node that is measuring a physiological parameter of the human body. This priority value is assigned on the basis of the importance of physiological parameters that are being collected. Consequently, we choose to assign higher priorities to sensor nodes monitoring organs like heart, brain, lungs, etc. and lower ones to those sensor nodes that are simply monitoring limb movements. Then, a priority mapping scheme is implemented in which these priorities are mapped to the NodeIDs. This mapping is maintained by the coordinator at all times and is used during the lifetime of the network. The mapping illustrated in Table 3.1 is done in ascending order,
with the most important sensor node being assigned the priority 1. This scheme is maintained by the coordinator and the sensor nodes do not have to carry out extensive computations, thereby keeping their lifetime unchanged.

The proposed scheme works by utilizing both these priorities and providing precedence to data based priority in case of an emergency.

### 3.2.2 MAC Layer

Since the proposed scheme provides QoS and guarantees low system latency through access scheduling and a novel MAC reactivity algorithm, this section provides an insight first into the working of a MAC layer in a WBAN followed by the novel specifications utilised by the scheme.

It is required by all sensor nodes and the coordinator/hub that they establish a time reference base (Figure 3.2) if the medium access is to be scheduled in time, where the time axis is divided into beacon periods/superframes. These superframes are of equal length and each beacon period is composed of allocation slots of equal length numbered from 0, 1, 2, ..., s, where $s \leq 255$. The coordinator is required to specify the boundaries/durations of the beacon periods and hence of the allocation slots therein. This is carried out by the coordinator by transmitting beacons at the start of each beacon period (superframe).

![Figure 3.2: Time Reference Base for MAC layer. [17]](image)
The coordinator and the sensor nodes communicate with each other through connection request and assignment frames as shown in section 2.3. A frame is an ordered sequence of fields that are delivered to or from the physical layer service access point. The general MAC frame format is as shown in Figure 3.3. A MAC frame consists of a fixed length MAC header, a variable length MAC frame body and a finite length Frame Check Sequence (FCS).

![Figure 3.3: General MAC Frame format.][17]

A MAC frame can be classified as a management, control or data frame. An example of a management frame is the beacon frame that contains Information Elements (IE) as shown in Figure 3.4 that depicts the Frame payload of beacon frames.

![Figure 3.4: Payload of Beacon Frame.][17]
A beacon frame is locally broadcast by the coordinator in every beacon period and defines the length of the beacon along with the durations of the different access phases. Figure 3.5 shows the various access phases that constitute the beacon period.

![Figure 3.5: Phases involved in Beacon period/Superframe. [17]](image)

The Exclusive Access Phase (EAP) is utilized for emergency transmissions. The Random Access Phase (RAP) and the Contention Access Phase (CAP) provide support for retransmissions in the beacon period. The Managed Access Phase (MAP) is the duration where resource allocation and scheduling takes place. The MAP is the only access phase that provides support for scheduled allocations in the beacon period. Typically each beacon period contains two EAPs, RAPs and MAPs and one CAP. The EAP1 and RAP1 precede the first MAP and the EAP2 and RAP2 precede the second MAP. The second MAP is followed by the single CAP.

The MAP is instrumental to our scheme as a time-slicing based scheduling scheme is employed for providing QoS and reducing system delay. The MAC capability field present in management frames like the beacon and the connection request frames (shown in section 2.3) contains the MAC capability format that determines the kind of access methods that are supported in the beacon duration of the WBAN. The MAC capability format is shown in Figure 3.6.

Since our scheme depends on MAP for scheduling transmissions, the scheduled access field is set along with the CSMA/CA field as RAP, EAP and CAP utilizes it as the
Figure 3.6: Information Elements in MAC Capability Format. [17]

preferred access methodology. Our scheme makes use of the scheduled polling [11] access scheme that is supported by scheduled access transmission. Under the scheduled polling access the coordinator/hub employs scheduled bilink allocations in which each node in the WBAN is polled and the data packets collected from them in the sequence defined by the coordinator. These scheduled allocations can be 1-periodic or m-periodic i.e., repetitive on the basis of the system specification. As stated earlier a time reference base is established to carry out synchronization and a guard period is defined in between each scheduled allocation.

The EAP indicator determines if an EAP will take place in the beacon period. The EAP is embedded in the Frame Control Format as shown in Figure 3.7. The EAP indicator is set by the coordinator if an emergency is detected or is kept unset if no emergency data was received.
3.2.2.1 Time Slicing

Since the proposed scheme provides QoS through priority based scheduling, it is important that the accompanying delay and latency with such a scheme is kept to a minimum. Since all the nodes are polled by the coordinator in the order of Node based priority it is necessary that the nodes with lower priorities are not kept waiting resulting in data loss due to time-outs. Therefore, the scheme employs time-slicing based scheduling coupled with prioritization in which each node is allocated a fixed number of slots for transmission. The MAP is divided into slots of equal duration which are then utilised by each node in the order of their priority and on the basis of the number of slots allocated to them for usage.

A device may or may not be able to transmit all its collected data in the number of slots allocated to it in a single MAP duration and hence the rest of the data can be transmitted in the next beacon period’s MAP. The reason that this does not impact the performance of the proposed scheme is that even if some fraction of data packets are transmitted in a later beacon period, the information already transmitted is generally enough to ascertain the well-being of a patient. Moreover, the data packets that are received by the coordinator are sufficient to detect any emergency situation.
The benefit of time slicing is that it helps in regulating the delay and latency of the system as the nodes with lower node priorities do not have to wait for a very long duration to transmit their data packets to the coordinator.

The total number of slots that are available is determined on the basis of the duration of the MAP and the slot size. The MAP is simulated as a thread-safe queue that contains a collection of time slots as shown in Figure 3.8. The number of slots in the queue is calculated as

\[ \text{No.of slots} = \frac{\text{Total MAP Duration}}{\text{slotsize}} \]  

(3.1)

The scheme ascertains QoS for high priority nodes by dividing the total number of nodes into two groups of approximately equal size. The first group contains the nodes with higher Node Priorities and the second group consists of nodes having lower Node Priorities. For example, if we have a total of 20 nodes we divide them into groups of 10 each where the first group contain the nodes with Node Priorities 1-10 and the second group contains nodes with lower Node Priorities 11-20. The first group containing the nodes with higher Node Priorities are allocated greater number of transmission slots during the MAP. The second group containing the nodes with lower Node Priorities are allocated lesser number of slots for transmission. As a result, the nodes with higher Node
Priorities are provided QoS to transmit larger amount of data as they carry physiological parameters that have higher criticality in comparison to other sensor nodes in a WBAN.

3.2.2.2 MAC Reactivity

As explained in Chapter 2, fading and path loss around the human body are major problems that hamper the performance of WBANs. Fading of the transmitted signal can result in data packets not reaching the coordinator. Also path loss and interference can result in incomplete transmission of data packets to the coordinator which results in the coordinator discarding them due to insufficient information. This can result in a huge number of retransmissions from sensor nodes to coordinator.

The proposed scheme reduces data loss through signal fading and path loss in WBANs by employing a novel MAC reactivity algorithm [19], [20]. As the MAP duration and slot sizes are fixed, the number of slots available for transmission are finite. However there are two scenarios that could arise -

A. All slots assigned to each of the nodes in the WBAN are utilised for transmission.

B. There could be unused transmission slots left out of the number of slots assigned to the nodes.

Also under the proposed scheme the coordinator maintains the count of the total number of packets received and also the count of the number of packets dropped due to path loss or interference in each beacon period. A threshold ratio $\mu$ is defined that is central to the MAC reactivity algorithm. The value of $\mu$ is calculated as -

$$\mu = \frac{\alpha}{\beta},$$  \hspace{1cm} (3.2)
where $\alpha$ is the number of packets dropped and $\beta$ is the number of packets received in a beacon period. The higher the value of $\mu$, greater are the number of retransmissions.

On the basis of a threshold value of $\mu$ defined by the system and the value of $\mu$ calculated in the current beacon period, the MAC reactivity algorithm decides to adjust the durations of MAP and CAP according to slot status of the system as defined above in the next beacon period of the WBAN. The psedocode of the MAC Reactivity algorithm is provided in Algorithm 1.

**Algorithm 1: MAC Reactivity**

```plaintext
Function RunCoordinator()
    while lifetime do
        currentMapDuration ← nextMapDuration
        currentCapDuration ← nextCapDuration
        slotQueue ← Queue[currentMapDuration÷slotSize]
        RunMap()
        $\mu ← \alpha ÷ \beta$
        if currentMapDuration ≠ originalMapDuration and
currentCapDuration ≠ originalCapDuration then
            if !slotQueue.isEmpty and $\mu > \muThreshold$ then
                nextCapDuration ← currentCapDuration +
                CalculateRemainingSlots(slotQueue)
                nextMapDuration ← currentMapDuration −
                CalculateRemainingSlots(slotQueue)
            end
            if slotQueue.isEmpty then
                nextMapDuration ← originalMapDuration
                nextCapDuration ← originalCapDuration
            end
        end
    end
Function RunMap()
    foreach node ∈ orderedNodes do
        if slotQueue.isEmpty then
            nextMapDuration ← originalMapDuration
            nextCapDuration ← originalCapDuration
            return
        end
        use allocated number of slots from queue
end
```

37
The original\textit{MAPDuration}, current\textit{MAPDuration}, next\textit{MAPDuration} are defined as global variables of the system. Also original\textit{CAPDuration}, current\textit{CAPDuration}, next\textit{CAPDuration} and the \textit{slotQueue} are defined as global variables of the system.

The original\textit{MAPDuration}, original\textit{CAPDuration} and the \textit{slotSize} are assigned initial values as per the system specification. The \textit{currentMAPDuration} is initialized as 0 along with the \textit{currentCAPDuration}. The next\textit{MAPDuration}, next\textit{CAPDuration} are initialized with value of the original\textit{MAPDuration} and original\textit{CAPDuration} respectively.

During the lifetime of the WBAN, the coordinator calculates the \textit{currentMAPDuration} from the next\textit{MAPDuration} of the previous beacon period. It also calculates the size of the \textit{slotQueue} on the basis of the \textit{currentMAPDuration} and the \textit{slotSize}. It then sends out this information to all the sensor nodes in a WBAN and polls each of them to get their data packets in the current beacon period. It also calculates $\mu$ on the basis of the number of packets received and dropped. It then checks if after the current beacon period, if there are transmission slots left unutilized in the \textit{slotQueue} and the value of $\mu$ is greater than the threshold, it allocates the duration of the remaining unutilized slots to the CAP for the next beacon period. Thereby, the values for the next\textit{MAPDuration} and next\textit{CAPDuration} are calculated and then assigned to the current\textit{MAPDuration} and current\textit{CAPDuration} for the purpose of the next beacon period.

In a different scenario, if the WBAN has been operating in the previous state where the CAP has been increased and all the slots assigned to the nodes have been used up in the current\textit{MAPDuration} or if a sensor node was unable to transmit due to lack of slots and $\mu$ is less than the threshold, the coordinator restores the next\textit{MAPDuration} and next\textit{CAPDuration} to their default values as defined by the system. These values
are then used as the currentMAPDuration and currentCAPDuration for the next beacon period. How we arrive at the optimal values for the threshold value of $\mu$, slot duration etc. is explained in Chapter 4.

### 3.3 Scheme Overview

This section provides a brief overview of the working of the proposed scheme as shown in Figure 3.9.

![Flowchart based representation of proposed scheme.](image-url)
In the proposed scheme data will be collected by the coordinator in the MAP using scheduled polling in the order determined by the Node based Priority assignment as shown in Table 3.1. The scheme initially starts with the coordinator transmitting a superframe with the original values defined by the system for the MAP and CAP durations. The coordinator polls all the sensor nodes in the MAP through scheduled polling in the order determined by the Node based Priority assignment as shown in Table 3.1 and collects the data from each of the sensor nodes. The node with Node Priority 1 will be polled first and the node with Node Priority 21 will be polled last for transmissions. All the sensor nodes utilize the transmission slots from the slot queue of the system for transmission of data packets. The sensor nodes can utilize, at the maximum, only the number of slots that has been designated to them by the system. At the conclusion of the current beacon period the coordinator calculates $\mu$ and checks the status of the slot queue and on the basis of these two factors, accordingly adjusts the MAP and CAP duration for the next beacon period.

In a scenario where an emergency is detected, i.e., by reading the User Priority embedded in the data packet transmitted by a node, the scheme employs the usage of the Exclusive Access Phase (EAP) in which the data is transmitted immediately. This is done as follows - if any node transmits emergency data in the current beacon period, the EAP indicator in the frame control in Figure 3.7 is set to 1 for the next beacon period by the coordinator. Once this superframe is transmitted to the sensor nodes, in the next beacon period the node transmitting in the emergency mode can immediately transmit its data in the EAP. This ensures that, in case of an emergency, there is no delay in transmission from a node having lower node based priority.

Thus, this scheme ensures that while the network is active, data with higher importance is always transmitted first regardless of the mode in which it is being transmitted, i.e.,
general or emergency. This makes sure that data regarded to be more important, is transmitted with very low delay. Since most of the computations are carried out by the coordinator, the scheme ensures an asymmetric processing structure which increases the life span of the sensor nodes. The scheme reduces the system latency through time-slicing prioritization and also reduces the chances of data loss due to interference, fading and collisions through the reactivity of the MAC layer. This drives the proposed scheme to have an effective QoS provisioning for sensitive data in a multi-hop WBAN.
Chapter 4

QoS scheme performance for

Autonomous Multi-hop WBANs

4.1 Implementation Details

This section provides insight into the system setup and implementation details of the proposed scheme. The scheme was simulated on SHOX- a Java based network simulator [21], [22]. The network deployment was done in a manner to mimic a WBAN where sensors measure a person’s different physiological parameters. The network is modeled to have a sensor monitor a specific body part and its associated physiological characteristics.

The network deployment is carried out on a field size of 250 cm * 250 cm which is deemed to be the maximum reachable area by the average human body after considering various body postures. A set of 22 nodes is deployed on the human body with each node monitoring a specific body part as per Table 3.1. The coordinator is designated with the NodeID 22 and is responsible for polling each sensor node and collection of data from them. Sensor nodes with NodeIDs 1-21 are responsible for the collection of various
physiological parameters of the human body. The network deployment is done according to the measurements of an average human body as shown in Figure 4.1.

Figure 4.1: Network deployment on the human body.
A coordinate based placement methodology has been applied for positioning of nodes within the specified dimensions of the deployment field. All the sensor nodes are considered to be on-body deployments with line of sight communication capabilities in order to avoid any discrepancies in radio properties. The network deployment in Figure 4.1 shows the nature of the topology used. We use a tree based multi-hop topology and the different colors indicate the number of hops needed from each node to reach the coordinator. An extensive discussion about the network topology is carried out in the next section.

4.1.1 Network Topology

The deployment of sensors on the human body is depicted in Figure 4.1 which is simplified and rearranged to display the existing links between the sensor nodes in Figure 4.2 in an equivalent tree topology. The equivalent tree based multi-hop topology representation is presented in Figure 4.2 in which the coordinator acts as the root node and the sensor nodes being its children. The tree has a depth of 5 and hence sensor nodes are at 1-5 hop distances from the coordinator. Choosing a distribution of multiple hops to the coordinator is useful in analyzing the proposed scheme under various network parameters.

The WBAN deployment in the simulation setup is considered to be static due to the assumption that it is free of link failures due to movements of the human body. This is due to the fact that the deployment of sensors on the human body is done in such a way that the relative position of the nodes to their parent remains primarily the same. Most of the mobility in a human body is attributed to the limbs, while rest of the network is relatively static.
As each node communicates only with its parent, we are only concerned about the existing links in the case of the sensor nodes monitoring the limbs. These links mostly remain static as well because the movements of the sensor nodes are relatively static to each other. For example, when a person moves his hand, the node monitoring the hand and the node monitoring the elbow almost always stay in the range of each other and can be assumed to be static. Therefore the WBAN deployment for the evaluation of the proposed scheme is maintained statically throughout the lifetime of the simulation.
4.1.2 Simulation Parameters

This section gives information about the various standards and specifications that the simulation adheres to. The simulation parameters that are used for simulating a WBAN for the performance evaluation of the proposed scheme are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Size</td>
<td>2.5 m × 2.5 m = 6.25 sq. m</td>
</tr>
<tr>
<td>Number of sensor nodes</td>
<td>22</td>
</tr>
<tr>
<td>IC Mote Simulated</td>
<td>CC2420</td>
</tr>
<tr>
<td>Transmission Power Level</td>
<td>2 (0.0013 mW)</td>
</tr>
<tr>
<td>Wireless Transmission Band</td>
<td>ISM Band (2.4 GHz)</td>
</tr>
<tr>
<td>Transmission Rate</td>
<td>256 kbits/sec</td>
</tr>
<tr>
<td>PLCP Preamble Length</td>
<td>90 bits</td>
</tr>
</tbody>
</table>

Our simulation models the sensor nodes on the CC2420 radio [23] which conforms to IEEE 802.15.4 [24]. We have tried to achieve as close as possible a scenario to IEEE 802.15.6 [17] by modifying the code base of SHOX to adhere to the BASN standard. For the same purpose, the PLCP preamble length in PPDU is set to 90 bits. The simulation uses the standard power level 2 for the CC2420 radio and also models other physical layer parameters accordingly. The wireless channel band is set according to the ISM band of 2.4 GHz and the bit rate for the simulation is set at 256kbps.

4.2 Performance Evaluation and Simulation Results

In this section, performance of the proposed scheme is evaluated through the results obtained from the simulations carried out. The performance of the scheme is evaluated against quantifying network parameters such as throughput, coverage and latency. Furthermore, the salient features of the scheme such as the two-layer priority mapping with
time-slicing, multi-hop tree topology and the reactive MAC layer are also assessed to understand their impact on WBAN performance.

### 4.2.1 Network Coverage

It is observed through simulations that the minimum power required to achieve complete WBAN coverage is 0.05 mW. As can be seen in the plot between the number of nodes connected vs the transmission’s signal strength in Figure 4.3, all the deployed nodes are connected at a transmit power of 0.05 mW. It can also be inferred from the graph that while using a multi-hop topology results in all 22 nodes in the WBAN being connected at 0.05 mW, using a single-hop topology allows only 16 nodes to be connected at the same transmit power. This establishes that using a single-hop topology in a WBAN results in sub-optimal power consumption for transmission.

![Network Coverage](image)

**Figure 4.3:** Network coverage achieved under proposed scheme: Single vs Multi-hop
This demonstrates that at a transmitting power of 0.05 mW, all sensor nodes are connected together and hence are able to transmit data appropriately to the coordinator. It can be observed from Figure 4.3 that at lower power levels, connectivity is not achieved between sensor nodes to form a complete network. It is also observed that for power values greater that 0.05 mW, the WBAN remains adequately connected. This establishes that the proposed scheme provides complete connectivity at a low power value of 0.05 mW while maintaining energy efficiency.

4.2.2 Transmission Time

Figure 4.4: Transmission Time taken for each hop under proposed scheme.

Figure 4.4 shows the amount of time that is required by a sensor node to transmit to the coordinator over a particular distance in our multi-hop QoS Scheme. The distance in Figure 4.4 is measured in terms of hops for the sake of simplicity. It can be observed
that even for a 5-hop distance, the total time taken for transmission is less than 0.5 seconds. For 1-hop distances, transmission time needed is as low as 0.09 seconds.

This establishes that the delay experienced in the proposed scheme is low, even in a multi-hop network scenario. This is really important in a scenario when a sensor node with a lower Node Priority is transmitting in the emergency mode and the proposed scheme should be able to forward the data quickly. Therefore, Figure 4.4 assists in establishing that the proposed scheme is robust as transmission times stay low even at longer transmission distances throughout the network topology.

### 4.2.3 Transmission Time vs Power Tradeoff

To optimize the performance of the network deployment scheme, simulations have been carried out to understand any tradeoffs between the transmit power and the transmission time over the different transmit distances between sensor nodes and the coordinator.

As can be seen from Figure 4.5, it is determined that a good tradeoff between the transmission power and the transmission time is achieved when the sensor node has to transmit data over a distance of 3 hops to the coordinator. Thus, the proposed scheme performs better when the distance between sensor node and the coordinator is around 3 hops. At this distance, a low latency value of 0.3 seconds is achieved at a lower transmit power of 0.027 mW. Therefore, in case of a multi-hop deployment, the use of the proposed QoS scheme could significantly improve the scalability and performance of the WBAN.
4.2.4 Transmission Overhead

As stated earlier, the proposed scheme first allocates bandwidth for coordinator/aggregator to sensor nodes communication and then to node-aggregator communications and retransmissions in that order. Therefore, average overhead per transmission determines the efficiency and throughput of the system under the proposed QoS scheme.

The power level is varied from 0.0001 mW to 1 mW which is the highest power value at which the CC2420 sensor can transmit. As can be observed from Figure 4.6, the average overhead per transmission stabilizes at a power value of 0.01 mW and stays the same thereon at roughly around 2 packets per transmission. Therefore, there is a very small difference between goodput and throughput of the WBAN under the proposed scheme. This is particularly important because a large value of overhead would result in excessive usage of bandwidth for retransmissions. Moreover, a large overhead can result
in longer network delays and higher power consumption per node which can impair
the performance of a WBAN. The proposed scheme guarantees a low overhead per
transmission and thereby provides higher energy efficiency and low delay for multi-hop
WBANs.

### 4.2.5 System Latency without Time-Slicing

Since the proposed QoS scheme adopts a priority based mapping solution on a multi-hop
WBAN it is important to ascertain the system latency in general mode of transmission
with no emergencies. A simulative analysis is carried out to understand the latency
times of such a system by finding the transmission completion time of the node with the
lowest Node Priority, i.e., priority value 21.
Figure 4.7 shows the transmission completion times of the sensor node with least priority as a function of total simulation time. The total simulation time is defined as the time required for all transmissions to complete including re-transmissions. When the scheme is implemented over a non-reactive MAC layer without any time-slicing, it is observed that the lowest system latency value of 3.44 seconds is achieved at a transmit power value of 0.06 mW. It may also be noted that the average system latency is below 7.5 seconds.

4.2.6 System Latency with Time Slicing in reactive MAC layer

When a reactive MAC layer with time slicing is implemented, the corresponding results that are obtained are shown in Figure 4.8. The Managed Access Phase (MAP) duration was taken as 7.5 seconds, as on an average, that was observed to be the time taken for
one complete transmission cycle. The time slot/slice duration is taken as 58 milliseconds. The slot size is arrived at by the following two contributing factors -

A. Average transmission time.

B. Data rate of the system.

The average transmission time is considered as 0.28 seconds long as that is the average time period required for carrying out a 2 or 3 hop transmission. We consider the average of only 2 or 3 hop communications as we had arrived at the conclusion that a 2-3 hop distance between sensor nodes and the coordinator would be optimal. This average transmission time period is then divided into 5 equal chunks to arrive at the time slot/slice duration. This is done to scale the simulation upto commercial WBAN data rates. It has been determined [1] that commercial devices transmit at a data rate of around 256 kbps. If we consider a single sample from a sensor device to be of 90 bits then in a time period of 0.28 seconds we transmit more than 300 samples as the data rate of the simulation is 256 kbps. Therefore, to scale down the simulation setup, we divide the average transmission time into optimal chunks that result into the final calculated duration of the time slot/slice to 58 ms.

The guard period in the simulation for the time-slicing scheduling is set at 10 µs. Simulations have been carried out for multiple slot combinations to determine the most optimal combination for providing QoS to higher priority nodes and achieving very low system delay.
It can be observed from Figure 4.8 that a time-slicing based scheduling scheme in the reactive MAC layer is able to bring down the average system delay to 3.5 seconds which is a quantum improvement over the delay recorded when the scheme operates on a normal sequential scheduling based MAC layer as shown in Figure 4.7.

It can also be understood that the average system delay of 3.5 seconds that is achieved is for the slot combination (4,2) in which every high priority node is allowed to utilize 4 slots and the low priority nodes, 2 slots, in the order of priority from the MAP slot queue. This combination resultantly also provides a 50 percent improvement in terms of QoS provided to the higher priority nodes in comparison to the lower priority nodes. Therefore, it can be concluded that a slot combination of (4,2) is optimal for such a system setting and is able to provide effective QoS while also reducing system latency.
4.2.7 MAC Reactivity

Multiple scenarios have been simulated to understand the system performance when the MAC reactivity algorithm was implemented in the proposed scheme. In the scenarios simulated, the system performance was degraded by increasing the path loss through introduction of interference and signal fading to understand the right threshold value for $\mu$. Using equation 2.1, 2.2 and 2.3 such path loss values for body surface to body surface communication were calculated at varying distances for Channel Model 3 (CM3) at 2.4 GHz [16] as shown in Figure 4.8. By utilizing these path loss values through multiple simulations, it is determined that the optimal value to be considered as the threshold value for $\mu$ is $\frac{1}{10} < \mu < \frac{1}{5}$ of the packets received.

![Path Loss vs Distance](image)

**Figure 4.9:** Exponential Path Loss Vs Distance.

It was observed that for values of $\frac{1}{10} < \mu$, the number of packets dropped were too high resulting in significant data loss in the WBAN. Using a reactive MAC layer with
the threshold value of $\mu$ as $\frac{1}{10} < \mu < \frac{1}{5}$ is effective in countering data loss due to path loss, fading, and interference in the WBAN. The coordinator is able to reactively adjust the MAP and CAP durations thereby providing more time for retransmissions to take place when there are higher number of packets dropped in the WBAN. This results in a greater throughput in the subsequent beacon period. The corresponding number of retransmissions for the calculated path loss values for both reactive and non-reactive MAC layer are shown in Figure 4.10.

![Figure 4.10: No. of Retransmissions in Reactive MAC Vs Non-Reactive MAC.](image)

This shows that the proposed scheme is able to effectively guarantee low latency, even in a multi-hop WBAN while also being able to productively react to loss of packets due to fading, path loss and interference around the human body. It is also able to carry out effective QoS provisioning through an optimal slot combination, all of which factors are really important for health monitoring.
Chapter 5

QoS Framework for Neighbor-aware Multi-hop WBANs

5.1 Introduction

Rapid advances in the WBAN technology has resulted in increasing affordability of WBANs. The IEEE 802.15.6 standard has been laid out to bring uniformity to the development process of WBANs and standardize it. These factors, coupled with many more, are likely to amplify the growth of WBANs, thereby increasing their concentration. Increased proliferation of WBAN deployment could pose to be a problem when there are a number of WBANs in each other’s vicinity. In case of Neighbor-aware WBANs such a scenario can result in lower throughputs, thereby degrading WBAN performance. A Neighbor-aware WBAN can be defined as a WBAN that can sense the presence of another WBAN in its communication range.
This chapter puts forward a framework that tries to address this issue in Neighbor-aware WBANs. This framework allows a WBAN to utilize the infrastructure of neighboring WBANs through a co-operative inter WBAN routing scheme and hence reduces data loss due to inter-WBAN interference thereby providing QoS. It is also imperative that WBAN standards for security and privacy are followed while allowing cooperative routing between WBANs while implementing such a framework.

5.2 Motivation

As explained previously in section 2.1.3, all the works that exist in the literature have considered interference as a problem and have attempted to minimize it. The reason is that, in all the above cases, an assumption has been made to allow uncoordinated inter-WBAN communication. Under such an assumption, the coordinator of each WBAN only communicates with the central base station that collects all the data. Also, it is assumed that by default all the sensor nodes would transmit their data to the base station through their respective WBAN coordinators. However, there could arise emergency situations where the coordinator could be strapped for bandwidth due to sudden or excessive bandwidth demand from the sensor nodes. It could also be possible that due to the implemented QoS scheme in a WBAN, certain nodes could be denied service for long periods resulting in time-outs and packet drops.

The work presented in this thesis provides a different perspective to inter-WBAN interference by proposing a framework that exploits the infrastructure of neighboring WBANs to resolve sudden additional bandwidth requests for transmission of critical data when the coordinator is not able to service these requests. In the proposed framework, a leaf node in the neighboring WBAN can service such requests thereby providing QoS to the
transmitting node resulting in reduced delay and improved performance. As packets are routed across multiple WBANs, the network graph is expected to become highly complex. Therefore, the framework also presents an effective fault localization technique as it is necessary to be able to effectively troubleshoot the source of data loss in a complex network topology.

5.3 Framework Elements

This section provides a detailed description of the various elements that constitute the proposed framework. The thesis first discusses the cooperative routing algorithm that is used to transmit data through neighboring WBANs to the base station. Route creation and candidate node selection are the two important steps involved in carrying out cooperative inter-WBAN routing and are presented in depth in the following sections.

Fault detection and localization is an important feature of the proposed framework as it helps to troubleshoot the network graph for any node failures. In such a network graph, each WBAN with its constituent coordinator and sensor nodes is examined to determine strongly connected components. The fault detection technique of the scheme is useful in detecting any node failures in a WBAN and is explained thoroughly in the sections below.

Finally, this section provides a holistic overview of the proposed framework explaining the necessity of having the above elements in the framework and their respective functions.
5.3.1 Cooperative Routing in Neighbor-Aware WBANs

The framework employs a cooperative routing scheme wherein data packets in need of emergent service are routed through a neighboring WBAN to the base station. If we want transmissions to be routed via neighboring WBAN, we would need to determine the best possible sensor node in the neighboring WBAN for forwarding these data packets. The node deemed most suitable for providing this service is called the candidate sensor node. In WBANs, sensor nodes can be classified into the following categories depending on whether or not they forward any data packets -

A. Non-leaf Nodes:

Any node that acts as a relaying node in a WBAN can be called a Non-leaf node. They transmit their own packets to the base station and also provide forwarding service to their child nodes.

B. Leaf Nodes

Any node in the network that does not have a successor, can be called as a leaf node. Such nodes generally have to handle their own data and have greater buffer availability than Non-Leaf nodes. The reason for greater buffer availability is that since they have to transmit only their own data packets, their transmit buffers remain relatively empty.

The framework selects a candidate sensor node from the available leaf nodes in the neighboring WBAN. The framework is designed to select a leaf node because such nodes are not required to handle any transmissions from a child node, as a leaf node is the final child node in a tree topology based WBAN. The assumption made is that all the WBANs have a similar architecture where the leaf nodes can be expected to have spare
slots, i.e., buffer to handle requests from a neighboring WBAN’s node for occasional transmission.

5.3.1.1 Weight Estimation and Assignment for Candidate Node Selection

It is intuitive to understand that the leaf node with least distance from the transmitting node would be the obvious choice to route the packets. Due to the absence of a direct mechanism for finding out distances of leaf nodes of various neighboring WBANs, the framework utilizes an indirect method. The possible candidate nodes in the range of the transmitting node are ranked in decreasing order of the link parameters to attain the required set of candidate nodes. Signal strength received from a neighboring WBAN leaf node is a good metric to determine the distance between nodes. The set of candidate nodes can hence be ordered according to associated weights derived from signal strength and link quality parameters.

Raju et al. [25] have determined that RSSI, on its own, does not allow accurate distance estimation as a particular RSSI value generally corresponds to a set of variable distances. Their research has verified that a combination of RSSI and LQI values help in more accurate estimation of distances between sensor nodes. While RSSI indicates the signal power received from a sensor node, LQI provides information about the Bit Error Rate (BER) of the system. This composite metric is utilized for weight assignment to all the leaf nodes of neighboring WBANs that are in range. On the basis of these weights a priority queue is created and the leaf node at the head of the queue is used for forwarding packets to the base station via its designated coordinator. If the best candidate is not able to provide service due to link quality degradation, the node next in line in the priority queue is chosen as the preferred candidate node.
5.3.1.2 Route Creation

The weight estimation and assignment step helps in determining the weight of each leaf node in a neighboring WBAN that is in range of the transmitting node. These candidate nodes are then ordered in the decreasing order of these calculated weights and maintained in a priority queue. This helps in selecting the best candidate node among the leaf nodes in neighboring WBANs along the path to the base station. The best candidate node that is obtained after this step is used as a packet forwarder for the transmitting node. The packet forwarder, once it receives the transmission, forwards it to the base station via the designated coordinator of the WBAN that it is a part of. Thus, the data packets get routed to the base station and the QoS provisioning to such nodes helps in boosting the throughput by optimal utilization of idle leaf nodes of neighboring WBANs.

5.3.2 Fault Localization and Recovery

As explained in previous sections, there might arise a need for a WBAN to transmit data packets with low system latency via paths that reduce transmission delay. When the coordinator of a WBAN is unable to service a transmission request, it becomes important to find alternative routes to transmit data. The proposed framework recognizes that in case of Neighbor-aware WBANs there could be alternative routes that span across multiple WBANs. The solution proposed by this framework determines the most suitable candidate node from neighboring WBANs and uses a cooperative inter-WBAN routing scheme to deliver data to the base station.

Such a mechanism that involves network routing spanning multiple WBANs makes the overall network topology complex. The inter-WBAN graph that is generated is naturally
prone to failures. These failures could be difficult to troubleshoot using simple manual methods. The proposed framework employs a modified Kosaraju-Sharir algorithm [26] to detect any link failures in the network graph and determine connected node clusters to identify failure zones in the network.

When transmission links are established between sensor nodes, the network topology changes from a tree to a graph network. The sensor nodes and the links between them correspond to the vertices and edges of a directed graph respectively. To understand any link failures it is important to determine the strongly connected components in the network graph. Using a modified version of the Kosaraju-Sharir algorithm, all strongly connected components in the network graph can be identified in \( O(v + e) \) complexity, where \( v \) is the number of vertices in the graph and \( e \) is the number of connection links.

Two iterations of Depth-First Search (DFS) are performed over the network. The first iteration of DFS discovers all the nodes of the graph while computing \( f(i) \), where \( f(i) \) denotes the order in which DFS discovers node \( u \). The transpose of the network graph \( G \) is then computed and DFS is performed on the transpose \( G^T \) in decreasing order of \( f(u) \). Examining the forest obtained from the second iteration of DFS gives us the strongly connected components of the network graph. The initial network topology and the resulting graph is stored at the base station. Implementing the Kosaraju-Sharir algorithm on the graph also provides information about the strongly connected components to the base station. By knowing the initial network configuration and the strongly connected components that are identified, it can be determined that network failure has probably occurred at one of the missing nodes that do not appear in any of the clustered strongly connected components.
5.4 Framework Overview

Figure 5.1 shows two WBANs A and B in the communication range of each other. In the depicted figure, sensor nodes numbered 1 to 7 in WBAN A are serviced by A’s
coordinator - sensor node 8. The coordinator collects their data and transmits it to the base station. Nodes 9 and 14 are leaf nodes of WBAN ‘B’ and hence are candidate nodes for servicing transmission requests from node 3 and 5 of WBAN ‘A’.

In the proposed framework, the coordinators of a WBAN can communicate with each other and form an ad-hoc inter-WBAN network. Only the leaf nodes of a WBAN have the capability of accepting transmissions from neighboring WBANs and forwarding these transmissions to the base station. It is assumed that all data that is exchanged between WBANs are encrypted using the laid out WBAN standards for security and privacy.

The WBANs that are considered in the scope of the framework presented in this thesis are presumed to be within the communication range of each other. Also the WBANs under consideration are assumed to be stationary, for some finite time, useful enough for carrying out transmission under the proposed framework. With reference to Figure 5.1, it is considered that neighboring WBAN ‘B’ has leaf nodes that have free slots that can meet the routing request from WBAN ‘A’. WBAN ‘A’ is modeled as being overloaded, thereby requiring B’s help for QoS provisioning to its nodes.

The coordinator in a WBAN has a beacon based discovery mechanism. Information about the channels that would be used for information exchange between neighboring WBANs and the sleep/awake cycle is interchanged through the respective beacons/superframes of the participating coordinators. On the basis of successful information exchange, i.e., handshake, the neighboring WBANs can utilize each other’s leaf nodes for forwarding data packets in case a need arises. The leaf nodes are chosen as they can provide relay services more effectively due to greater buffer availability. This results in efficient QoS provisioning for service-deprived nodes and distributed utilization of available buffer and allows the WBANs to coexist cooperatively.
Whenever the services of the leaf nodes of WBAN ‘B’ are requested by WBAN ‘A’, the RSSI and LQI values of all the leaf nodes in ‘B’ are used for calculating their weights and these nodes with their associated weights are then put into a priority queue. This queue is present as global information throughout the transmission lifetime and is referred to select the best possible candidate node from WBAN ‘B’ for relaying A’s data. On the basis of the selected candidate node, a cooperative routing scheme routes the data to the base station by forming a combined routing tree of the participating WBANs. The equivalent routing tree of WBAN ‘A’ and ‘B’ is presented in the following chapter.

Under the proposed framework, the WBANs operate on the CSMA/CA channel access mechanism. To mitigate any reservation requests to WBAN ‘B’ from other neighboring nodes an RTS (Request To Send)/CTS (Clear To Send) mechanism is used. The framework assumes that only single links exist between any two vertices in the network graph. As explained earlier, the initial network graph is used for fault detection and localization. Using it as the reference and the current network scenario, the strongly connected components can be derived. The second pass of the Kosaraju-Sharir algorithm helps in discovering any disconnected components by comparing the initial network graph and the strongly connected components. Thereby, any fault in the network can be detected by the framework by determining the disconnected components.
Chapter 6

QoS framework performance for Neighbor-aware Multi-hop WBANs

6.1 Implementation Details

The proposed framework has been evaluated by simulating two WBANs ‘A’ and ‘B’ such that they are in each other’s communication range as shown in Figure 5.1. The WBANs have been modeled to comprise of eight sensor nodes each with identical sensing, data processing and radio transmission capabilities. The coordinator units of A and B are designed to communicate with each other and hence can form an adhoc inter-WBAN network. The leaf nodes of both WBANs are expected to provide forwarding services to other sensor nodes of the neighboring WBANs.
In the simulation, WBAN A is modeled as the overloaded WBAN with additional requests for bandwidth emanating from its sensor nodes. WBAN B is configured to have leaf nodes that have empty slots to meet the request for additional bandwidth from sensors of WBAN A. The best candidate node is selected for transmission from amongst the leaf nodes of WBAN B to carry out cooperative routing to the base station. The simulations are carried out on the Java based ‘SHOX’ simulator with the WBANs working on stock MAC and PHY layers of 802.15.4 with incorporations from 802.15.6 specification.

### 6.1.1 Network Topology and Routing Tree

The simulation assumes a scenario where all the nodes are implanted on the surface of the human body and are in line of sight of each other. This is done to maintain uniformity across the sensor nodes in terms of radio properties. A coordinate based placement setup was adopted for positioning nodes within the specified dimensions of the deployment field. The WBANs are simulated as static networks that are devoid of any mobility.

Once the best candidate node has been chosen a weighted routing tree is created between the participating WBANs to carry out inter-WBAN cooperative routing. As depicted in Figure 5.1, two WBANs have been simulated such that cooperative routing could take place between them. The resultant weighted routing tree is shown in Figure 6.1.

The different colors of the sensor nodes identify which WBAN they belong to. Node 9 and 14 in WBAN ‘B’ are identified as candidate leaf nodes. It can be seen that nodes 3 and 5 of WBAN ‘A’ route their packets through node 9 and 14 of WBAN ‘B’ respectively. It can be further seen that in turn the data packets of child nodes of 3 and 5 also get routed through the leaf nodes of WBAN ‘B’. Once the packets are received by nodes
Figure 6.1: Resultant Routing Tree from Neighbor-aware WBANs A and B.
9 and 14, they are routed through WBAN ‘B’ to reach its coordinator - node 16. The coordinator then routes these packets to the base station represented by node 17.

### 6.1.2 Simulation and Link Quality Parameters

This section gives insight into the various standards and specifications that the simulation of the proposed framework adheres to. The simulation parameters that were utilized to simulate two Neighbor-aware WBANs are shown in Table 6.1.

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<thead>
<tr>
<th>Parameter</th>
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<td>CC2420</td>
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<td>Transmission Power Level</td>
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<td>Wireless Transmission Band</td>
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<td>Transmission Rate</td>
<td>256 kbits/sec</td>
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<tr>
<td>PLCP Preamble Length</td>
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<td>Sensor Node Density</td>
<td>1.943 per sq.m</td>
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<tr>
<td>Average Hop Distance</td>
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</tbody>
</table>

Crossbow’s TelosB mote (TPR2420CA) has been modeled as the sensor node in the WBAN deployment utilized for the simulation. The TelosB mote has a CC2420 chipset and an integrated RF transceiver that complies with IEEE 802.15.4/ZigBee standard. The simulation models the radio on the CC2420 and hence works on the 2.4 GHz ISM band with a data rate of 256 kbps. The radio communication takes place on 16 * 3 MHz bandwidth channels that are seperated 5 MHz apart from the center frequency of adjacent channels. An encoding standard of 32 chips using 4 bits/symbol is used as per CC2420 specifications. An enhanced version of orthogonal quadrature phase shift keying (OQPSK) with direct sequence spread spectrum (DSSS) is utilised as the modulation scheme [27].
The CC2420 stores the RSSI and LQI values for all received packets. It is required by the standard, for the RSSI values recorded, to be linear and not vary from actual RSSI values by more than ±6 dB. Such a margin is indisputably wide, and calls for the use of another metric for link quality based performance evaluation or distance estimation [28]. LQI symbolizes the correlation between the received and the decoded symbol. The LQI is calculated only on packets received. However RSSI is calculated for all the packets that are received or discarded. This helps in calculating the noise baseline in absence of transmissions. Typical values of LQI can range between 50 and 110 depending on the maximum and minimum quality of the frames received.

6.2 Performance Evaluation and Simulation Results

This section evaluates the performance of the proposed scheme through the results gathered from the simulation. Since such a framework has not been devised previously, there do not exist many works in literature to which the performance of the proposed framework can be compared to. However, the performance of the framework is evaluated against network parameters such as throughput, overhead, transmission time etc., and the advantages of the proposed scheme are explained in the following sections.

6.2.1 Transmission Time

It is determined through simulations that the effective time taken for transmission of a packet is not greatly impacted though the implementation of such a framework. When a packet has to be routed through a neighboring WBAN, there could be a possibility that the time taken for transmission of the packet could be higher than when it would be routed through its own coordinator. However, as can be seen from the plot for
effective time taken for transmission per packet, the average transmission time required is observed to be around 1 second, which is quite low for a multi-hop WBAN. These results also take into consideration the number of retransmissions needed for transmitting the same packet in case it is dropped. This shows that on an average the time taken for packet transmission is not very high and hence implementing the framework on WBANs does not cause additional transmission delays in the system.

6.2.2 Transmission Time vs Distance

Although the best candidate leaf node is selected on the basis of a composite RSSI-LQI metric, it is found that the leaf node obtained is generally also the nearest leaf node according to the euclidean distance from the transmitting node.
Figure 6.3: Transmission Time taken for successful transmission over multiple hops.

The plot between the transmission time taken vs distance in hops, shown in Figure 6.3, is observed to follow a near linear progression. There are no outliers recorded while implementing the proposed framework on neighbor-aware WBANs. This indicates that the network performance is optimal when it comes to transmission time over multiple hops in a neighbor-aware multi-hop WBAN.

6.2.3 Transmission Overhead

The effective transmissions per packet vs distance plot is shown in Figure 6.4. It can be understood from Figure 6.4 that the number of transmissions undertaken for successful transmission of a packet is not very high even over increasing distances. As can be seen, for even a transmission distance of 3.00-3.25 metres, the number of transmissions required for delivery of a packet averages out to 1.20 which clearly demonstrates the robustness of the inter-WBAN network.
Figure 6.4: Effective Transmissions per successful packet transmission over distances.

Figure 6.5: Number of packets lost over varying distances.
The above observation can be substantiated by understanding the lost packets vs distance plot shown in Figure 6.5. It can be easily inferred that the packet loss is not very high, even over increasing distances. This shows that the implementation of the framework over neighbor-aware WBANs does not adversely impact the transmission overhead.

The gathered results show that the proposed framework is able to carry out cooperative inter-WBAN routing successfully in Neighbor-aware WBANs. It is also effective in carrying out fault localization and recovery, when the network graph grows in size. The framework is able to perform all the above functions without significantly impacting any of the quantifying network parameters.
Chapter 7

Conclusions and Future Research

7.1 Summary

This section summarizes the research work presented in this thesis. The work carried out in this thesis deals with the issue of providing QoS in multi-hop Wireless Body Area Networks. It considers two different perspectives of WBAN functioning to put forward solutions to solve the problem of QoS provisioning. The first type of WBAN functioning brought under purview is of a multi-hop WBAN working as an autonomous and independent entity. The other scenario which this thesis covers is of multi-hop WBANs behaving as neighbor-aware, cooperative entities that can aid each other by providing QoS through inter-WBAN communication.

In Chapter 2, existing issues and challenges related to QoS provisioning in WBANs in the above scenarios were explained. Also, requirements for an effective QoS scheme were defined. Chapter 3 put forward a QoS scheme for effective QoS provisioning in Autonomous multi-hop WBANs. It explains the salient features of the proposed scheme...
such as the two-layer priority mapping technique and the time-slicing based resource scheduling.

Data Priority and Node Priority are the two levels at which priority mapping is carried out in the scheme. In general mode of transmission, the sensor nodes of the WBAN are polled in order of the Node Priority. The Data Priority associated with the physiological data that is transmitted, is used to detect any emergencies. In case of an emergency, the data from an emergent node is transmitted immediately in the next beacon period.

In order to reduce system latency, a time-slicing based resource scheduling technique is coupled with a two layer priority mapping scheme. A novel MAC reactivity algorithm for WBANs is explained that helps to improve throughput of WBAN in case of excessive data loss due to interference, fading and path loss.

Chapter 4 presents the results attained from the performance evaluation of the scheme described in Chapter 3. The results signify the efficiency and effectiveness of the proposed scheme as it is successful in providing QoS in accordance with the requirements laid down in Chapter 2.

Chapter 5 describes a novel framework for providing QoS in Neighbor-aware multi-hop WBANs. A cooperative inter-WBAN routing scheme is used to service additional bandwidth requests that routes these packets through leaf nodes of neighboring WBANs. Leaf nodes are chosen due to greater availability of transmit buffer as they have no successors in the routing tree. The candidate node selection for transmission of packets is done through a composite RSSI and LQI metric evolved for inter-WBAN cooperative routing. The framework incorporates a fault detection and recovery feature that uses the modified Kosaraju-Sharir two pass algorithm to isolate any failed sensor nodes in the network graph.
The results arrived at in Chapter 6 through performance analysis of the framework, validates the fact that QoS can be provided in Neighbor-aware WBANs by implementing the salient features of the proposed framework.

7.2 Conclusions

This section elucidates upon the conclusions that were derived from the research work presented in this thesis. An analysis was carried out to understand the performance of the QoS scheme for Autonomous multi-hop WBANs and the QoS Framework defined for multi-hop Neighbor-Aware WBANs. The following sections elaborate on the findings extracted from the analysis carried out.

7.2.1 Autonomous multi-hop WBANs

This thesis presents a unique cross-layer solution for providing QoS in Autonomous multi-hop WBANs. The new scheme adopts an asymmetric processing structure in which most of the energy consuming computations are carried out by the resource rich aggregator, resulting in an increased lifetime of energy starved nodes. It uses a two layer priority mapping technique that utilizes time-slicing based resource scheduling for providing QoS in the WBAN. A MAC reactivity algorithm has been implemented in the MAC layer that allows it to sense current system performance and allocate resources accordingly for future transmissions.

The reactive MAC layer is able to effectively increase the system throughput in case of data loss due to channel impairment through fading and path loss around the human body. Through this reactivity, the scheme is also able to improvise WBAN performance
in case of degradation due to interference. The proposed QoS scheme provides a precedence allocation mechanism for immediate transmission of data in case of an emergency. Energy efficiency is maintained as a tree based multi-hop routing strategy is employed at the network layer.

The performance evaluation shows that the proposed scheme optimally prioritizes sensitive data with minimal overhead and improves network performance by reducing data loss due to interference without impacting coverage, throughput and latency of a multi-hop WBAN.

### 7.2.2 Neighbor-aware multi-hop WBANs

The second part of this thesis puts forward a novel framework to tackle the problem of providing QoS in case of Neighbor-aware multi-hop WBANs. The framework uses a new inter-WBAN cooperative routing technique that allows servicing of occasional routing requests by sensor nodes of neighboring WBANs. The framework uses a distinct scheme for selection of candidate sensor nodes that involves the computation of a combined RSSI and LQI score.

In addition, the framework also addresses the issue of system failures that arise due to sensor node failures in the network graph. As inter-WBAN cooperative routing results in increased network graph complexity, the modified two-pass algorithm proposed by the framework allows easy identification of disconnected sensor nodes from the strongly connected components of the network graph.

Performance evaluation of extensive simulations involving multiple WBANs has produced encouraging results. The framework is instrumental in provisioning QoS for service starved nodes as it successfully routes packets from these sensor nodes through
neighboring WBANs. It is able to reduce system latency and increase throughput while having minimal data loss and delay. Furthermore, it demonstrates the capability of troubleshooting the network by carrying out effective fault detection and localization.

7.3 Future Research

This section provides a few ideas and directions, in which the work presented in this thesis, can be extended. The first section listed below throws light on future research that could be carried on Autonomous multi-hop WBANs under the purview of the proposed QoS scheme. The latter section provides suggestions for extension of the proposed framework for providing QoS in Neighbor-aware multi-hop WBANs.

7.3.1 Autonomous multi-hop WBANs

The QoS scheme proposed for Autonomous multi-hop WBANs is mainly designed keeping in mind that the positions of sensor nodes with respect to their parents, remain relatively static. However, there could arise such scenarios where mobility of a WBAN might need to be considered while also providing QoS. This would present another set of challenges related to network topology reorganization and pro-active QoS provisioning. To tackle these challenges each sensor node would have to maintain a candidate parent set and route packets through one of them on the basis of the priority mapping scheme. The reactivity algorithm of the MAC layer would have to be accordingly altered to improve the throughput of the system in case of data loss.

In a uniform and static network topology, issues could arise due to energy-hole problem which occurs when sensors that are close to the coordinator run out of energy faster than the nodes at the periphery. To resolve this issue a residual energy based routing
algorithm [29] could be employed with the QoS scheme to ensure distributed energy consumption and effective QoS provisioning.

It is believed that the proposed scheme can be easily extended to static Neighbor-aware multi-hop WBANs where resource scheduling and allocation must be coordinated across multiple WBANs. However, in such a scenario it would be important to take care of conflicting priority-mapping schemes implemented in the participating WBANs.

Finally, the proposed scheme could be evaluated on a test bed of appropriate sensors that conform to IEEE 802.15.6 standard once they become commercially available.

7.3.2 Neighbor-aware multi-hop WBANs

The QoS framework proposed for Neighbor-aware WBANs also applies in the case of static WBANs only. The simulations carried out to evaluate the framework can be altered to check the performance and validity of the same under conditions of mobility.

Research can also be undertaken to identify the best security schemes [30] that could be applied to inter-WBAN cooperative routing as sensitive information is passed to the base station through multiple WBANs. In such a scenario it is imperative to provide security measures that do not allow intruders to compromise sensitive medical information.

7.4 In conclusion

WBANs are a part of a relatively new wireless networking paradigm that is expected to grow enormously in the coming years. Increasing interest of researchers in wearable technology has made it possible to push its frontiers to use it for numerous purposes. With multiple wearable devices either attached on or implanted in the human body,
there is a need for a wholesome networking technology that would allow these devices to safely and successfully transmit their data. This is facilitated by a WBAN that provides these devices with the flexibility to communicate under various network topologies and architectures.

This thesis’ contribution has been to provide effective methods that could ensure QoS in multi-hop WBANs, that would allow prioritization of sensitive data while maintaining low system latency, delay and high throughput. These methods are also capable of optimizing energy consumption and reducing data loss due to signal fading, path loss and interference.

The research carried out in thesis is, however, only a milestone on the pathway to development of a generic QoS scheme that could be applied to a WBAN without giving any special considerations to network topology and underlying MAC layer protocols. The challenge is to innovate on this work in a manner that could greatly impact and improve the quality of human life.
Bibliography


Bibliography


