Congestion Control Mechanism for Sensor-Cloud Infrastructure

by

Sara Ghanavati
Bachelor of Computer Software Engineering

Submitted in fulfilment of the requirements for the degree of

Master of Science

Deakin University
2015
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Date: 11 August 2015
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To him, who taught me another language to live.
Acknowledgement

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- Davood Izadi, Jemal Abawajy and Sara Ghanavati (2013), A New Energy Efficient Cluster-Head and Backup Selection Scheme in WSN, 14th *Proceeding of the Information Reuse and Integration Conference (IEEE IRI)*, 2013, San Francisco, USA.
2012:

Abstract

Recent advances in wireless communications and integrated circuits have enabled design, development and implementation of wireless body area networks (WBANs). This class of network is paving techniques to develop innovative remote healthcare monitoring systems. The pervasive healthcare systems provide continuous monitoring for the chronically ill and elderly people to survive them in their independent lives. Despite having significant improvements, there are still many considerable issues and challenges that might influence quality of service (QoS) of WBANs. Therefore, the main objective of this research is to identify the existing gaps in providing a better QoS in the networks. Although many problems can be addressed in this area, only two of them are studied in this thesis. First, this study will develop a sensor-Cloud system that integrates WBANs with Cloud computing to enable real-time sensor data collection, storage, processing, sharing and management. The sensor-Cloud system can be used for remote real-time patient monitoring and analysis of patients' health status irrespective to time and space through an integrated low-cost and low-power sensor network and Cloud computing. Second, a congestion detection and control protocol is proposed to ensure acceptable data flows are maintained during the network lifetime. In this approach, the nodes play an important role in detecting congestion and also prioritising the data received by them. That essentially helps to curb down problems caused due to congestion occurrence in healthcare applications. The proposed protocol detects congestion at the first step (detection phase) by using a type-2 fuzzy logic system (T2-FLS). In case of existing congestion in the network, then it will be controlled and mitigated by the proposed rate adjustment phase. In this phase, physiological signs will be discriminated to ensure enhancing QoS by transmitting highly important data.
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Chapter 1

INTRODUCTION

Recent advances in Wireless Sensor Networks (WSNs) technologies such as wearable and implantable sensors have introduced the realization of Wireless Body Area Networks (WBANs). A WBAN consists of biomedical sensor nodes that can be integrated in or on a human body [1]. Sensors in WBANs are placed wisely to record biological and physiological changes such as body temperature, blood pressure, glucose level or Electrocardiography (ECG) signals. The collected data then will be forwarded to a Base Station (BS) for further process. Typically, a BS has more power than other body sensors and is able to analyse and transfer the collected data to the next destination [2]. The BS in this scenario can be a Personal Digital Assistant (PDA) which is close to the user and receives data from the sensors. Important issues in WBAN applications include ensuring high level of performance, reliability and accuracy [2]. Therefore, it is always necessary to consider quality of service (QoS) in WBANs. QoS is based on the requirements of WBANs
and can be used in different meanings and prospective. Nevertheless, QoS in any WBANs is used to enhance the performance of the network for users [3]. In this thesis, QoS is analysed based on the consideration of different requirements such as energy consumption, delay, throughput and packet loss ratio.

1.1. Background and Motivation

Monitoring physiological and vital parameters for different diseases in humans is one of the major challenges in healthcare applications. To overcome this challenge, WBAN is suggested as a new sub-field of WSNs. Other terms commonly used for WBANs include Wireless Body Sensor Networks (WBSNs), Body Area Networks (BANs) or Body Area Sensor Networks (BASNs). WBANs can be used in variety of real-word applications such as medical and emergency services, consumer electronics, health fitness as well as lifestyle monitoring and personal health applications [4]. Although detailed features can be different from one application to another in WBANs, the main aim of all applications is to improve quality of life [5].

WBANs are able to provide continuous health monitoring services for diagnosis of patients. Importantly, it can monitor activities of a patient without distracting their normal lives [1]. In terms of healthcare costs, saving patients in hospital has a huge expenses regard to the services and staff. Therefore, in order to provide a low cost and better quality healthcare system, it is needed to move toward e-health systems. The term e-health describes the combined use of electronic communication and information technology in the healthcare systems to have a safer, more efficient and better quality healthcare [6]. E-health systems
will give health practitioners faster and secure access to all information they need to treat patients.

Despite significant improvements, there are still several constraints related to WBANs such as limited buffer capacity, bandwidth, processing speed and energy. Those constraints can negatively influence the network QoS especially in emergency situations [1]. With very limited capacities of bandwidth and storage, the buffer is highly likely to be overwhelmed by large volumes of sensor readings. This problem, which is intuitively known as congestion issue, has intimidated almost all kinds of networks and appears to be even more challenging in life-threatening applications. To solve this problem, this thesis focuses on how to detect and control congestion especially during the high demand and emergency event monitoring process. Vast amounts of data generated during critical periods may result in a poor performance that may affect the underlying applications. In particular, we aim to control congestion and minimize the effect of traffic overload due to massive sensor readings during concurrent data transmissions. In other words, we are targeting to reduce severe effects from congestion problem where packets are simultaneously conveyed, causing the system to become unable to accommodate the incoming packets.

1.2. Research Problem

Despite the wide acceptance of WBANs in various remote control and monitoring applications, there are still obvious challenges that need to be addressed. Important QoS issues such as packet loss, delay, real-time guarantees, energy efficiency and network throughput still remain to be solved [7-11]. Sensor nodes are designed to be relatively tiny,
battery-powered and low-cost. These design characteristics make them prone to suffer from low memory, bandwidth and processing power and so limit their performance to a certain level [12].

In WBANs, the total amount of the sensed data accumulated at each sensor node can be relatively large. This problem may cause contention among packets waiting to get through the next node which has limited capacity [8]. From its theoretical definition, congestion represents a state of traffic overloading as a result of buffer overflow. Congestion is mainly driven by many-to-one data sending approach in WBANs. In an emergency situation, where a great number of sensors forward the sensed-data to a few sink nodes, a sudden surge of data transmission occurs. This will result in high reporting rates at the sink node and may create a shortage of resources in terms of offered bandwidth and buffer space. The huge amount of reporting data may also create severe packets' contention at the full buffer and cause severe QoS degradation such as increase in transmission time, high numbers of packet losses and extra energy consumption. Therefore, congestion in such critical scenarios should be avoided by all means.

This thesis is focused on heavy congestion problem that may occur when multiple leads from a patient have data to be sent to the gateway which is constrained by limited resources, and sensors from several patients are also sending their readings simultaneously. A congestion scenario in WBAN is illustrated in Figure 1.1a. This scenario may repudiate the intermediate nodes' ability to cope with further incoming streams from the downstream nodes, causing considerable packet losses. Congestion may waste energy and useful resources to the extent that may collapse many real-time applications in WSNs and WBANs
which require high quality assurance [13]. Thus, reliability and timely delivery are important issues to be addressed in these domains [14, 15].

The consequences of congestion problem are even worse in a higher number of hops traversed. The further the packets travel, the more energy is wasted and the effect of congestion can also be massive. It may cause data to become obsolete due to high transmission delays and retransmission processes. Due to unavailable space, the sensed-data waiting to be accepted at the sink node may finally become stale and expire. This fact could lead to inaccuracies in information and may also involve the loss of much information.

In healthcare applications, ensuring timely arrival of the sensed data during critical periods is crucial. For instance, in healthcare monitoring of ECG data, the signals should be received within a specific period of time to be valid for a decision making process. Late arrival of the data and the loss of information in such a situation are intolerable as information will appear to be obsolete, causing a false diagnosis that could endanger the patient. Congestion may also cause some part of patient's abnormal ECG signals to be lost. As a consequence,
wrong information about the patient's current condition will be received by physicians and this will lead to false diagnosis as shown in Figure 1.1b.

As such, ensuring the timely packet delivery and maintaining accurate information in those real-time applications are among greatest importance as it will help to avoid false alarms that might lead to wrong diagnoses. Based on the all aforementioned issues, congestion avoidance is a topic worth studying. Therefore, it motivated us to come up with a new and reliable solution to control congestion in healthcare WBAN applications.

1.3. Research Methodology

There are many techniques includes statistical and Covariance Intersection (CI) based methods used to enhance the QoS in WBANs. However, most of them are not capable to cope with the uncertainty of the data produced by sensor nodes. Moreover, the inflexibility of the methods prevents processing the data realistically [16]. Applying these methods requires very complex and computational effort for having optimal performance [17]. In contrast, flexibility of fuzzy systems provides us with the opportunity to edit and display given information at any point of the structuring. In addition, the 3D display and surface gives us a clear picture of the output of the system. Therefore, we decided to use fuzzy logic systems as in many previous works the sensors were equipped with the systems [18-20]. Type-1 fuzzy logic systems (T1FLS) use fixed fuzzy memberships that cannot directly address variable conditions. Therefore, uncertain measured parameters in applied systems would be neglected by T1FLS and the performance obviously will be negatively influenced. As a result, Type-2 fuzzy membership functions that use membership degrees
which are themselves fuzzy sets were developed. Type-2 fuzzy sets are very useful when there is a difficulty in determining appropriate membership function with ambiguity. Type-2 fuzzy sets allow us to handle linguistic uncertainties. T2-FLS technology has been regarded as a way to increase the fuzziness of a relation means increased ability to handle inexact information in a logically correct manner [21]. The fuzzy logic toolbox used in this thesis was built in MATLAB. Moreover, MATLAB provides the capability to observe the dynamic changes in the sensors circumstances during simulation execution [22]. Therefore, we use MATLAB to simulate the congestion detection subsystem of our approach.

In addition, we use OPNET to provide a discrete event simulation engine. OPNET is used to simulate scenarios in our virtualized WBAN and configuration of the nodes’ attributes. To merge these two software, we use MX interface that is been provided by MATLAB and extensively used by other approaches in the same area of work [23-28]. The interface allows C++ programs to call functions developed in MATLAB. In fact, MATLAB engine in our simulation is started by OPNET at the beginning of the simulation by using functions to pint to locations of MATLAB commands. Using the same language help us to also exchange variables between MATLAB and OPNET in our simulations.

The inputs of the developed approaches we generate synthetic data. We use a Gaussian distribution with its mean and covariance matrix representing the expected value and its uncertainty (10% of the value). Then, the values are normalized to fit in the [0, 1] as the inputs of the fuzzy system. Then, we extract linguistic variables out of the normalized data. In each experiment, 20% of the data is used for training the fuzzy system to determine the membership functions and also the rules as well as the required threshold values for solutions. Then, we used 80% of the data to test the proposed solutions. In those simulations
and experiments, various parameters were used to examine and demonstrate the viability of the proposed solutions compared to the similar baseline solutions.

1.4. Research Aims and Significances

The overall aims of this thesis are:

I. To develop a patient monitoring framework which emphasizes the use of Cloud infrastructure and WBANs to collect, analyse and store the health data. The significance of the proposed framework is that the new system will enable quality healthcare to be provided remotely and patients can be monitored continuously without having to go to the hospitals. The system will be capable of facilitating self-monitoring for patients. It also assists physicians to make diagnoses and manage the patients’ records conveniently in a real-time manner.

II. To propose a congestion control algorithm for use in the designed sensor-Cloud framework with the main advantages of improving the overall network throughput and energy efficiency, simultaneously. The proposed scheme has also a significant effect on decreasing packet loss ratio and end-to-end delay of the system. The main feature of the propose algorithm is that it is able to classify physiological signals and assign them different priorities. Thus, it would be possible to provide a better quality of service for transmitting highly important vital signs.

1.5. Research Contributions

The primary contributions of this thesis are summarised as follows:
i. *A Cloud-Based WBAN Framework for Remote Healthcare Monitoring.* The first contribution of this thesis is to develop a Cloud-enabled WBAN architecture for collection and management of body sensor data. In this framework, each patient is equipped with a set of wearable or implanted wireless sensors. The sensors collect various health physiological signs and forward the data to an assigned smartphone or PDA. Initial processing is performed by mobile applications and later on the collected information will be relayed on Cloud subsystem for model evaluation. In the proposed approach, patients can view their health records and prescriptions on their mobile phones on a continuous, periodic and on-request basis. We will discuss the complete life cycle of data analysis workflows which include data collection, storing, analysis, and presentation. As a case study, an EMG remote monitoring application with the help of proposed framework is presented.

ii. *A Congestion Detection and Control Approach in WBANs.* The second and main contribution of this research is to propose a new congestion detection and control approach for use in healthcare WBAN applications. The proposed approach consists of three main steps. At the first step, local information of sensor nodes is sent to a T2-FLS to analyse the network traffic. Based on the fuzzy system output, congestion level will be estimated. In case of congestion, parent nodes dynamically compute and allocate the new transmission rate for each of its children. The main objective of the rate adjustment stage is to prioritize physiological signals and send them based on their level of importance. Finally, the system will take advantage of an implicit congestion notification method to send notification messages through the network. Performance of the proposed protocol is then analysed through simulation studies. The proposed
approach, compare to the existing approaches, enhances performance of the system by reducing energy consumption, packet loss ratio, end-to-end delay and in turn increasing the total network throughput.

1.6. Thesis Organization

The remainder of the thesis is organized as the following:

Chapter 2: This chapter provides an extensive literature review of WBANs and their related challenges. This chapter will begin with an understanding of specific features of WBANs. Following that, we discuss about the congestion problem in WBANs, and present a comprehensive review of existing congestion control approaches with a discussion on the advantages and disadvantages of these methods.

Chapter 3: This chapter presents a sensor-Cloud architecture for use in remote healthcare applications.

Chapter 4: This chapter presents a method to firstly detect and then control congestion in the sensor-Cloud infrastructure with the help of T2-FLS and prioritization service.

Chapter 5: This chapter presents performance evaluation of our proposed congestion control protocol using simulation studies.

Chapter 6: This chapter summarizes the main contributions of this thesis and proposes some possible future work.
Chapter 2

LITERATURE REVIEW

This chapter provides a comprehensive review of wireless body area networks (WBANs) and various quality of service (QoS) issues in such networks. Then, we focus on the problem of congestion in WBANs. In this chapter, an in-depth analysis of the existing approaches is presented to identify the addressed research gap.

2.1. Introduction

WBAN have been an attractive research area and is used for various applications. WBAN technology is a subfield of existing research in the field of Wireless Sensor Networks (WSNs) [29], and can be considered to be a specialization of biomedical engineering. The main differences between WBANs and WSNs are listed in Table 2.1. WBANs are generally linked with the human body where fewer nodes are deployed than traditional WSNs. With a few number of nodes, even limited data loss in WBANs could be
significant, whereas data loss in a WSN is less of an issue as nodes may yield redundant information. Therefore, each WBAN node needs to provide certain QoS guaranties. This may require additional measurements to ensure successful reliable data delivery.

QoS term is defined based on different factors in WBANs. However in all meaning, QoS is used to enhance the performance of the network for users [3]. As we already mentioned, QoS in this thesis is analysed based on the consideration of different requirements such as energy consumption, delay, throughput ratio and packet loss. These parameters are recognised as the most important factors in WBANs based on the inherent features of this type of network [30].

Table 2.1. Comparison of WBANs with WSNs [4]

<table>
<thead>
<tr>
<th>Comparison measures</th>
<th>WSNs</th>
<th>WBANs</th>
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<tbody>
<tr>
<td>Network Size</td>
<td>Cover a large area (from few meters to thousand meters)</td>
<td>Limited to the human body (few meters)</td>
</tr>
<tr>
<td>Node Size</td>
<td>Size of nodes can vary (small nodes are preferred)</td>
<td>The smallest size of nodes is required</td>
</tr>
<tr>
<td>Node Accuracy</td>
<td>Number of nodes help to increase the accuracy</td>
<td>Each node should be highly robust and accurate</td>
</tr>
<tr>
<td>Node Replacement</td>
<td>Replacement can be performed easily</td>
<td>Implanted nodes are difficult to be replaced</td>
</tr>
<tr>
<td>Node Functionality</td>
<td>Redundant nodes are used</td>
<td>No redundancy</td>
</tr>
<tr>
<td>Application Environment</td>
<td>Anywhere-Extreme in weather or noise</td>
<td>In, on, or a human body</td>
</tr>
<tr>
<td>Power Supply</td>
<td>Capable of changing or re-charging of power resources more frequently due to the larger size of nodes</td>
<td>Use of tiny nodes cause difficulty in replacement or re-charging the power supply</td>
</tr>
<tr>
<td>Security Level</td>
<td>Vary depends on type of application</td>
<td>Needs to be highly secure and confidential</td>
</tr>
<tr>
<td>Wireless Technology</td>
<td>WLAN, GPRS, Zigbee, Bluetooth and RF</td>
<td>802.15.6, ZigBee, Bluetooth, UWB</td>
</tr>
<tr>
<td>Mobility</td>
<td>Typically fixed and static</td>
<td>Due to the motion of patient, the network is mobile</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Generally easy to access</td>
<td>Difficulty to access the implanted node</td>
</tr>
<tr>
<td>Context Awareness</td>
<td>Not imperative due to the static structure</td>
<td>Quite significant due to the mobile and sensitive nature of human body</td>
</tr>
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2.2. **WBAN Main Features**

In this section, some of the specific features of WBANs are discussed:

2.2.1. **Node Types**

Generally, only less than a few dozen sensor nodes are used in WBANs. In terms of network size, WSNs can be deployed over a vast area up to several thousands, while sensor nodes in WBANs are limited to the size of human body [5]. In WBANs, sensor nodes send their gathered information to a Base Station (BS) known as coordinator. Due to the low transmission range, the network area of WBAN communication is normally within a few meters, while the area for WSNs can reach to a few kilometres. Figure 2.1 shows a WBAN which is consisted of several body sensors such as Electrodiagram (ECG), blood pressure, Glucose and motion sensor. For example, ECG [31] is one of the most popular biomedical sensing system these days. As it has been investigated in [32, 33], ECG can monitor a human heart activities. Another type of body sensor is blood pressure sensor which can monitor flow and pressure in a blood vessel [34, 35]. Glucose sensor, as it has been extensively used in many projects [36, 37], can monitor Glucose level in real-time.
2.2.2. Node Characteristics

Small size of sensor nodes is usually preferred in most of the WBAN applications. As patient comfort is an important factor in WBANs, size of implantable or wearable sensor nodes must be as small as possible. Apart from the size, accuracy of data provided by sensor nodes is an extreme challenge in WBANs [5]. That is because the number of nodes is extremely limited in WBAN. Hence, nodes need to be very accurate to reimburse the accuracy without data redundancy [38]. Furthermore, another unique feature of a sensor in a WBAN is that it is able to perform multiple tasks at a same time [4].
2.2.3. Limitation of Resources

Limitation in available memory, bandwidth, processing capabilities and energy consumption are among resource limitations of a WBAN. The main reason for strict resource limitation in WBANs is the very small size of nodes. These resource limitations cause several challenges and difficulties in implementing WBANs. For example, battery usage is a critical issue in such networks. This is because for those sensors implanted in the human body, changing or replacing the sensors is not feasible [39].

2.2.4. Accessibility

Node accessibility is among the main concerns in WBANs. Sensor nodes especially those implanted in the human body are not easily accessible. That is because a surgical operation is needed for the replacement of an implanted sensor node. In addition, the process of node replacement can cause damage to internal organs and blood vessels [38].

2.3. WBAN Applications

WBANs have been receiving considerations in different areas with the main purpose of improving healthcare services and addressing problems of old patient treatment methods. As Table 2.2 shows, WBAN applications are divided into two main categories: in-body and on-body applications. On-body application can be also classified into medical and non-medical applications based on IEEE 802.15.6 [1]. Each type of application has its own specific technical requirements. For example, required energy consumption for Glucose sensor is extremely low, while it is quite high for blood pressure monitoring application. In
following, medical and non-medical applications and their subclasses shown in Figure 2.2, have been discussed in detail.

Table 2.2. WBAN In-Body/On-Body technical features [1]

<table>
<thead>
<tr>
<th>Application Type</th>
<th>Sensor Node</th>
<th>Data Rate</th>
<th>Duty Cycle % per time</th>
<th>Energy Consumption</th>
<th>QoS</th>
<th>Privacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Body Applications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glucose Sensor</td>
<td>Few Kbpc</td>
<td>&lt; 1%</td>
<td>Extremely Low</td>
<td>Yes</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Pacemaker</td>
<td>Few Kbpc</td>
<td>&lt; 1%</td>
<td>Low</td>
<td>Yes</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Endoscope Capsule</td>
<td>&gt; 2 Mbpce</td>
<td>&lt; 50%</td>
<td>Low</td>
<td>Yes</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>On-Body Medical Applications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECG</td>
<td>3 Kbpc</td>
<td>&lt; 10%</td>
<td>Low</td>
<td>Yes</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>SPO2</td>
<td>32 Kbpc</td>
<td>&lt; 1%</td>
<td>Low</td>
<td>Yes</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Blood Pressure</td>
<td>&lt; 10 bpc</td>
<td>&lt; 1%</td>
<td>High</td>
<td>Yes</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>On-Body Non-Medical Applications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Music For Headsets</td>
<td>1.4 Mbpce</td>
<td>High</td>
<td>Relatively High</td>
<td>Yes</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Forgotten Thing Monitor</td>
<td>256 Kbpc</td>
<td>Medium</td>
<td>Low</td>
<td>No</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Social Networking</td>
<td>&lt; 200 Kbpc</td>
<td>&lt; 1%</td>
<td>Low</td>
<td>No</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

2.3.1. Medical Applications

As it has been predicted in [40], 15% of worldwide population will reach the age of 65 and more by year 2025. With the increasing number of aged people all over the world, healthcare costs will also increase significantly [41]. To manage this problem, early detection and treatment of diseases is an ideal solution. To achieve that, WBAN technology has been widely used. WBANs open a wide area to develop healthcare monitoring and remote control patient treatment methods [42]. In fact, WBANs provide an opportunity for practitioners with the ability of monitoring physiological behaviours of a patient even if the patient is not in hospital environments. In case of an emergency situation, patients’ medical information will be collected and forwarded through the network to inform a doctor about abnormal situations [43, 44].
WBAN medical applications can be further divided into three subclasses as shown in the Figure 2.2. The main features of each category is discussed in the following paragraphs:

- **Wearable WBAN**: As Figure 2.2 shows, some of the most important wearable WBAN applications are sport training, sleep staging, asthma and wearable health monitoring. In sport training application, wearable devices are attached to a human body to monitor body characteristics in activities such as swimming or cycling. The main requirement for this type of application is that the sensor nodes should not influence athlete’s performance [4]. In sleep staging application, a specific feature sensor monitors bio potential signals of a patient’s head. The previous sleep monitoring systems all needed connecting cables from head of the patients which interrupt their sleeps. Instead, sleep staging application can act wirelessly and consequently patients feel more comfortable [45]. For people suffering from allergic disease such as Asthma, an attached sensor can realize air health quality to help early diagnosis of an abnormal patient situation [46]. Finally, wearable health...
monitoring applications play an important role in every day human’s life. The devices are easy to use and provide real-time health monitoring for patients in both in-hospital and out-hospital locations [4].

- **Remote Control of Medical Devices:** As the number of aged people is increasing, a system that can provide variety of medical services for patients within their home is required. Ambient Assisted Living (AAL) system has a huge potential to help elderly people to decrease their dependency to intensive private care. Besides increasing the quality of life, AAL also can decrease healthcare costs considerably [47]. In patient monitoring application, WBANs are used for monitoring patient vital signs such as heart rate, blood pressure and body temperature to provide appropriate real-time reactions [4].

- **Implant WBAN:** Cardiovascular diseases (CVDs) are the main reason of over 30% of death all over the world. It has also been predicted that by 2030, 23.3 million people will die because of heart disease and stroke. These days, by implanting ECG sensors in the human body, many CVDs can be detected in the early stages [31]. Overall, WBANs can provide a convenient long-term monitoring system for patients with cardiac disease conditions [48]. WBAN has also an important role in detecting cancers in the early stages. Cancer detection application can diagnose cancer cells in the human body with the main aim of fast detection and continuing monitoring of the patient [4].
2.3.2. Non-Medical Applications

The use of WBANs in non-medical applications has been also investigated in recent years [30]. Real-time streaming is an example of a non-medical WBAN application. In this application, audio or video streams are captured or transferred by sensors. The main goal of the application is to control entertainment devices or body information-based entertainment service remotely [4]. WBANs also can be used in entertainment applications such as gaming or social networking with the purpose of gestural game control or mobile body motion activities. WBANs can also be used to detect emergency situations such as fire by using off-body sensors [5].

2.4. WBAN Performance Requirements

Due to the unique constraints in WBANs, there are some challenges that should be considered in developing the networks. In following, some of the main challenges and requirements in WBANs are discussed.

2.4.1. Security and Privacy

As communication is performed wirelessly in WBANs, security and privacy are among major areas of considerations. In fact, practitioners need to make sure that patients’ vital information is confidential and has not been altered during the communications. Therefore, providing appropriate security and privacy mechanisms are among crucial factors in WBANs.
2.4.2. Data Transmission Parameters

Due to the diversity of WBAN scenarios, data transmission parameters are different from each application to another. The required values for data transmission parameters in different applications are shown in Table 2.3 [5, 39, 49].

Table 2.3. Requirements of selected WBAN applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Data Rate</th>
<th>Bandwidth (Hz)</th>
<th>Accuracy</th>
<th>Topology</th>
<th>Setup Time</th>
<th>Latency</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>72 kbps</td>
<td>100-500</td>
<td>12 bits</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 250ms</td>
<td>&lt; 10-10</td>
</tr>
<tr>
<td>EMG</td>
<td>320 kbps</td>
<td>0-10,000</td>
<td>12 bits</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 250ms</td>
<td>&lt; 10-10</td>
</tr>
<tr>
<td>EEG</td>
<td>43.2 kbps</td>
<td>0-150</td>
<td>12 bits</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 250ms</td>
<td>&lt; 10-10</td>
</tr>
<tr>
<td>Hearing</td>
<td>200 kbps</td>
<td>-----</td>
<td>12 bits</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 250ms</td>
<td>&lt; 10-10</td>
</tr>
<tr>
<td>Glucose Monitoring</td>
<td>1600 kbps</td>
<td>0-50</td>
<td>16 bits</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 250ms</td>
<td>&lt; 10-10</td>
</tr>
<tr>
<td>Audio</td>
<td>1 Mbps</td>
<td>-----</td>
<td>-----</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 100ms</td>
<td>&lt; 10-5</td>
</tr>
<tr>
<td>Voice</td>
<td>50-100 kbps</td>
<td>-----</td>
<td>-----</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 100ms</td>
<td>&lt; 10-5</td>
</tr>
<tr>
<td>Video</td>
<td>&lt;10 Mbps</td>
<td>-----</td>
<td>-----</td>
<td>Star</td>
<td>&lt; 3ms</td>
<td>&lt; 100ms</td>
<td>&lt; 10-3</td>
</tr>
</tbody>
</table>

As it can be seen from the given information, data rates vary from simple with low rate to more complicated data such as video streams. Overall, the data rates are not still high. However, if any of the applications use several of these sensors together, data rate will reach over few Mbps. In the case, as most of the current existing low power radios are not able to pass such transmission rate, congestion can occur. Data rates given in the table can be calculated by using E.q. 2.1 [50]:


20
\[
\text{Data rate} = 2 \times \ f_{\text{max}} \times k \tag{2.1}
\]

where \( f_{\text{max}} \) is the maximum frequency and \( k \) is the number of bits. The data transmission accuracy is named as Bit Error Rate (BER). This measurement shows the rate of packet loss in each application. BER is mainly defined based on the application data rate. For example, low data rate devices can tolerate a high BER (e.g. 10^{-4}) [5].

2.4.3. Mobility

Sensors in WBANs can be implanted or attached into the surface of a human body. Patients can also be in a mobile situation such as walking or running. Thus, a WBAN cannot be considered as a static network all the time. Sensors’ locations are also depending on the type of the applications. For example, in ECG application that measures the activity of a human heart, sensors are attached close to the heart to sense information quickly [39]. Overall, sensors should be located based on the targeted data location. However, there is not a full agreement among researches about the exact location of different sensors in the human body [51].

2.4.4. Energy Consumption

In WBANs, integrated batteries in sensor nodes provide the required energy for network tasks. Due to the small size of sensor nodes in WBANs, batteries are also small and are able to save limited amount of power. Mainly, there are three categories for energy consumption in a WBAN: sensing information, wireless communications and data processing [39]. As Figure 2.3 [52] describes, wireless communications such as Wi-Fi,
wireless USB, ZigBee and Bluetooth consumes higher amount of saved energy compared to sensing part and processing circuits in a typical WBAN.

Figure 2.3. Comparison of average energy consumption of wireless communication and processing circuits in a typical WBAN

2.4.5. Usability

A WBAN should be set up simply, as nurses or practitioners are not expert to configure or fix the network. Therefore, it is an important factor for sensor nodes to have the ability of self-organizing and self-maintaining. Additionally, a sensor node should have the capability of joining the network automatically and set up routes once it has been placed.
2.5. WBAN Topologies

Network topology is defined as a way that sensor devices can communicate with each other in any network. The topology of a network also determines how devices can be placed through the network. The most applicable topologies for WBANs are described as follows:

2.5.1. Point-to-point topology

Point-to-Point (P2P) is the simplest topology used in WBANs. As shown in Figure 2.4, in Point-to-Point (P2P) topology only two sensors with a permanent link are directly connected with each other.

![Figure 2.4. P2P topology](image)

2.5.2. Star Topology

In a star topology, all sensor nodes are connected to a central coordinator as shown in Figure 2.5. The communication between the nodes is only possible via passing all the information through the coordinator. The advantages of the star topology are simplicity, lower network cost, less energy consumption, low latency, and high bandwidth capacity. The major weakness of a star topology is a single point of failure. The whole communication
fails when the central node is failed. Other drawbacks of this topology are poor scalability, higher power consumption of the central node and limited spatial coverage [53].

2.5.3. Mesh Topology

Each node in this topology is capable of doing all the routing operations as well as data communications. The main advantage of this topology is the multiple paths provided to each node which help to continue the communication processes in case of the failure of one or more nodes.

Other features of this topology are scalability, large spatial coverage, fault tolerance, distributed processing, medium complexity and balanced energy consumption. The
disadvantages of mesh topology are higher node costs, complex routing operations, high latency, and low bandwidth [53].

2.5.4. Cluster Tree Topology

Figure 2.7 shows a general scheme of cluster tree topology. In this topology, nodes from one star topology can communicate to the nodes of other star topologies via their central nodes. The advantages of a cluster tree topology are low power consumption, large spatial area coverage, increased scalability and medium complexity. The disadvantages of this topology contain high latency, low reliability and low bandwidth capacity [53].

![Figure 2.7. Cluster Tree topology](image)

2.5.5. Hybrid Topology

A combination of star and mesh topologies is called hybrid topology. Figure 2.8 shows an example of a hybrid topology. The main advantages of hybrid topology are large spatial coverage, high potential reliability, and scalability. The drawbacks are high complexity, high latency, asymmetrical power consumption, and low bandwidth [53].
2.6. Communication Architecture of WBANs

WBANs provide wireless communication in or on a human body by means of wireless sensors. Figure 2.9 shows a general architecture of a WBAN. The architecture can be classified into three different tiers as follows: Tier-1: Intra-BAN communication, Tier-2: Inter-BAN communication and Tier-3: Beyond-BAN communication. The detailed description about each tier is given in the following paragraphs.

Figure 2.9. Communication architecture of WBANs
2.6.1. Intra-BAN communications

The term of Intra-BAN communication is used for the radio communications within a WBAN (between body sensors inside the body) and for the communications between WBAN and Tier-2. The defined radio transmission range in Tier-1 is about 2 meters in or around the human body [4].

As it is shown in Figure 2.9, body sensors are responsible to collect vital information from the body and then forward it to the Personal Server (PS) which is located in Tier-1. The PS can be integrated on a PDA, cell phone or home PC. The main responsibility of the PS is to forward vital data to a medical server through the network [54].

2.6.2. Inter-BAN communications

Inter-BAN communication can be referenced to the communications between PS (Tier-1) and one or more access points (APs) in Tier-2. In WBANs, Tier-2 is responsible to interconnect the network with other accessible networks such as Internet to facilitate daily usage [30]. Two paradigms of inter-BAN communication model are discussed in the following paragraphs:

- **Infrastructure based architecture:** The most popular paradigm of inter-BAN communication is infrastructure based architecture. This architecture assumes limited space for an environment such a surgery room in a hospital. The reason for its popularity is the flexibility of the architecture as well as large bandwidth capacity with the centralized control specially in situations with limited space condition [30].
Due to the centralized structure, the access points (APs) can also be used as a database server in some applications.

- **Ad-hoc based architecture:** This architecture is the second most popular scheme of inter-BAN communication. The main feature of this architecture is that several APs are placed to help sensor nodes for data transmission. The APs in the structure are deployed in a form of mesh topology. This way of interconnection helps the overall network to cover an area up to one-hundred meter. This coverage area is quite larger than the coverage area in comparison with infrastructure based model [1].

2.6.3. **Beyond-BAN Communication**

The last layer of WBAN architecture is called beyond-BAN communication (Tier-3). The main purpose of designing this layer is for use in metropolitan areas. In order to make a wireless connection between inter-BAN communication and beyond-BAN communication in the network, a PDA can be used. The beyond-WBAN communication tier enhances the coverage range for a remote patient monitoring system. That is because this tier offers practitioners or nurses with accessing patient’s medical information through the Internet or any other cellular network [5]. A database is also an important module of Tier-3. Normally, a database keeps patients’ medical history and their related profiles. Therefore, users such as doctors or patients can be notified of an emergency status via Internet or any other service. In fact, Tier-3 enables saving all essential information of a patient which are useful for their future treatment especially in an emergency situation [5].
2.7. Modelling of WBAN and Cloud integration

The general concept of Cloud Computing refers to a new technique capable of delivering enterprise IT. Cloud computing also delivers more scalable and reliable storages which allow dynamic data integration from various resources. In addition, Cloud-based services provide flexible deployment of applications in case of the client requirements have been changed. The applications of Cloud computing are not just limited to provide virtual machine (VM) instances for servers and other Internet facing services. Rather, the Cloud model can be applied to any type of datacentre regardless of its operational goals [55]. One interesting application of Cloud computing is in healthcare informatics. Health care systems require continuous and systematic innovation in order to remain cost effective, efficient, and timely, and to provide high-quality services [56]. By using Cloud computing, unlimited recourse of data can be accessed anytime and anywhere in the world [55, 56]. In addition, it can ease data processing and data management as explained in following:

- **Data Processing:** Data gathered from wireless sensors need complicated computational tasks to reveal patients’ health status [57]. In this case, real-time processing of huge amounts of received data streams from WBAN is a memory and energy intensive task [30]. However, Cloud infrastructure can help to run numerous processing tasks simultaneously and in a real-time manner [58].

- **Data management:** The way that data are collected, analysed and stored, need to be highly considered in WBANs [57]. One of the reasons that make data management a challenging issue is that data may be distributed in time
or space in WBANs [59]. Time distribution means occurrence of several activities in different times, while they have been managed to have a same goal. Space distribution refers to activities that take place in different locations, while they are managed by a same data network [57]. In this case, a Cloud computing solution could simplify the management of distributed data by using methods such as data fusion.

The efficient management of the large amount of monitored data collected from various WBANs is an important issue in pervasive healthcare systems [60]. Since WBANs are limited in terms of memory, energy, computation, and communication capabilities, they require a powerful and scalable high performance computing and massive storage infrastructure for real-time processing and storing of the data as well as on-line and off-line analysis of the processed information. Nowadays, Cloud computing technology is able to provide variety of services to store and analyze a huge amount of gathered data in a scalable and low cost manner [61].

The integration of WBANs and Cloud computing can facilitate to build an intelligent, autonomous, cost-effective, scalable and data driven pervasive health-care services platform to realize the long-term monitoring, analysis, sharing and management of health status at any time and any place. Nevertheless, the research regarding the WBAN-Cloud integration platform is still in its infancy, and several technical challenges remain to be addressed to maximize the opportunities [62].
2.7.1. Cloud-Enabled WBANs for Pervasive Healthcare

Real time health care applications require robust information technology infrastructure to provide expected levels of responsiveness. To approach such purposes, the use of Grid computing in those applications has been deeply investigated. There is number of different biomedical research projects were initiated that exploited grid resources to perform parallel computations [63, 64]. However, Grid based e-health that is mainly targeted for the research community requires massive computational power to analyse huge heterogeneous vital data for research purposes. To overcome limitations of Grid technology, Kuo et al. [65] introduced numerous opportunities of Cloud computing to improve health care services. Since then, the usage of Cloud computing has been increased significantly in e-health real time applications. One such work is introduced by Pandeyet al. [33] that utilized Aneka [34] framework to develop an autonomic Cloud environment for hosting ECG data analysis services. They proposed the use of simple heuristics with the purpose of providing elastic infrastructure for ECG processing service. In that approach they considered response time as the only Quality of Service (QoS) factor. Despite Cloud computing being very promising and effective in real time e-health applications, several challenging and unresolved issues may negatively influence the success of the marriage between cloud computing and WBANs. Some of these issues are related to the integration between WBANs with hybrid clouds and communication standard used in WBANs [66, 67]. Another considerable challenging issue is the integration of cloud computing with mobile services [68]. To overcome the issues and challenges, Ahnn et al. in [69] proposed a cloud computing-based energy-efficient and distributed mobile health monitoring. In this
approach, some parts of the application components are run, possibly in a parallel manner, on the cloud to avoid draining the batteries of the mobile devices.

Another important issue in such systems is electronic medical profiles storage and retrieval. To overcome the issues, there are many systems have been developed to utilize the abundant resources of the cloud to build unified and synchronized profiles for the patients [70]. Fox et al. [71], developed a cloud computing infrastructure for collaboration sensor centric applications on the Future Grid. They attempted to study the characteristics of cloud computing infrastructure for message-based collaboration applications, where media based collaboration has not been addressed. Han et al. [72] described a content-centric cloud-based collaboration platform. They considered implementing the collaborative medical application on their system, where computation intensive application like a volume rendering is used for MRI analysis. Hsieh et al. [73] developed a distributed framework of a Web based telemedicine system. They applied two types of servers namely Web servers and data servers. This framework is based on CORBA technology and a distributed database fragmented on different sites. This system is not flexible to allow the integration of non-CORBA systems. As a result, it requires an intermediary middleware to handle the heterogeneity between different health systems as well as a huge development effort to adapt the system to the integrated system requirements. Omar and Taleb-Bendiab [74] proposed a multilayer SOA based e-health services architecture. It consists of six main components responsible for defining interactions among different layers. The authors failed to provide details of architectural design and detailing the implementation and its complex challenges. Kart et al. [75] described a distributed e-healthcare system that uses SOA as a mean of designing, implementing, and managing healthcare services. The system includes a clinic
module, a pharmacy module and patient’s interfaces. They all are implemented as Web services. Various devices can interact with these modules, including desktop and server computers, personal digital assistants, smartphones, and even electronic medical devices, such as blood pressure monitors. Yang et al. [76] investigated how healthcare entities, using SOA, can leverage their common services to automate multiple business processes and strengthen the complete interoperability. Kart et al. [75] designed and developed a SOA-based platform for home-care delivery to patient with CDs. This paper shares some of the goals with our project with regards to monitoring patients with CDs. However, it differs in many aspect related to data dissemination through Cloud environment, power conservation, performance consideration, and value-added services, including prevention service (e.g., lifestyle adjustment, diet program).

2.8. Congestion Control Mechanisms

In recent years, several congestion control mechanisms have been studied for WSNs related to WBANs. The proposed protocols are different based on three main factors, namely, congestion detection method, congestion notification and congestion adjustment rate systems [23]. In following, several congestion control approaches and their shortcomings have been described.

CODA (Congestion Detection and Avoidance) [77] is an energy efficient and low cost congestion detection protocol. In the approach, congestion is detected by determining queue size as well as buffer capacity at the midway sensor nodes. The method also uses an open-loop hop-by-hop backpressure method to distribute notification messages through the
network about congestion occurrence. A multi-source regulation mechanism also has been proposed to adjust the data rate and alleviate congestion. CODA also uses AIMD (Additive Increase, Multiplicative Decrease) technique to control data packet flow. However, for congestion notification messages, CODA needs great amount of energy. CCF (Congestion Control and Fairness) [78] has been proposed to alleviate congestion by controlling current packet service time. When congestion is detected in the network, CCF starts to reduce the transmission rate of the down-stream nodes using a distributed method to ensure high delivery rate at the destination. In addition, all sensors have the same throughput which means fairness is achieved in the proposed algorithm. CCF is also compatible with any MAC protocol and functioning in the transport layer of the network. However, this method is not quite efficient due to the following reasons. Firstly, when sensor nodes have low traffic load, the network will have very low throughput. Secondly, as CCF sends information about each sub-tree node to their parents, it can result in wasting energy and increasing overall traffic overflow in the network.

Sankarasubramaniam et al. proposed an congestion control algorithm called Event-to-Sink Reliable Transport (ESRT) [79]. ESRT is a centralized scheme that sink regulates WSN to function in an optimal load rate. To control congestion, the sink sends control messages to the source nodes. The advantage of this method is that it can work in a dynamic topology. However, broadcasting reporting message continuously decrease overall network capacity. Furthermore, ESRT is a centralized method to detect and control congestion that can result in increasing traffic overflow, packet collision and energy consumption. Priority-based Congestion Control Protocol (PCCP) [80] is a cross-layer based upstream congestion control that defines congestion as the ratio of packet inter-arrival time to the packet service
time. PCCP introduces priority index for each node, in which sensors with higher priority index can use more network bandwidth. In order to decrease congestion, PCCP takes advantage of a hop-by-hop mechanism. Although the proposed method supports fairness among sensor nodes, it has not included packet recovery service. In [81], authors proposed an algorithm called QCCP-PS (Queue based Congestion Control Protocol with Priority Support). The proposed method controls congestion, based on the queue length as an indicator and node priority. QCCP-PS improved the PCCP by controlling the queue length more finely. However, the proposed method has a major problem due to lack of any mechanism for handling prioritized heterogeneous traffic in the network.

Hull et al. [82] proposed a congestion control protocol called Fusion. This mechanism controls the queue size of each intermediate node to detect congestion. If queue size exceeds predefined value, the monitored node set a specific bit in every outgoing packet. In fact, Fusion uses implicit notification scheme to notify neighbours about the situation. Fusion maintains fairness among the sensor nodes by giving each node a chance to transmit. In addition, it was successful to achieve high throughput at high traffic loads. However, one of drawbacks of this method is that the rate adjustment subsystem is not smooth which can have negative impact on link utilization and fairness. Furthermore, frequent use of the wireless radio for channel probing leads to higher energy consumption.

Yin et al. in [83] proposed a “Fairness-Aware Congestion Control Scheme” (FACC). This scheme controls congestion and achieves fair bandwidth allocation for data flows. FACC considers packet loss rate at the sink node to detect congestion. In this method, sensor nodes based on their location are divided into two groups, near sink nodes and near source nodes. When the near sink nodes recognise that a data packet is lost, they send a Warning Message
(WM) to the near source node. After receiving the message, near source nodes send a Control Message (CM) to the source nodes to notify them about the issue. The source nodes then adjust their transmission rate based on the current sending rate and current traffic on the queue. After receiving CM, data transmission rate will be adjusted based on newly calculated sending rate.

Wan et al. [84] proposed a method called Siphon. This method aims to control congestion besides handling funnelling effect. Funnelling is referring to a situation when several workloads are generated simultaneously and need to be transferred to sink nodes quickly. Funnelling issue increases traffic around sink nodes which leads to packet drop. To overcome this challenge, virtual sinks (VSs) are randomly distributed across the sensor network. VSs take the traffic load off the already loaded sensor node. In the proposed scheme, initially virtual sink discovery is done. Virtual sink discovery is initiated by the physical sink as explained in [84]. Node initiated congestion detection, based on past and present channel condition and buffer occupancy as in CODA. After congestion detection, traffic is transmitted from overloaded physical sink to virtual sinks. This is performed by setting redirection bit in network layer header.

Ali Rezaee et al. proposed a data centric congestion management called Healthcare aware Optimized Congestion Avoidance (HOCA) [23]. The suggested protocol firstly tries to avoid congestion by using multipath and QoS aware routing protocol. If congestion could not be prevented, the method will use an optimized congestion control mechanism to mitigate it. HOCA considers energy consumption, lifetime and fairness to present an efficient congestion control protocol. In [85], authors proposed a queue management based congestion control for WBANs. The proposed method mainly focuses on effective
management of queue to ensure reliability and decrease packet loss. In [27], a Learning Automata based Congestion Control Protocol (LACCP) was presented. The proposed method used learning automata to adjust intermediate node arrival and source sending rate. LACCP also considers all requirements of types of traffic loads. To control congestion, a mechanism based on the learning automaton has been placed in the sink. The intermediate nodes based on their type of data receives a priority. In this scheme, higher priority classes are given more bandwidth than the lower priority classes. However, the central scheme of LACCP is a disadvantage of the method. Misra et al. [86] proposed an Learning Automata-Based Congestion Avoidance Scheme (LACAS) for healthcare applications in WSN. The Learning Automata (LA) was placed in every intermediate sensor nodes to control node’s incoming rate. The method intelligently “learns” from the past history and develops its performance significantly. The main drawback of this method is that its environment suggests only binary responses for any action selected by the automaton. Tao and Yu [87] proposed an congestion control mechanism called ECODA (Enhanced congestion detection and avoidance). ECODA uses a three-step congestion detection and control approach. First, it detects congestion based on a dual buffer thresholds and weighted buffer differences. Then, the method takes advantage of a flexible queue scheduler by considering data packets priority. Last, it uses a hop-by-hop congestion control method to alleviate congestion. In [88], the authors presented an accurate feature extraction method to compress the healthcare signals to reduced congestion. Compression data can reduce data rate. For this purpose a method based on multi-scale wavelet analysis is presented.

In Table 2.4, we compare and summarize the above-explained congestion control protocols for WSNs and WBANs based on QoS constrains. The table clearly shows that the existing
developed protocols have not sufficiently improved the performance of the networks. Therefore, we felt that there is a need to further explore the congestion algorithms that can be designed to satisfy the three important QoS constraints in both homogeneous and heterogeneous environments.

Table 2.4. List of Congestion Control Algorithms in Selected QoS Metrics

<table>
<thead>
<tr>
<th>Proposed Method</th>
<th>Method Type</th>
<th>QoS Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODA [77]</td>
<td>Centralized</td>
<td>×</td>
</tr>
<tr>
<td>CCF [78]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>ESRT [79]</td>
<td>Centralized</td>
<td>×</td>
</tr>
<tr>
<td>PCCP [80]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>QCCP-PS [81]</td>
<td>Distributed</td>
<td>×</td>
</tr>
<tr>
<td>ECODA [87]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>FACC [89]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>LACAS [86]</td>
<td>Distributed</td>
<td>×</td>
</tr>
<tr>
<td>Fusion [82]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>Siphon [84]</td>
<td>Distributed</td>
<td>×</td>
</tr>
<tr>
<td>HOCA [23]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>Samiullah et al. [85]</td>
<td>Distributed</td>
<td>✓</td>
</tr>
<tr>
<td>LACCP [27]</td>
<td>Centralized</td>
<td>✓</td>
</tr>
<tr>
<td>Hu et al. [88]</td>
<td>Distributed</td>
<td>×</td>
</tr>
</tbody>
</table>

2.9. Chapter Summary

This chapter presented an overview of WBANs and related challenges. Firstly, WBANs were introduced by giving a brief comparison of WBANs and WSNs. Following this section, we discussed about WBAN different applications. After that, performance requirements of WBANs were discussed. Next, this chapter presented WBAN
communication model and also highlighted the network topologies. Then after, the problem of congestion was introduced as the main contribution of this thesis. We focused more on the existing approaches that have been developed with the purpose of enhancing QoS. The literature showed that even though several works has already been done in the area of congestion control in WSNs, but this issue has not been fully addressed in WBAN applications.
Chapter 3

SENSOR-CLOUD FRAMEWORK FOR REMOTE HEALTHCARE MONITORING

Due to recent technological advances in wireless communications and low-power sensor devices, wireless body area networks (WBANs) are becoming increasingly popular in pervasive healthcare monitoring. However, continuous collecting of patients’ physiological signs will result in large amounts of monitored data that require a scalable architecture for storage and analysis. This fact motivates the integration of WBANs with Cloud technology to manage and store humongous data effectively. In this chapter, we propose a Cloud-based WBAN framework for real-time health monitoring of patients. The significance of the proposed framework is the use of mobile technology and Cloud computing to provide services for ill and elderly people in their independent lives. This study describes the general
design of the proposed approach as well as a case study for the real-time monitoring and analysis process of Electromyography (EMG) healthcare system.

3.1. Introduction

Thanks to recent medical device improvements, hospitals are now able to remotely collect patient data from bedside monitoring devices. The remote collection and analysis of medical data has provided many opportunities for clinicians and researchers. Data collected from patients provide the ability to extrapolate observations based on populous and historical data. Recently, WBANs is becoming a promising technology in the field of ubiquitous and remote healthcare monitoring. A WBAN has the capability to collect patients’ vital data as well as establish a communication link to send the collected information to a medical centre.

However, the appropriate resource management of large amounts of monitored data is a critical issue in remote electronic healthcare systems [52]. In addition, there are several constraints related to using WBANs such as limited memory, power supply and communication capabilities [30]. In order to store and process data in a real-time manner, WBANs require a powerful and scalable computing resources and storage capabilities. Cloud technology can be a powerful tool to resolve the mentioned challenges. Using of Cloud computing will reduce the cost of service and also increase the utilization of the system [90]. In addition, doctors and medical staff can access to patients information in a real-time and secure manner [91].
The motivation for our work comes from the fact that although there have been several works to automate existing healthcare systems, these solutions still have technical challenges and remain insufficient [52, 92, 93]. Unfortunately, the provided solutions are incapable of providing a robust underlying platform that is highly available, expandable and secure [68, 90, 93-95]. They also slightly make use of varying Cloud services to benefit from Cloud capabilities.

In this chapter, we present a reliable and self-configurable system architecture that integrates WBAN with Cloud computing technology for use in critical care. The proposed framework supports the storage and analysis of vital data using variety services that hosted in the Cloud subsystem. It also enables large-scale data sharing services among end-users via mobile technology. We will also describe a case study based on our system architecture for people who suffer from neuropathy disorders. To evaluate the usability of our framework subsystems, functionality of each component is also explained in details.

3.2. Technical and Architectural Requirements

Dealing with private health data needs to consider several technical requirements and challenges. In the following paragraphs, we list WBAN related challenges in designing a remote Cloud-based healthcare framework:

- **Security:** security of patients’ health information is a highly critical subject in electronic biomedical systems [96]. Therefore, powerful security mechanisms are needed to provide a secure and reliable environment to communicate and share vital
data. As Table 3.1 shows, there are several security solutions that can protect sensitive data in different scenarios [97-99].

- **Reliability**: another key requirement of healthcare applications is reliability. As investigated in [100], the reliability related issues are categorised into three main classes: reliable data collecting, reliable data communication and reliable data analysis. Reliable data collection and communication need be insured through WBAN layers. The reliably of data analysis belongs to the application layer that can be a Cloud subsystem or any other used infrastructure.

- **Interoperability**: One of the required factors in WBANs is to ensure seamless data transfer to promote information exchange and uninterrupted connectivity.

- **Heterogeneity**: WBANs should be capable of integrating different sensors in terms of complexity, power efficiency, storage, and ease-of-use. Furthermore, it should provide a common interface between the sensors and a storage service to facilitate remote storage and viewing of sensed data.

- **Data validation and consistency**: data from several sensor nodes need to be collected and then need to be analysed in a seamless manner. Wireless sensors are in risks of communication, hardware and network failures that can result in flaw information. It is vital that the collected data is authenticated and data quality is kept to reduce any error in the data and identify possible weakness in the infrastructure.

- **Interference reduction**: WBANs typically uses wireless connectivity for data transmission. Therefore, it is needed to reduce interference and increase the co-existence of sensor nodes with other networked devices. This is an important factor
to make sure that the functionalities of WBAN nodes are not affected due to the presence of other devices capable of possible disruption in seamless data transmission.

Table 3.1. Security issues in healthcare application and possible solutions [97]

<table>
<thead>
<tr>
<th>Security threats</th>
<th>Security requirement</th>
<th>Possible security solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unauthorised access</td>
<td>Key establishment and trust setup</td>
<td>Random key distribution, Public key cryptography</td>
</tr>
<tr>
<td>Message disclosure</td>
<td>Confidentiality and privacy</td>
<td>Link/network layer encryption, Access control</td>
</tr>
<tr>
<td>Message modification</td>
<td>Integrity and authenticity</td>
<td>Keyed secure hash function, Digital signature</td>
</tr>
<tr>
<td>Denial of Service (DoS)</td>
<td>Availability</td>
<td>Intrusion detection, Redundancy</td>
</tr>
<tr>
<td>Node capture</td>
<td>Resilience to node compromise</td>
<td>Inconsistency detection and node revocation, Tamper-proofing</td>
</tr>
<tr>
<td>Routing attacks</td>
<td>Secure routing</td>
<td>Secure routing protocols</td>
</tr>
<tr>
<td>High level security attacks</td>
<td>Secure group management, intrusion detection, secure data aggregation</td>
<td>Secure group communication, Intrusion detection</td>
</tr>
</tbody>
</table>

3.3. Proposed Framework

The main requirement of a remote healthcare system is to provide a secure, reliable and self-configurable service result in easier life for patients. In addition, the speed of data collection, storage and retrieving the saved information are critical factors of the system’s performance. In case of an abnormal condition, the system needs to provide monitoring facilities for users in the smallest possible time. Let \( S = \{s_1, ..., s_n\} \) represents the wireless sensor nodes attached or implanted based on the monitoring purpose on a patient body. In the proposed framework, a patient can be defined by a three-tuple \( \{P_{id_m}, S_1, D_j\} \) where \( P_{id_m} \) refers to the identification number of the m patients, \( S_1 \) symbolizes the sensors’ ID and \( D_j \) is...
the associated doctor or medical staff. From a healthcare parameter point of view, a symptom can be represented by a three-tuple \( (\tau_k, \mu, \gamma) \) where \( \tau_k \) is the symptom ID and \( \mu \) and \( \gamma \) are the minimum and maximum tolerable values that already assigned for that specific health parameter. For example, to monitor body temperature, \( \mu \) and \( \gamma \) are assigned as 36.8° and 37.8° respectively. As a result, if a patient temperature falls out of this range, the system can detect an abnormal situation.

Table 3.2. Notations

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Set of deployed sensor nodes</td>
</tr>
<tr>
<td>( P_{idm} )</td>
<td>Unique Id number of patients in the system</td>
</tr>
<tr>
<td>( D_j )</td>
<td>Associated medical staff</td>
</tr>
<tr>
<td>( \tau_k )</td>
<td>Unique Id number of healthcare parameters</td>
</tr>
<tr>
<td>( \mu, \gamma )</td>
<td>Minimum and maximum tolerated values related to each application</td>
</tr>
<tr>
<td>( T_R )</td>
<td>Monitoring period from startTime to time ( t_H )</td>
</tr>
<tr>
<td>R</td>
<td>Risk or impact of a disease in case of the late monitoring service</td>
</tr>
</tbody>
</table>

In this chapter, it is assumed that each sensor can only measure one unique health parameter. Consequently, \( \{S_k(S_i, \tau_k) | 0 < i < k\} \) denotes sensor \( S_i \) can only measure physical sign \( \tau_k \). Table 3.2 presents the notations used in this chapter. The main objectives of the proposed health monitoring framework can be described as:

\[
\text{Minimize } T_R \{ \cup \{P_{idj} (1 < j \leq m)\} \} \tag{3.1}
\]

\[ \forall P_{idj} \mid \text{if monitored value } \leq \mu \text{ OR } \geq \gamma \rightarrow \text{Emergency status} \tag{3.2} \]

\[ \exists t_R \mid t_R < t_H \text{ AND } t_R \rightarrow R \tag{3.3} \]
The objective of Eq. 3.1 is to minimize $T_R$ which is the responding time of the system in which a disease or risk (impact of particular abnormal condition) is detected. Constraint (3.2) states that any monitored value which is placed out of acceptable tolerated values will be considered as an abnormal situation. In this case, patients may need emergency services based on the type of monitoring. If the abnormal condition is not detected in an appropriate time, the risk ($R$) could be considerably high. The objective of Eq. 3.3 is to define the shortest time $t_H$ in which there is no $t^R$ that can detect the risk ($R$) and $t^R$ is beyond $t^H$.

In fact, the monitoring period should be from $\text{startTime} \rightarrow t^H$ where at $t^H$ patients need healthcare services.

3.3.1. Framework Description

The main goal of our proposed framework is to automate patients monitoring process by means of a set of body sensors and a Cloud medical centre. The proposed system monitors health status of patients and forwards collected data via a smart phone to Cloud for further computational process and storage. Cloud technology provides this opportunity to adjust the system’s tasks and performance based on the users’ needs. Figure 3.1 shows the general architecture of the proposed framework. Specifically, the framework is composed of three subsystems which provide real-time monitoring of patients. In following paragraphs, the key components of the proposed framework are explained:

1) **WBAN module**: The first module of the framework is based on Intra-BAN communication model which has been already explained in Chapter 2. This module is the
lowest layer of a healthcare monitoring system composed of two main procedures described in following:

I. Data collection phase: In this phase, a patient’s vital signs such as blood pressure, blood glucose or temperature are monitored using body sensor nodes. There are adequate sensor nodes such as ECG (ElectroCardioGraphy), EMG (ElectroMyoGraphy), motion sensor, temperature sensor, etc. These sensor devices are able to sense, process and transmit health data [101].

![Figure 3.1. Cloud-based architecture for remote healthcare monitoring](image)

II. Transmission phase: In this phase, the collected data will be transferred to a PDA or a cellular phone via wireless communication. PDA is responsible to receive data from sensors and then forward it to a Cloud centre for monitoring and storage. It also sends control messages to sensors to make sure about their correct functioning. There are several transportation protocols available for WBANs such as Bluetooth over IEEE 802.15.1, Zigbee over IEEE 802.15.4, UWB over IEEE 802.15.6, and
radio frequency identification (RFID). However, based on study in [102], communication protocols such as Bluetooth and Wi-Fi are not enough energy efficient to use in WBANs. Normally, after one to two weeks, an integrated small battery will be run out of energy over using Bluetooth. To solve this problem, the IEEE 802.15.4 standard was specifically designed to support low power and energy usage for WBANs [103].

2) **Cloud-based module:** The Cloud subsystem allows patients to submit their personal and medical information through WBAN gateway. The medical records are accessible by doctors, administrators and patients from a client-server web service at any time. Authentication is needed for each time accessing Cloud. This module provides the three types of Cloud services namely SaaS, PaaS and IaaS. SaaS service offers various applications that are necessary for working with health data. The PaaS includes tools such as Operating System (OS), Database Management System (DBMS) and virtualisation as well as servers, storage and networking. Lastly, IaaS provides the physical infrastructure needed for fundamental computing resources in a heterogeneous healthcare system. Cloud service also provides a platform for development, testing and execution of software needed by both patients and medical staff. In addition, one of the crucial factors in this module is that the information needs to be delivered on-time, accurate and reliable. This is only accessible when end to end latency is low and packet delivery rate is high. These performance parameters will be studied in the next chapter. At this level of concept, there is no need to exactly state what is the logical or physical design of the Cloud module. It suits to say that the Cloud provides the standard interfaces for application integration.
3) **End-user module (Monitoring phase):** This module offers patients with intelligent monitoring services in a real-time manner. It consists of a variety of applications that are used for analysing health information. This module also can have a terminal in emergency centres, medical centres or family members of patients in case they need to connect to the system. End-users can subscribe to the service to become updated automatically about the latest transferred medical data.

Collecting and then processing the data are performed based on the monitoring type. Specifically, three types of monitoring schemes are proposed for this framework: continuous, on-request and periodic. Continuous monitoring performs when an intensive monitoring is needed for patients. In this case, sensors continuously collect vital data and send them for further analysis. The on-request monitoring process is started based on a request from any authorised person in the system such as patients, doctors or nurses. Finally, monitoring process can be established based on a periodic pattern. This is usually based on a defined starts and ends time from the controller of the system.

The described three modules are the main constituents of our framework. There are several advantages in the proposed framework such as eliminating manual data collection, simplifying the set up process and also speeding the monitoring process as patients’ health condition can be under control even when they are at home. In addition, Cloud services has the responsibility to organise and distribute the data, As a result, it facilitates indexing and makes data available for system users.
3.3.2. Framework Design Flow and Algorithm

Figure 3.2 depicts the design flow of our proposed framework. The monitoring process can be initiated by any authorised person such as patients, caregivers, etc. At the first step, system checks users’ authentication to provide them with a permission to enter the service. Patients’ information can be indexed based on the identification number or any other unique identity such as DNA sample. Next, the system needs to setup configurations such as entering patients’ detail, associated doctors or nurses as well as type of monitoring application and where the patient is located. The required information about each type of health application already exists in the Cloud. After logging to the system, type of monitoring service needs to be selected. As mentioned earlier, in order to increase the network performance, three types of monitoring service have been defined. In case of on-request service, both patients and medical staff can subscribe to the system to initiate the process. As shown in the flowchart, if flag status is set to 1, there has been an available request to start the service. Otherwise, there is no available request from the end-users. This type of service is especially designed for situations when patients’ conditions are considered as normal, although they still need to be under monitoring service. The advantage of this service model is less network traffic and power consumption due to on and off request facility. In the periodic mode, monitoring service will be performed based on a pre-defined period of times. The main feature of this model is that the system can switch to the sleep mode to save power supply. At the sleep state, communication links and several functions of the system will be switched off. Lastly, continues mode is designed for situations when patients need highly critical care. Although this service model may result in higher network
traffic and battery consumption, it needs to be available for patients with undesirable conditions.
After configuration set up, sensors start gathering information and forwarding the data to the base station. The base station in this application is a PDA or cellular phone with the capability of receiving data and then analysing and distributing to the next module. Based on the propose framework, most of the computing calculations and decision makings occur in the Cloud module. For example, one of the defined analysing patterns for the Cloud module can be based on the comparison of a monitored healthcare parameter and its defined maximum and minimum values. If monitored value placed in the pre-defined range, the health status is normal. Otherwise, health condition can be considered as a warning or emergency situation. The system can automatically diagnose the health status based on the discrepancy between the monitored value and the minimum and maximum defined value of the healthcare parameter. If discrepancy is too high based on the historic and pre-defined data of patients, situation can be considered as emergency. As emergency centres and ambulances are already established a communication link, system can automatically subscribe to them to get service. For patients at home, real-time location can be obtained by Time Difference of Arrival Time (TDAT) method. In outdoor and hospital environments, using Global Positioning System (GPS) and Geographic Information System (GIS) will help to obtain patients’ location quickly. Back to the service models, if discrepancy is out of the acceptable range gently, situation can be considered as warning. In this case, based on caregivers’ prescription, patients need a medical visit. In addition to the provided services, it is possible to install high speed cameras in a patient location to access to the video
streaming and other multimedia facilities. At the end of the process, medical information can be saved in the Cloud centre for future services.

The proposed framework process for m patients can be formally specified as following:

Algorithm 1: Monitoring process algorithm

```
INPUT: \( S \) // \( S = \{S_1, S_2, \ldots, S_n\} \) -- Set of attached body sensor
INPUT: \( \mathcal{L} \) // \( \mathcal{L} = \{P_{id}, S_i, D_j | S_i \in S, 1 \leq i \leq n\} \) -- Set of monitored patient
INPUT: \( \eta_c \) // \( \eta_c = \{\text{“Continuous”, “On-request”, “periodically”}\} \) -- Monitoring schemes
INPUT: \( \nu_s \) // \( \nu_s = \{\tau_k, \mu, J\} \) -- Vital sign parameters
INPUT: flag // flag = \{0,1\} -- Request for service
OUTPUT: Healthcare service based on he condition of the patient

BEGIN
1: WHILE (TRUE) DO
2: Login to the Cloud service
3: For \( i \leftarrow 1 \) to m DO
4: IF ( \( \eta_c = \text{“Continuous”} \)) THEN
5: Start reading from sensor \( S_i \)
6: IF ( \( \mu < \text{collected symptom} < J \)) THEN
7: PRINT (\{“Normal status”\})
8: ELSE
9: IF (discrepancy between collected and tolerated value is high) THEN
10: PRINT (“Emergency status”)
11: Inform practitioner or emergency center
12: Obtain patient’s location by GPS or GIS
13: ELSE
14: PRINT (“Warning status”)
15: Patient’s condition need to be monitored
16: ENDIF
17: ENDIF
18: ELSE
19: IF ( \( \eta_c = \text{“Periodically”} \&\& (\text{actualTime} < \text{periodTime}) \)) THEN
20: For \( t \leftarrow 1 \) to specified wait time DO
21: Go to 5
22: ELSE
23: IF ( \( \eta_c = \text{“On-request”} \&\& (\text{flag}=0) \)) THEN
24: Go to Sleep mode
25: ELSE
26: flag \( \leftarrow 0 \)
27: Go to 5
28: ENDIF
29: ENDIF
30: ENDIF
31: If requested, saved monitoring history in the Cloud storage
32: ENDWHILE
END
```
3.4. Case Study: an Electromyography (EMG) Process Analysis

In this section, we illustrate the applicability of our proposed framework in real scenarios. The main objective is to prove the usefulness of the main components of the framework where patients need to be remotely monitored. For this purpose, we study a case study for patients who suffer from Myopathy or Neuropathy diseases. Generally, muscles disorders occur occasionally. Therefore, patients need a continuous monitoring and online analysis system to identify abnormalities. In this case, using a remote healthcare monitoring system can help patients to continue to their normal lives while being under monitoring. The proposed WBAN Cloud-based framework can be used in different medical scenarios to detect muscles disorders in a continuous and efficient manner.

Electromyography (EMG) is an electro diagnostic test to evaluate functioning of muscles and their cooperated nerves [104]. EMG technique aids to diagnose disorders such as muscular neuropathy and myopathy [105]. EMG waveform is the electrical display of the muscles activations. Figure 3.3 shows a high level view of the case study described in this chapter. The overall functionality of the proposed framework for an EMG monitoring process is explained as following:
I. In the case, wireless EMG sensors are attached to a patient body as well as a PDA or a smart phone that is capable of transferring information through the Internet according to the patient’s location (e.g., home, hospital, or out-door environment).

II. Patients need to create their profile once they subscribe to the system. The create profile task presents a user interface that allows patients to submit their personal details. The task named store data is responsible for storing the patient details in a cloud based storage repository indexed by patient ID. Patients may choose to observe and analyse their data every hour, after every meal or some fixed time intervals during a day. In addition, type of monitoring service (continuous, on-request ad periodically) need to be selected by end users such as patients or caregivers.

III. The wireless EMG sensor module collects patient’s data and forwards it to the mobile device via Bluetooth without user intervention; whenever patients or doctors subscribe to the system. An EMG signal is very small and to be amplified by means of an amplifier to be visible on a display. Frequently more than one amplification stages are needed, since before the signal could be displayed or recorded, it must be processed to eliminate low or high frequency noise, or any other factors that may affect the outcome of the data.
IV. The collected data then will be transmitted to the EMG web service analysis by means of a client software in the PDA. The software is usually hosted by Cloud software stack. The communication is performed via a home network connection or directly via the PDA’s data connectivity.

V. The analysis of the patient data is accomplished by an analyse task. The analysis process involves several computations on stored data that primarily consist of data pre-processing, attribute selection and classification. The analysis task carries out numerous computations over the received data using the existing demographic data and the patient’s historic data. Computations concern comparison, classification and systematic diagnosis of muscles activations can be time-consuming in long time periods for large number of users.

VI. Once the analysis process is completed, then the information can then be relayed wirelessly to doctors, paramedics and patient’s mobile devices for final validation and clinical diagnosis. Doctors will then analyse the information extracted from the EMG graphs, and choose whether the waveforms belong to a normal condition or to a type of muscles disorders.

VII. Patients’ medical histories are maintained by the management centre of the local private and secure Cloud. Based on the user’s configuration, practitioners or emergency centres can access the stored information if needed. Furthermore, relatives of the users can be notified about any unregular situations via automated notification messages. In addition to the discussed services, Cloud also provide virtual resource optimization management, Mobile Device Management (MDM) and Genesis Integration Server
(GIS) deployment. The use of Cloud computing also provides the ability of transferring high quality video streaming from remote cameras in users’ location.

VIII. The analysis results are then sent to the patient’s PDA and also their assigned doctor. Because of Cloud service support and the improved communication bandwidth, doctors or other caregivers can communicate with patients directly by mobile devices in the form of medical video streaming. If needed, the patient can then be asked to visit a healthcare facility.

IX. The monitoring and computing processes are repeated according to the patient’s preference options such as hourly, daily or even longer during a predefine period of time.

The described functionalities are the task classes for the integrated components of the system. Figure 3.4 also depicts a general EMG process analysis based on the previous explorations by several medical research groups [105-107].
The process can be integrated into the SaaS layer of the Cloud system to analyse the data inputs. The application process will be initiated by sending request command either with patient’s intervention or without it as a regular basis. At the first stage, by putting electrodes on the skin surface, EMG raw data are generated as numerical reading of the received signal. Then, it goes through the amplification process to increase the magnitude of the EMG signal. The next task is the rectification of the raw EMG signal to a signal polarity frequency [107]. As the raw EMG signal have both positive and negative components, rectification helps to ensure the raw signal is not zero in overall. The motor units action potential trains (MUAPTs) is the procedure in which an EMG signal is separated into its constituent. In
medical environments, studying features of MUAP waveform helps to making diagnosis of neuromuscular diseases. Other user commands such as comparison and retrieve historic graph give extra functioning options to the users. For example practitioners can compare all available EMG data of patients or retrieve the previous EMG calculated graphs from the Cloud storage. After displaying a signal graph, then the results will be stored in a Cloud storage centre. Figure 3.5 shows two examples of the EMG graph output. The output graphs can help to the practitioners to be aware about the patient’s status remotely.

![Graphs showing results of EMG data](image)

Figure 3.5. Graphs showing results of EMG data (a) EMG data graph of a healthy patient (b) EMG data graph of a Myopathy patient

### 3.5. Chapter Summary

WBAN has recently enabled remote monitoring of patients health status in a broad range of applications. They have the capability to monitor a large group of users and consequently gathering huge amounts of related data. This scenario requires a scalable architecture for data collection, storage, processing and analysis. Integration of Cloud technology into WBANs can create a scalable and flexible infrastructure to provide online and offline storage and analysis of contextual data. In this chapter, we proposed a Cloud-enabled architecture for the collection and management of body sensor data. In this
framework, each patient is equipped with a set of wearable or implanted wireless sensors. The sensors collect various health physiological signs and forward the data to an assigned smartphone or PDA. The initial processing is performed by mobile applications and later on the collected information will be relayed on Cloud subsystem for model evaluation. We also discussed the complete life cycle of data analysis workflows which include data collection, storing, analysis, and presentation. As a case study, we demonstrated an EMG remote monitoring application with the help of proposed framework. In the proposed approach, patients can view their health records and prescriptions on their mobile phones on a continuous, periodic and on-request basis. As it has been discussed, one of the main issues in the proposed sensor-Cloud architecture is how to control high traffic load or congestion. This problem has been investigated in the next chapter.
A CONGESTION DETECTION AND CONTROL APPROACH IN WBANs

One of the major challenges in healthcare WBAN applications is to control congestion. Unpredictable traffic load, many-to-one communication nature and limited bandwidth occupancy are among major reasons that can cause congestion in such networks. Congestion has negative impacts on the overall network performance such as packet losses, increasing end-to-end delay and wasting energy consumption due to a large number of data retransmissions. In life-critical applications, any delay in transmitting vital signals may lead to death of a patient. Therefore, to enhance the network quality of service (QoS), developing a solution for congestion estimation and control is imperative. In this chapter, we propose a new congestion detection and control protocol for remote monitoring of patients health status using WBANs. The proposed system is able to detect congestion by considering local information such as buffer capacity and node rate. In case of congestion, the proposed
system differentiates between vital signals and assigns priorities to them based on their level of importance. As a result, the proposed approach provides a better quality of service for transmitting highly important vital signs.

4.1. Introduction

In general, congestion means excessive loads in a network. In healthcare applications, different biosensors with different bandwidth allocation requirements send vital data simultaneously. Thus, it is likely that congestion occurs in such applications especially in case of emergency situations.

If congestion occurs at a single node, this can result in degradation of the overall network performance. Congestion can also highly result in impairments in the QoS of healthcare applications. In life-critical applications involving large numbers of patients, congestion is extremely undesirable and may lead to death of a patient. Therefore, design a protocol that can properly address the problem of congestion with respect to the QoS requirements is crucial. Evidently, it is not possible to completely eliminate congestion for any type of network. However, it is possible to control congestion to minimize its consequences such as packet losses and excessive energy consumption.

In most of the existing congestion control approaches [78, 82, 108, 109], data rate is reduced immediately after detecting congestion. However, in healthcare applications, it is not desirable to decrease the sending rate of sensitive traffic streams straightaway. In addition, since the existing congestion control protocols for WSNs do not consider the special nature of the signals carried in a WBAN, they cannot be directly applied in WBANs. For instance,
delay is a critical parameter in healthcare applications where life-critical information needs
to be received on-time. Thus, this is crucial to consider delay more than any other factor in
the proposed scheme. Furthermore, in healthcare WBAN applications we may have
different types of data flows with different priorities. Therefore, it is very important to be
able to differentiate patient vital signs in case of congestion. In this case, prioritization of
health data makes it possible to route the most critical data first. Therefore, a new congestion
control mechanism for healthcare WBAN applications with respect to the related special
features is required to be developed.

Congestion detection and control approach is generally performed in three separate steps:
congestion detection, rate adjustment and congestion notification. In this chapter, we
provide an in-depth study about each step and propose an alternative congestion detection
and control protocol. The proposed protocol benefits from the use of a Type-2 Fuzzy Logic
System (T2-FLS) to detect congestion. If the fuzzy output shows that there is congestion in
the network, then the proposed approach differentiates patients’ physiological signals based
on their level of importance. Then, it will adequately adjust the transmission rate and control
congestion effectively.

4.2. Problem Description

In order to deal with the congestion problem in healthcare applications, we need to
focus on many-to-one communication model. Many-to-one communication is referred to a
situation when several sensor nodes send information to a single sink at a same time. In
most of WBAN scenarios, a PDA or smart phone acts as a single sink node and collected
data are transferred through this node. In this case, congestion is likely to happen especially around the sink node.

Basically, two types of congestion can occur in WBANs [86], namely, node-level congestion and link-level congestion. Node-level congestion can be caused due to buffer overflow in a particular node. In most of the node-level congestion situations, packet arrival rate is higher than packet service rate which occurs mostly in nodes closer to sinks. Link-level congestion is referred to a situation when wireless channels are shared by more than a few nodes and since sensors compete for the available channels at the same time, congestion is likely to happen. Both types of congestion have direct impact on QoS of WBANs. Figure 4.1 shows a general view of two types of congestion in sensor networks.

![Figure 4.1. A high level scheme of node-level and link-level congestion](image)

So far, several communication protocols have been proposed for traditional WSNs [53, 110, 111]. However, they are not well adapted to the specific features and application requirements of WBANs. For instance, Bluetooth protocol based on IEEE 802.15.1 provides nearly 1 Mbps data rate [112]. This level of data transmission consumes a high amount of power resources which makes this protocol unsuitable to be applied in WBANs.
The Ultra Wide Band (UWB) is another communication protocol which consumes less power consumption compared to the Bluetooth. However, this protocol also cannot be applied in WBANs since it has considerable data packet losses particularly for inside body data transmission [113]. Due to the mentioned shortcomings of WSN protocols, a new standard known as IEEE 802.15.6 [114] developed for WBANs. The main objective of the proposed standard is a low power, low cost and well adapted transmission protocol for on and inside a human body. Nowadays, this standard is widely used in implementing low transmission networks such as WBANs. However, this standard can also have a direct impact on causing congestion due to its low transmission rate.

Due to the diversity of WBAN applications, data transmission rates can highly vary from kbit/s to Mbit/s. Table 4.1 shows data rates of the most popular WBAN applications [5, 39, 49, 115, 116]. The highest data rate that can be sent over a given bandwidth is determined by two main factors, bandwidth and the signal-to-noise ratio. The relationship is given by the Shannon formula [50]:

\[
C = B \times \log(1 + \text{SNR})
\]  

(4.1)

where \( C \) is the maximum bit rate, \( B \) is the channel bandwidth, \( \text{SNR} \) is the power signal-to-noise ratio, and the log is to base 2.

The reliability of data transmission is defined by Bit Error Rate (BER). This value is used as a measure for the packet loss rate in WBAN applications. As shown in Eq. 4.2, BER is mainly depends on the application data rate [5].

\[
\text{BER} = \frac{\text{Number of errors}}{\text{total number of bits sent}}
\]  

(4.2)
Overall, the data rates are not very high in WBANs. However, in case of using several types of body sensor nodes such as ECG, EMG or glucose monitoring together, data rates will easily reach over few Mbps. In addition, in case of an emergency situation, irregular data stream rate will also cause burst traffic in the network. In this situation, as most of the current existing low power radios [117] used in WBANs are not able to pass such transmission rate, congestion may occur.

<table>
<thead>
<tr>
<th>Application</th>
<th>Data Rate</th>
<th>Bandwidth (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>72 kbps</td>
<td>100-500</td>
</tr>
<tr>
<td>EMG</td>
<td>320 kbps</td>
<td>0-10,000</td>
</tr>
<tr>
<td>EEG</td>
<td>43.2 kbps</td>
<td>0-150</td>
</tr>
<tr>
<td>Hearing</td>
<td>200 kbps</td>
<td>-----</td>
</tr>
<tr>
<td>Glucose</td>
<td>1600 kbps</td>
<td>0-50</td>
</tr>
<tr>
<td>Audio</td>
<td>1 Mbps</td>
<td>-----</td>
</tr>
<tr>
<td>Temperature</td>
<td>120 kbps</td>
<td>0-1</td>
</tr>
<tr>
<td>Motion</td>
<td>35 kbps</td>
<td>0-500</td>
</tr>
<tr>
<td>Blood saturation</td>
<td>16 kbps</td>
<td>0-1</td>
</tr>
<tr>
<td>Cochlear implant</td>
<td>100 kbps</td>
<td>-----</td>
</tr>
<tr>
<td>Artificial retina</td>
<td>50-700 kbps</td>
<td>-----</td>
</tr>
<tr>
<td>Voice</td>
<td>50-100 kbps</td>
<td>-----</td>
</tr>
<tr>
<td>Video</td>
<td>&lt;10 Mbps</td>
<td>-----</td>
</tr>
</tbody>
</table>

4.2.1. Problem Formulation

Assume that there are set of $S = \{s_1, s_2, \ldots, s_k\}$ sensor nodes that are deployed on a human body. These sensor nodes are collecting and routing data packets through a PDA or a smart phone. We formulate the addressed congestion control problem as follow:

Maximize $T_c$ \hspace{1cm} (4.3)

\[ Cl(s_j) \leq Cl_{\text{max}} \] \hspace{1cm} (4.4)
\[ n(s_j) < \beta_{s_j} \quad (4.5) \]

\[
\text{IF } P_{s_i} > P_{s_j} \text{ THEN } D_{s_i} < D_{s_j} \quad (4.6)
\]

In Eq. 4.3, the objective is to maximize the network throughput subject to maintaining or enhancing QoS in a WBAN. Constraint (4.4) ensures that the congestion level in each node is satisfied by a user-defined threshold. Constraints (4.5) presents that the amount of received data packets must be less than its available buffer capacity. Constraint (4.6) ensures that a node with higher priority should have less delay in routing its data to a destination.

The main purpose of this research is to develop a congestion control scheme that solves the above formulated problem. Table 4.2 lists some of the notations used in the problem formulation.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_{s_i} )</td>
<td>Available buffer in a node</td>
</tr>
<tr>
<td>( \mathcal{C}l(s_j) )</td>
<td>Congestion level for node ( s_j )</td>
</tr>
<tr>
<td>( n(s_j) )</td>
<td>Number of data packets that are transferred to ( s_j )</td>
</tr>
<tr>
<td>( D_{s_i} )</td>
<td>Delay of receiving data from node ( s_i )</td>
</tr>
<tr>
<td>( P_{s_i} )</td>
<td>Priority of node ( s_i )</td>
</tr>
<tr>
<td>( T_c )</td>
<td>Overall network throughput</td>
</tr>
</tbody>
</table>

### 4.3. Congestion Detection and Control Approach

Congestion control algorithms are classified into source-based or network-based methods [118]. Source-based algorithms are deployed at end-hosts where transportation protocols are responsible to detect congestion. Network-based algorithms, on the other hand, are implemented at intermediate nodes, especially routers. Based on the degree of
congestion detected in the network, source-based algorithms adapt the rate at which the application is sending traffic. This mechanism is popularly known as end-to-end congestion control. In network-based algorithms, intermediate network equipment are responsible for detecting oncoming as well as subsisting congestion and provide feedback to senders for indicating the situation.

Our proposed protocol can be classified as network-based algorithms as it detects and controls congestion in the intermediate nodes. Figure 4.2 shows the general architecture of the proposed congestion detection and control system.

![Figure 4.2. The structure of proposed protocol](image)

Similar to the other approaches, the proposed system consists of three subsystems, namely, congestion detection unit (CDU), congestion notification unit (CNU), and rate adjustment unit (RAU). The CDU measures data rates and buffer capacity of the intermediate nodes to
determine the congestion level. If congestion is detected, the transportion protocol broadcasts congestion information from the specious node to the other upstream and source nodes. Congestion notification unit takes advantage of implicit piggyback technique to avoid causing extra data traffic and also decreasing energy consumption. Once a node is notified about the congestion, it should adjust its transmission rate accordingly. The RAU then calculates the new rate for each upstream node based on the current congestion level and node priority. The detailed description about each subsystem is presented in the following sections.

4.3.1. Congestion Detection Unit (CDU)

Congestion detection method is an important part of designing an accurate and efficient congestion management protocol. In this unit, irregularities of traffic patterns are detected. Congestion detection mechanisms can be further categorized into local and global methods [119]. Local congestion detection is performed at intermediate nodes by considering node features such as buffer capacity or congestion index. Global congestion detection, on the other hand, is performed around sink nodes where features such as inter packet arrival time and packet loss rate are used to detect congestion. As congestion is detected in the early stages at the local detection model, it is preferred over the global type. For the same reason, we setup congestion detection unit at intermediate nodes instead of sink. For this purpose, we developed a type-2 fuzzy logic system (T2-FLS) for our system. To the best of our knowledge, this is the first congestion detection approach that uses T2-FLS in WBANs. The main reason that we used T2-FLS is that the type-2 fuzzy sets generalize type-1 fuzzy sets. A type-2 fuzzy set allows us to incorporate uncertainty about
the membership functions (MFs) into fuzzy set theory. Sensor nodes manufacturers are aiming to produce the most accurate wireless sensor nodes to uniformly and consistently collect and process data. However, the reality is that the produced sensors are never ideal as they carry uncertainty in their measurements. Therefore, users never can be 100% sure about the created measured values [120]. In fact, any individual measurement, $x$, is expected to be presented a bit different to the true value, $x'$. That is due to the existed uncertainties that cause errors in the measuring process. The error is calculated by Eq. 4.7.

$$\phi = x' - x$$  \hspace{1cm} (4.7)

It is not important how an event (e.g. temperature) is measured by a sensor or how close the measurement is to the true value, never can it be sure that it is accurate. For example the uncertainty in measured temperature of a human could be up to $\phi = 0.068$ [115].

To overcome the problem, it has been proven that an interval type-2 (IT2) FLS significantly improves robustness to measurement noise and background traffic volatility compared to a classical T1-FLS. Indeed, IT2 FLS method is a solution to build in a response to unforeseen network conditions. That is because the uncertainty in the boundaries of its MFs provide the scope for an additional flexibility in the controller’s response compared with the crisp boundaries of the MFs of T1 controllers [121].

The fuzzy logic controller is composed of four main components: fuzzification interface, rule base, inference mechanism, and defuzzification interface [122]. The fuzzifier plots each crisp input value to the corresponding fuzzy sets. The fuzzified values are then processed by the inference scheme. Interference mechanism consists of a rule base and various methods for inferring the rules. The rule base is a series of IF-THEN rules that relate the...
input fuzzy variables with the output fuzzy variables using linguistic variables. Fuzzy inference scheme process all the defined rules in a parallel manner. The inference rules govern the manner in which the consequent fuzzy sets are copied to the final fuzzy solution space. The defuzzifier performs defuzzification task on the fuzzy solution space. As a result, a single crisp output value from the solution fuzzy space is obtained.

The main objective of our fuzzy system is to detect the congestion level of each sensor node based on the fuzzy output. Figure 4.3 shows the proposed FLC in a sensor node.

![Figure 4.3. Proposed FLC](image)

Our developed T2-FLS estimates the existed congestion in a node by using local information as inputs, which are the buffer capacity (B) and node rate (R). Then, based on the output of T2-FLS the system is able to figure out whether there is congestion in a node. That would be determined by comparing fuzzy output with a user defined value (μ). The parameter μ is defined based on the application specific features such as data transmission rate and bandwidth capacity. If the output is more than the specific threshold value, rate adjustment procedure will be called. The input variables for our developed system, which have been designed based on interval methods, are defined as follows:

1. **Buffer capacity (B)**
Current buffer capacity ($B$) is considered as the first input for the T2-FLS. $B$ is computed as below:

$$
B = \frac{(T_p - C_p)}{T_p}
$$

(4.8)

In which $C_p$ is number of buffered packets and $T_p$ is the buffer size. Therefore, when $C_p$ is zero, it means that $B$ is maximal (buffer is empty) and when $C_p$ is equal to $T_p$, it means that the $B$ is minimal (buffer is full) and no more packets will be accepted. As a result, the greater $B$ is, the more likely the node becomes congested. Figure 4.4 shows the membership function of $B$.

![Figure 4.4. Buffer capacity function plot](image)

II. Node Rate ($r$)

Node rate ($r$) is considered as the second input for T2-FLS. Let $\overline{T^i_s}$ denotes the average service time of the current data packet at node $i$. The average service time is defined as a period of time which is taken to successfully transmit a data packet over the MAC layer. The average service time $\overline{T^i_s}$ can be calculated by using exponential weighted sum formula as below [26]:

$$
\overline{T^i_s} = (1 - \beta) \overline{T^i_s} + \beta \cdot T^i_s
$$

(4.9)
where $\beta$ is a constant between $0 \leq \beta \leq 1$. Now, we can calculate a node rate, $r_i$, based on the obtained average service packet service time:

$$r_i = \frac{1}{T_i}$$  \hspace{1cm} (4.10)

Figure 4.5 shows the membership function of the node rate ($r$).

Set of linguistic values for inputs MFs are \{VS, S, M, H, VH\} which are representing very small, small, medium, high and very high values, respectively. The output function for T2-FLS as shown in Figure 4.6 consists of six MFs to calculate the node congestion degree. Set of linguistic values for MFs output are \{LL, LM, LH, HL, HM, HH\} representing low-low, low-medium, low-high, high-low, high-medium and high-high, respectively.
Those linguistic values are increasing in turn from left to right, and the LL and HH represent the lightest and heaviest states of the congestion degree, respectively. Table 4.3 demonstrates decision rules of the employed fuzzy controllers to describe the congestion status of a node. Based on the five linguistic values for inputs, the total numbers of possible fuzzy inference rules are equal to $5 \times 5 = 25$.

<table>
<thead>
<tr>
<th>Rule NO</th>
<th>Input Variable</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Buffer Capacity (B)</td>
<td>Node Rate (r)</td>
</tr>
<tr>
<td>1</td>
<td>VS</td>
<td>VS</td>
</tr>
<tr>
<td>2</td>
<td>VS</td>
<td>S</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>M</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>25</td>
<td>VH</td>
<td>VH</td>
</tr>
</tbody>
</table>

The output of fuzzy congestion detection subsystem is in the range of 0-1. This crisp value demonstrates that with higher values of output, the probability of congestion is more.

**4.3.2. Rate Adjustment Unit (RAU)**

The main objective of RAU unit is to adjust traffic rates of upstream nodes. For this purpose, we differentiate incoming traffic rates into several classes. Organizing network traffic is the main basis of applying proper QoS features to each class. The number of traffic classes is an administrative task and is application specific. In healthcare applications, we are dealing with human physiological signs. The main objective is to prioritise traffic streams based on their level of importance. In reality, some vital signs are more important than others. For example, heart rate signal has the highest priority than other signals such as temperature in most of medical applications. Thus, in case of high traffic load, it is
necessary to transmit the most important information first. In our proposed model, we assume that there are five different traffic classes, namely: heart rate (ECG), blood pressure (BP), muscles controller (EMG), glucose level (GL) and temperature (T). It is possible to extend the traffic classes to support a large number of tasks without loss in generality. However, in this study we selected the top five important vital signals in healthcare applications. We allocate the highest priority level to the heart rate signal and less priority level to temperature. In fact, higher traffic classes need to have higher throughput and less delay. As shown in Figure 4.7, the five traffic classes assigned to the ECG, BP, EMG, GL and T data stream, respectively. This classification is application-dependent and can be varied based on the situation of each patient.

![Figure 4.7. Priorization unit in each PDA](image)

As the above picture shows, each traffic class has its separate queue. In the PDA, a traffic class identifier is provisioned to navigate each arriving data packet to its corresponding sub-queue. We assume the single-path network in which each node has only one next hop to route the data. The type of a data packet is located in the header part of the packet. Then, a weighted fair queueing (WFQ) scheduler [123] is used to route data to MAC layer based on
their weighted priority. WFQ is a method of automatically smoothing out the data flows in packet-switched communication networks by categorizing packets. The aim of this method is to minimize the average latency and also avoid exaggerated discrepancies between the transmission efficiency afforded to narrowband versus broadband signals. In WFQ, data flows with higher assigned weight are sent out first. In fact, the method basically help to sort out different type of data based on their assigned priority. In our proposed protocol, the WFQ is following the below constraint:

\[ \text{Weight}_{c_5} \geq \text{Weight}_{c_4} \geq \text{Weight}_{c_3} \geq \text{Weight}_{c_2} \geq \text{Weight}_{c_1} \]

where \( \text{Weight}_{c_5} \) is the assigned weight for the most important data flow (ECG in our case) and \( \text{Weight}_{c_1} \) is regarded for the less important data flow (Temperature in our case).

4.3.2.1. Rate Adjustment Calculation

In the proposed protocol, we define static and network priority for each node \( i \). Static priority \( P_{static}^i \) at each node \( i \) can be calculated as:

\[
P_{static}^i = \sum_j S_{priority}^j \tag{4.11}
\]

The objective of Eq. 4.11 is to calculate static priority at node \( i \) based on its child traffic priority \( S_{priority}^j \). The parameter \( 0 \leq S_{priority}^j \leq 1 \) describes the jth traffic source priority at node \( i \) where \( j \) is a sensor attached on a patient’s body. We assume there is a set of five sensor nodes with different priority \( j \{ECG, BP, EMG, GL and T\} \) that collect and send information toward the sink. Defining the value of \( S_{priority}^j \) is an administrative task and is application-based. For example, for a patient with heart disease the value of ECG traffic
source priority should be high enough to be able to differentiate this parameter from other low traffic priority classes. Now, network priority $p_i^{\text{network}}$ is defined as:

$$p_i^{\text{network}} = p_i^{\text{static}} + p_i^{\text{transit}}$$  \hspace{1cm} (4.12)

where $p_i^{\text{transit}}$ is the transit data priority forwarded through node $i$.

Let $r_{\text{sink}}$ be the sink output rate and is calculated based on Eq. 4.10 by using the exponential weighted sum formula. The maximum transmission rate $r_c^{\text{max}}$ of each child node $c$ is obtained as:

$$r_c^{\text{max}} = r_{\text{sink}} . \left(\frac{p_c^{\text{network}}}{p_{\text{sink}}^{\text{network}}}\right)$$  \hspace{1cm} (4.13)

where $p_{\text{sink}}^{\text{network}}$ is the sum of network priority of all the sink’s child node and is defined as follows:

$$p_{\text{sink}}^{\text{network}} = \sum_{j \in \text{child}(s)} p_j^{\text{network}}$$  \hspace{1cm} (4.14)

To be able to analyse incoming traffic to the sink node, we need to then calculate $r_{\text{in}}^{\text{sink}}$ using the output rates from its child nodes $r_{\text{out}}^j$:

$$r_{\text{in}}^{\text{sink}} = \sum_{j \in \text{child}(s)} r_{\text{out}}^j$$  \hspace{1cm} (4.15)

Now, sink node can calculate and distributes the new share rate for is child nodes as follows:

$$r_{\text{new}}^c = r_{\text{out}}^c + \left\{ (\Delta r_{\text{sink}}) \cdot \frac{p_c^{\text{network}}}{p_{\text{sink}}^{\text{network}}} \right\}$$  \hspace{1cm} (4.16)

$$\Delta r_{\text{sink}} = r_{\text{sink}} - r_{\text{in}}^{\text{sink}}$$  \hspace{1cm} (4.17)

In the proposed approach, we considered two different transmission rates for each sensor node $i$, input rate ($r_{\text{in}}$) and output rate ($r_{\text{out}}$). Each node $i$ calculates its total input rate based
on its child output rate. Furthermore, each node $i$ calculates the new share rates ($r_{new}$) of its child nodes. As sink node has no parent, the sink output rate is calculated by using exponential weighted sum formula which has already been explained.

Based on Eq. 4.15, any decrease in the output traffic rates of child nodes will turn to a decrease in incoming traffic rate for the associated parents. Consequently, this will lead to an increase in the value of $\Delta r^i$ based on Eq. 4.17, resulting in an increase for other child node rates. Furthermore, the amount of increase is dependent on the predefined network priority of each child node. This means that transmission rate of nodes with higher priority will increase more than those nodes with lower priority. On the other hand, when some child nodes produce more traffic, then input rate to the parent node $i$ will become greater than its previous value. This makes the value of $\Delta r^i$ to become negative. Thus, to prevent any packet loss and high delay, each child node decreases its transmission rate. As it is shown in Figure 4.8, the WFQ scheduler is provisioned in the output of each node to service the packets in virtual queues, based on the priority of source or child’s traffic.

![Figure 4.8. Rate adjustment model](image)

The following algorithm illustrates the proposed congestion detection and control method. As shown in line 2, T2-FLS checks traffic status of a sensor node by considering the node
transmission rate and buffer capacity. In line 3, the output of fuzzy system is compared with a pre-defined system value. If congestion is detected, then rate adjustment function is called to allocate the best sharing rate to each upstream node based on the network conditions. Then, based on the defined formula, the new transmission rate is calculated. Finally, based on line 16, the new rate is sent to the neighbour nodes via implicit messages.

Algorithm: Congestion detection and control algorithm

INPUT: (N: Node transmission rate, B: Buffer capacity)
OUTPUT: Adjusted transmission rate

BEGIN
1: WHILE (Event NOT Detected) DO
2: \( \text{Out}_n \leftarrow \text{FLC} (N, B) \)
3: IF \( \text{Out}_n \geq \mu \)
   Congestion is detected
5: Call (RateAdjustmentFunc());
6: ELSE
7: Normal traffic detected
8: END IF
9: RateAdjustmentFunc(){
10: Calculate \( P_{\text{static}}^i \) of each node \( i \) using Eq. (4.11)
11: Calculate \( P_{\text{network}}^i \) of each node \( i \) using Eq. (4.12)
12: Calculate \( r_{\text{out}}^i \) of each child node of parent \( i \) using Eq. (4.13)
13: Calculate \( r_{\text{in}}^i \) of parent \( i \) using Eq. (4.14)
14: Calculate the transmission rate of each child node which is allocated by parent node \( i \) according to Eq. (4.16)
15: Call (ImpNotificationFunc());
16: ImpNotificationFunc(){
17: send the new transmission rate to the child nodes via an implicit message}
18: END WHILE
END Algorithm

This is also important to analyse the computational complexity of the proposed algorithm. When congestion happens in a network, this is a crucial factor to moderate with the available bandwidth and also energy resources. So, the proposed algorithm needs to have a low computational and recourse usage burden. Based on the proposed formula, each sensor node \( i \) uses a few summations and multiplications to calculate the priorities and new share rates.
Therefore, we can observe that the computational burden is linear with respect to the network size.

4.3.3. Implicit Congestion Notification (ICN)

Once congestion has been detected in the network, necessary information should be broadcasted from the congested node to the upstream source nodes. There are two main methods for congestion notification [118]: Explicit Congestion Notification (ECN) and Implicit Congestion Notification (ICN). In explicit congestion notification, the congested node uses special control messages to notify other nodes about the congestion. As a result, this method will increase the network overhead. In implicit congestion notification, the notification message can be sent along with the header of data packets. In our approach, the notification message is sent with the sensory data due to avoiding heavy traffic creation. When a node receives a new rate assignment message from its upstream node, the node is expected to adjust its traffic rate accordingly.

4.4. Chapter Summary

In this chapter, we proposed a new congestion detection and control approach for use in healthcare WBAN applications. The proposed approach consisted of three main different stages. In the first stage, local information of sensor nodes was sent to a T2-FLS to analyse the network traffic. Based on the output of fuzzy system, the congestion level will be estimated. In case of congestion, parent or upstream nodes calculate and allocate the new transmission rate for each of their child nodes. The main objective of rate adjustment
subsystem was to prioritize physiological signals and sent them based on their level of importance. Although the main components of the proposed method has been analysed in a healthcare monitoring application, it is also applicable to other applications with even larger numbers of sensors. Performance evaluation of the proposed protocol is presented in the next chapter.
Chapter 5

SIMULATION RESULTS AND PERFORMANCE EVALUATION

In this chapter, we evaluate performance of our proposed protocol using simulation studies. The results of the experiments are compared against PBCCP (a prioritization based congestion control protocol for healthcare monitoring application in wireless sensor networks (WSNs)) [24] and PHTCCP (congestion control protocol for wireless sensor networks handling prioritized heterogeneous traffic) [124]. The reason behind choosing these two protocols is that both share some similarities to our work. PBCCP is one of the latest congestion control protocols for use in healthcare applications. The method provides a congestion control approach for real time monitoring of patients’ vital signs in WBANs. PBCCP uses a learning automata based AQM mechanism at intermediate sensor nodes to control congestion. The method was successful in terms of achieving a better performance in end-to-end delay, drop ratio and queue length. PHTCCP is another congestion control
protocol which ensures efficient rate control for prioritized heterogeneous traffic. This scheme uses packet service ratio for detecting congestion in WSNs. The protocol also takes advantage of using a hop-by-hop rate adjustment scheme for heterogeneous traffic. PHTCCP was evaluated in terms of required memory, normalized throughput and energy efficiency.

5.1. Performance Metrics

We consider a number of metrics to evaluate performance of the proposed congestion detection and control approach. The main metrics are described as followings:

- **Network Throughput**: Throughput is a crucial factor whenever we are dealing with congestion issues. Throughput is a measure that shows the average rate of receiving data packets over a communication protocol with respect to the total number of data packets transmitted. Throughput can be calculated using the below formula:

  \[
  \text{Throughput} = \frac{\text{Total received data}}{\text{Total transmitted data}} \quad (5.1)
  \]

  In healthcare applications, this measure is very important as medical vital data need to be received at their destinations in a high reliable rate.

- **Packet Loss Ratio (PLR)**: PLR is the difference of total data sent by sensor nodes and received at a destination with respect to the total data sent. Following formula calculates the defined PLR:

  \[
  \text{PLR} = \frac{\text{total data sent} - \text{total data received}}{\text{total data sent}} \quad (5.2)
  \]
• **End-to-end Delay**: Delay is another fundamental parameter especially in critical applications such as healthcare. End-to-end delay is defined as the time spent in transmitting a data packet from the source node to a destination. End-to-end delay can be calculated by using Eq. 5.3.

\[
\text{Delay} = \{ \text{Packet Arrival Time} - \text{Packet Start Time} \} \quad (5.3)
\]

• **Jitter**: The time difference in packet inter-arrival time to their destinations is called jitter. In fact, jitter is the variation in the time between packets arriving. Jitter is commonly used as an indicator of stability and consistency of a network [125]. Jitter is also an important metric to determining QoS of a network. In remote healthcare applications, some sensors are responsible for recording and transferring video or voice data from patients. These types of sensors are not normally jitter-tolerant [24]. Therefore, jitter need to be lowered or if possible completely removed in such applications. Eq. 5.4 shows how delay jitter can be calculated:

\[
\text{Jitter} = \{(\text{Packet Arrival}+1) - (\text{Packet Start}+1)\} - \{(\text{Packet Arrival}) - (\text{Packet Start})\} \quad (5.4)
\]

• **Energy Consumption**: The communication model for energy consumption used in our evaluation is as explored in [126]. The transmitter dissipates energy to run the power amplifier and radio electronics is shown in Figure 5.1.
The required energy for transferring a k-bit message to d distance can be calculated by using Eq.5.5.

\[
E_{TX}(k, d) = E_{eiec} \cdot k + E_{amp} \cdot k \cdot d^2
\]  
(5.5)

Energy consumed in receiving k-bit message can be computed by Eq.5.6. Where based on the referred algorithm $E_{eiec} = 50\text{nJ/bit}$ and $E_{amp} = 100\text{pJ/bit/m}^2$.

\[
E_{Rx}(k, d) = E_{eiec} \cdot k
\]  
(5.6)

5.2. Experimental Setup

We use MATLAB and OPNET to evaluate the performance of the proposed protocol. Congestion detection approach with type-2 fuzzy logic toolbox and other required functions are run in MATLAB. The simulation process is carried out by using OPNET. As the main programming language of both software is C++, we are able to create a link between the two. Therefore, the proposed protocol is simulated by making connection between MATLAB and OPNET using C++ compiler. If congestion is detected, then MATLAB calls OPNET software. We used Location-Aided Flooding (LAF) protocol [127] as routing protocol and 802.11 as MAC layer protocol. In this simulation, we use a simple single path tree topology. The used network topology is as illustrated in Figure 5.2. In the first trial of simulations, we assume that all the sensors remain active during the simulation.
time. In addition, we consider that all sensor nodes have the same priority. The reported simulation results show the average from 5 runs of experiment at a 90% confidence interval.

Figure 5.2. The single path topology used in the simulation

Table 5.1 represents the simulation parameters used in this chapter.

<table>
<thead>
<tr>
<th>Deployment</th>
<th>Simulation</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Size</td>
<td>Time</td>
<td>Application Type</td>
</tr>
<tr>
<td>Deployment Type</td>
<td>Transmission Range</td>
<td>Packet Size</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>Initial Node Energy</td>
<td></td>
</tr>
<tr>
<td>Transmission Range</td>
<td>Initial Service Rate</td>
<td></td>
</tr>
<tr>
<td>Initial Node Energy</td>
<td>Network Architecture</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1. Simulation parameters

5.3. Performance Results and Discussion

In the following sections, we present performance results of the proposed protocol:
5.3.1. Network Throughput

Figure 5.3 compares the total normalized throughput of the PBCCP, PHTCCP and the proposed approach. In this simulation, all the sensor nodes are supposed to be in normal situation and have the same importance and priority. Similar to PBCCP, we also considered fixed service time for all sensor nodes.

As can be seen from the given Figure, the proposed approach maintains a high level of throughput that is between 0.9 and 1 during the time intervals. PBCCP shows a slightly lower performance than our proposed protocol. That is because each sensor node in PBCCP is required to train itself based on the received feedback from other neighbours to ensure about dropping or relaying data packets. The calculation complexity of the process will consequently result in reducing the overall network performance.

Simulation results also show that PHTCCP has the worst throughput that is between 0.84 and 0.9 approximately. This poor performance is due to its low capability of figuring out the appropriate level of data ratio in source nodes in a high traffic load condition of the network.

The figure proves that the proposed approach has the best performance. That is because the proposed method can use the network capacity well and thus maintain a high throughput during the time intervals. The proposed approach takes advantages of using a Type-2 fuzzy logic system to come up with more accurate decisions in detecting congestion in the sensor nodes. In addition, the proposed scheme consists of using a prioritization scheme to adjust the source nodes’ rate based on nodes’ importance and incoming traffic from child nodes.
As a result, the proposed protocol is able to adjust the nodes rate efficiently and achieve a high throughput level.

![Normalized throughput comparison](image)

**Figure 5.3. Normalized throughput comparison**

### 5.3.2. Packet Loss

To analyse the packet loss ratio (PLR) of the proposed approach, we compare performance of our protocol against both PBCCP and PHT CCP. Figure 5.4 represents the packet loss ratio over time with the initial source rate of 100 packets per second. In this, we run the simulation long enough to ensure it reaches a steady-state. We also analyse performance of the proposed protocol from the number of dropped packets with respect to the offered traffic loads as shown in Figure 5.5.

As it can be seen from the Figure 5.4 and Figure 5.5, our congestion control mechanism shows the highest performance compared to PBCCP and PHT CCP. For example, after 200 seconds in Figure 5.4, PLR of the proposed scheme is reached to about 0.02 while it is 0.04
and 0.1 for PBCCP and PHTCCP, respectively. As it is obvious from the given figure, PBCCP cannot outperform our proposed approach. That is because intermediate sensor nodes in PBCCP are not able to realize the occurred congestion in the network. When the sink node detects any anomaly in the received data, then it detects that there is a possibility of congestion for a particular patient. In fact, sink node in the network is responsible to inform the source nodes about the possible congestion by sending feedback messages. The described scheme increases message traffic in the network as a consequent. The higher traffic means the higher possibility of collision in the sensor networks. Therefore, packet loss increases as a result of collision in the network.

![Packet loss rate comparison over time](image)

Figure 5.4. Packet loss rate comparison over time

Lastly, PHTCCP has the weakest performance compare to the proposed approach and PBCCP. That is because the proposed congestion detection system is not highly accurate and it only considers packet service ratio to estimate congestion level of each sensor node. In fact, they assumed that the sensor nodes use the same amount of their provided buffer
capacity in the entire network life time. That assumption is not a realistic assumption for a sensor network in a real life scenario.

![Graph](image)

Figure 5.5. Packet loss rate comparison with respect the offered traffic load

Our proposed approach has the best performance based on the provided results. That is because each sensor node is capable of analysing their current conditions to figure out whether they face congestion issue. Therefore, intermediate sensor nodes do not need to receive a feedback message from the sink node. They also consider node rate as well as buffer capacity to ensure about the congestion problem. As a result, we reduced the data packet traffic in the network while at the same time enhanced the accuracy of detecting congestion.

5.3.3. End-to-End Delay

Figure 5.6 shows end-to-end delay for the three protocols as a function of time. We run the simulation until the output of the proposed approach reaches the steady state. As it
is clear, the end-to-end delay of PBCCP and PHTCCP are higher and more unstable compared to our proposed protocol. The end-to-end delay for PHTCCP is the highest and about 0.8 s while it is less than 0.5 s for PBCCP and our protocol at the same offered traffic loads. This is because the proposed protocol is able to detect congestion in advance and then calculate the best sharing rates for intermediate nodes. This fact helps to decrease the end-to-end delay considerably. In addition, PHTCCP could not assign the exact needed priority for different types of data flows in the network. In this case, if burst traffic happens for a specific type of sensor, the protocol is not able to efficiently control the incoming rates and this will result in an increase in the overall network delay. In addition, the high rate of PLR in this method will consequently result in increasing delay in receiving data.

Figure 5.6. End-to-end delay over time

Figure 5.7 represents the delay jitter simulation for PBCCP, PHTCCP and the proposed method. As can be seen from the Figure, the jitter of our proposed protocol is lower and more stable than other two schemes. This is an important achievement for our protocol that
is able to decrease end-to-end delay and jitter in the network. As already discussed, delay is completely undesirable in healthcare applications where vital data need to be received on-time.

![Figure 5.7. Jitter comparison over time](image)

**5.3.4. Energy Performance**

In this section, we calculate the required energy for successful transmissions of specific number of data packets in the network. Figure 5.8 compares energy consumption in the proposed approach against PBCCP and PHTCCP. The figure illustrates how the average energy consumption ($J$) varies when the source sending rate increases.

As it is evidenced, the average energy consumption of the proposed approach for transferring different traffic loads is less than PBCCP and PHTCCP. For example, at an offered traffic load of 400 kb/s, the proposed protocol decreases the energy usage by about 20% and 50% compared to PBCCP and PHTCCP, respectively.
Figure 5.8. Average energy consumption per packet with respect to traffic load

Figure 5.9 also represents the variation in the average energy consumption as a function of time, with the initial rate of 500 kb/s. This chart also represents a higher performance of our protocol in compared to the others. In both provided figures, PBCCP shows a weakest performance compared to the proposed approach. This could be due to some reasons. First, due to the number of messages that are broadcasted by sink nodes to inform other nodes about the congestion. Moreover, the amount of messages that required to be transmitted among the sensor nodes cannot be avoided in increasing the energy consumption. The figure also proves that PHTCCP has the most inefficient energy consumption performance. That is because of its high PLR as PHTCCP is not able to accurately estimate congestion in the intermediate sensor nodes.

As it was expected, our proposed method shows the best performance in terms of energy consumption. That is because data packet rates are wisely adjusted during the high traffic
load in the network. In addition, the protocol takes advantages of a better congestion detection system.

![Figure 5.9. Average energy consumption per packet over the time](image)

### 5.3.5. Effect of Prioritization

In all previous simulations, we assumed that all sensor nodes have the same priority. In this simulation trial, we classify sensors to five different traffic classes with different priority levels. Table 5.2 shows the five considered traffic classes with their assigned priority weights.

<table>
<thead>
<tr>
<th>Class 1 (w=0.9) ECG</th>
<th>Class 2 (w=0.7) BP</th>
<th>Class 3 (w=0.4) EMG</th>
<th>Class 4 (w=0.2) GL</th>
<th>Class 5 (w=0.1) T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Normalized Throughput</td>
<td>0.395</td>
<td>0.235</td>
<td>0.133</td>
<td>0.058</td>
</tr>
<tr>
<td>Average End-to-end Delay</td>
<td>0.015</td>
<td>0.027</td>
<td>0.031</td>
<td>0.037</td>
</tr>
</tbody>
</table>
Based on the given data, ECG sensor has the highest and temperature (T) has the lowest priority value. Based on the previous definitions, higher priority means achieving higher level of throughput and therefore lowest level of delay.

Simulation results about the normalized throughput of each sensor node in a period of 350 sec are shown in Figure 5.10. As can be seen clearly, ECG class has the highest normalized throughput and T class has the lowest throughput.

![Figure 5.10. Normalized throughput over time with considering node priority](image)

Figure 5.11 shows the end-to-end delay of each traffic class over time. The simulation results from the given figure also prove that ECG has the lowest and T has the highest end-to-end delay.

As it can be revealed from the results, the proposed protocol was successful to allocate network capacity to each sensor node based on the priority level. As it has been discussed in Chapter 4, any increment in the transmission rate of sensor nodes is depend on the defined
priorities for them. It means that high priority nodes will get larger increase to their transmission rates compared to low priority nodes.

![Graph showing end-to-end delay over time with considering node priority]

Figure 5.11. End-to-end delay over time with considering node priority

5.4. Chapter Summary

In this chapter, we evaluated performance of the proposed congestion detection and control approach by simulation studies. We used MATLAB and OPNET concurrently to evaluate the performance of the proposed protocol. The congestion detection phase was simulated in MATLAB and rest parts of evaluation were carried out by OPNET. The experimental results were compared against PBCCP which is one of the latest congestion control protocol for use in healthcare applications and PHTCCP which is a congestion control protocol that ensures efficient rate control for prioritized heterogeneous traffic. Simulation results confirmed that the proposed protocol outperforms PBCCP and PHTCCP algorithms in terms of network throughput, packet loss ratio, end-to-end delay and energy
efficiency. We also demonstrated that the proposed protocol is able to achieve desired level of throughput and end-to-end delay according to the specified priority for different traffic types.
Chapter 6

SUMMARY AND FUTURE RESEARCH DIRECTIONS

The purpose of this thesis is to develop solutions for the existing research problems in wireless body area networks (WBANs) that negatively influence their quality of service (QoS). We firstly introduced a sensor-Cloud monitoring framework that integrates WBANs with Cloud computing. The proposed framework enabled real-time sensor data collection, storage, processing, sharing and management services. As the main contribution of this thesis, a new congestion detection and control protocol for use in sensor-Cloud infrastructure was proposed.

6.1. Conclusion

The first addressed research problem in this thesis was to develop a reliable and self-configurable system that integrates WBANs with Cloud computing technology for use in
remote healthcare monitoring system. To achieve this goal, a deep exploration and study was managed on many of the existing monitoring frameworks available in the literature. That deals with analysing the advantages and disadvantages of the existing proposed frameworks for remote healthcare services in WBANs. Based on our findings, although there were several works to automate existing traditional healthcare systems, these solutions still had technical challenges and remained unsatisfactory. They also slightly made use of varying Cloud services to benefit from Cloud capabilities. Therefore, we came up with the idea of developing a patient monitoring framework that supports storage and analysis of vital data using variety services that hosted in the Cloud subsystem.

In the proposed framework, we thoughtfully considered three subsystems to provide real time monitoring of patients. The first module of the framework was based on Intra-BAN communication model. This module was the lowest layer of the healthcare monitoring system which was composed of two main phases. In the first phase, patients’ vital signs such as blood pressure, blood glucose or temperature was monitored using body sensor nodes. In the second phase, the monitored data was transferred to a PDA or a cellular phone via wireless communication. For transportation protocol, we used IEEE 802.15.4 standard which was specifically designed to support low power and energy usage for WBANs.

The second subsystem of our proposed framework was a Cloud-based module. The Cloud subsystem allows patients to submit their personal and medical information through WBAN gateway. The medical records are accessible by doctors, administrators and patients from a client-server web service at any time. Authentication is also needed for each time accessing the Cloud.
The last subsystem was the end-user module which offers patients intelligent monitoring services in a real-time manner. It consists of a variety of applications that are used for analysing health information. This module can also have a terminal in emergency centres, medical centres or family members of patients in case they need to connect the system. End-users can subscribe the service to become updated automatically about the latest transferred medical data.

We specified three types of monitoring schemes for our framework, namely, continuous, on-request and periodic. Continuous monitoring is set when an intensive monitoring is needed for patients. The on-request monitoring process is started based on requests from any authorised person in the system such as patients, doctors or nurses. The periodic monitoring scheme works based on a pre-defined start and end time by a user.

We discussed the complete life cycle of data analysis workflows included data collection, storing and analysis as well as presentation. As a case study, we demonstrated an EMG remote monitoring application using the proposed framework. There are several advantages in the proposed framework such as eliminating manual data collection, simplifying the set up process and also speeding the monitoring process as patients’ health condition can be under control even when they are at home. In addition, the Cloud services are responsible to organise and distribute the data. As a result, it facilitates indexing and making data available for system users.

The second addressed research problem in this thesis was to propose a congestion detection and control approach for use in sensor-Cloud infrastructure. We developed a method which was consisted of three subsystems, namely, congestion detection unit (CDU), congestion
notification unit (CNU), and rate adjustment unit (RAU). In CDU, we developed a type-2 fuzzy logic system (T2-FLS) which is capable of estimating congestion in intermediate nodes by considering buffer capacity (B) and node rate (R). Then, based on the output of T2-FLS the system is able to figure out whether there is congestion in a node. If congestion is detected, then RAU will be called to adjust share rates among intermediate nodes. For this purpose, we differentiate incoming traffic rates into several classes based on their level of importance. We considered a virtual queue for each traffic class. In PDA, a traffic class identifier was provisioned to navigate each arriving data packet to its corresponding sub-queue. The type of data packet is located in the header part of each data packet. We also assumed a single-path network in which each node has only one next hop to route the data. Then, a weighted fair queueing (WFQ) scheduler is used to route data to MAC layer based on their weighted priority. Rate adjustment was performed by parent nodes based on the current available resources and the priority of child nodes. In our approach, notification messages are sent with data packets to avoid heavy traffic creation. Once a sensor node receives a new rate adjustment message from its neighbors, the node is expected to adjust its traffic rate accordingly.

We compared our results against PBCCP and PHTCCP which both are among latest congestion control approaches for use in sensor networks. Simulation results proved that our proposed protocol outperforms both PBCCP and PHTCCP algorithms in terms of network throughput, packet loss ratio, end-to-end delay and energy efficiency. We also demonstrated that the proposed protocol is able to achieve desired level of throughput and end-to-end delay according to the specified priority for heterogeneous traffic.
6.2. Future Directions

Our extensive study on QoS control in WBANs identified a number of research problems that we could not solve in this thesis due to time and other limitations. We list out a number of future research directions in line with the problems discussed in this thesis. There are opportunities to enhance the proposed solutions and explore other potential issues to ensure the technology can perform at its best to benefit users.

In this thesis, we proposed a sensor-Cloud infrastructure to monitor patient health status. However, it is important to emphasize that the use of Cloud is featured by a number of open issues, such as security and privacy. Further improvements can be made to introduce additional privacy techniques that help to protect patients’ critical information.

We also analysed the proposed framework in an EMG case study. Further research potential is observed in the development of other case studies that can demonstrate the range of applications that can be enabled by the proposed monitoring system (e.g. mass fear detection system, group activity monitoring, emergency support system, etc).

This is also an important factor to analyse the cost of the proposed healthcare monitoring system in order to be usable by different ranges of people.
References


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