VRIJE UNIVERSITY, AMSTERDAM
Department of Computer Science

# Evaluating the performance of Bio-sensors in Wireless Networking

Rosmi Rehman

Supervisors
Prof. Dr. D. C. A Bulterman

Dr. Pablo Cesar

Ir. Chen Wang

Second Reader
Dr. Frank Nack

# Abstract

Companies and service providers are deeply interested on the impact their products have on people. Physiological sensors (GSR, ECG..) are useful means to understand the user's experience: their interest on an activity, their engagement, or their boredom.

In this thesis we analyzed the networking performance of physiological sensors in crowded environment. Polling was the MAC protocol used by the sensors, as it is collision free. It was compared against ALOHA which has higher level of collisions. The performance of these protocols in physiological sensors in 868 MHz is studied through extensive experiments. The impact of hindrance, distance and scalability were studied. The performance of the system is affected negatively by the above factors. Overall, Polling has shown better performance than ALOHA. The impact of the position of placement of the sink node on the sensor deployed area was studied. The packet reception of the sink node in different location varies with different arrangement and number of groups of sensors.

## Acknowledgements

I would like to express my sincere gratitude to my advisers Dr. Pablo Cesar and Ir. Chen Wang for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis.

I owe my deepest gratitude to my supervisor Prof. Dr. Dick Bulterman for the time he dedicated towards helping me resolve my doubts and the valuable suggestions given by him. I would like to show my gratitude to Dr. Frank Nack who found time to read my thesis and grade it.

I am indebted to Distributed and Interactive System group of CWI, for giving me an opportunity join their team as intern and for giving access to the research facilities. Without their precious support it would not be possible to conduct this research.

I would like to thank Ms. Xintong Zhu for helping me in organizing and conducting experiments. Also I thank my family and my friends in Vrije University, Amsterdam and Amrita University, India for their support and encouragement.

# Dedication

This work is dedicated to my teachers, family and friends who believed in me and encouraged me in every walk of life.

'Quote text here.'

*Guy Quoted*

# Contents

# List of Tables

# List of Figures

# Chapter 1

# Introduction

User Experience is defined as "a person's perceptions and responses that result from the use or anticipated use of a product, system or service" by the international standard on ergonomics of human system interaction [1]. The knowledge about user experience is important for product/ manufacturers, as it is about how a user feels about the system, service or product [18]. Traditionally user experience was measured/ monitored by getting verbal or written feedback from the users, using questionnaires or interviews. These methods are not perfect, since they are subjective. More recently, physiological sensors started to be used, since they provide more accurate and objective data about the user experience [2]. Usually, user experience studies were performed in a lab environment. Studies show that the results we get from lab experiments cannot be directly generalized to field experiments [2]. To understand the experience of a group of people attending an event, physiological sensors can be deployed in large scale. For example, the Distributed and Interactive System (DIS) research group organized an event called "Smart fashion" as part of "CWI in Bedrijf 2015: Everything Smart". In the event, a part of the audience were connected to galvanic skin response sensors to measure their engagement during a presentation by fashion designer Borre Akkersdijk. The speaker was also wearing ECG sensor, GSR sensor and accelerometers. The engagement of the audience, the speaker's heart rate and position were displayed in real time on a screen (figure 1.1). The audience's engagement level was represented with the help of balloons. When the engagement of the users increased the

Figure 1.1: Real time user experience monitoring from Smart Fashion event.

height of the balloon (corresponding to the user) increased. The use of physiological sensors for measuring the engagement of students in e-learning and real class environment is discussed in [4]. In [3] and [2], the authors describe how GSR sensors can be used to measure the engagement of the audience of a live performance.

## 1.1 Motivation

There are many challenges to be tackled when using physiological sensors in crowded events like a theater play or a dance performance. Firstly, the physiological sensors need to collect data and communicate them to one or more central nodes. The data has to be gathered and analyzed to properly understand the reactions of the people. Secondly, decision should be made about the communication standards (Wi-fi, Bluetooth, Zigbee etc.) to be used for developing the sensors. Thirdly, a MAC layer protocol has to be chosen to assure good performance. After developing the sensors they should be extensively tested to make sure that they are working and that they give the right data. In user experience studies the data should be sent to a central node in real time with minimal delay as the user's response needs to be synchronized with the performance. Unlike the sensors used to measure environmental characteristics which need to send data when an event occurs [45] or several times a day [46], physiological sensors need to send data regularly as the physiological parameters can change in short time intervals. If the data has to be shown in real time, then it is not advisable to retransmit the packet. The retransmitted packet will arrive later, which make it irrelevant for real time display. The usual method to assure reception of a packet is by sending an acknowledgment. But in a congested network acknowledgments introduce more congestion. These are the main problems when using physiological sensors in the wild.

In this thesis, I focus on the networking aspect associated to physiological sensors for performing user experience studies. In order to understand the characteristics, capabilities and functionality of the sensors, extensive experiments were done. The experiments focused on understanding the performance of the ALOHA and Polling protocols without retransmissions and acknowledgments in different scenarios. The sensor performance was checked in line of sight path and hindered path. In order to understand the scalability of the network, experiments were performed with a varying number of sensors. The possible range was measured by varying the distance between the sink and the sensor nodes. The major experiments where on how the placement of sink node in different positions in the sensor deployed area affects the packet reception efficiency. The experiments were done with one, two and three groups of sensors. The experiment with more than one group of sensors gives an idea on how collocation of groups effect influence the performance. All these experiments were conducted with Jeenode sensors in the frequency range of 868 MHz. The results of the experiments show that the performance of sensors decrease when increasing the number of sensors and the distance between the sink and the sensors. The range attained by our sensors varied depending on the MAC protocol used: for ALOHA 50m was the maximum range whereas for Polling the maximum range was 60m. Using more than one group of sensors in the same location degrades the performance. As expected the results shown better performance for Polling over ALOHA. The placement of sink node in different position did not show any significant effect on the performance for single group of sensors. When two groups of sensors were arranged on two sides of the hall, the packet reception was maximum when the sink node was placed on the center of the two groups. For three groups of sensors the efficiency was maximum when the sink node was placed on the edge of the sensor deployed area. These results were due to the particular arrangement of sensors in the area. The practical receiving rate of the sink node was found to be 6.25 ms.

## 1.2 Contributions

The major contributions of this thesis are listed below.

- *Performance analysis of wireless communication of physiological sensors in noiseless frequency band of 868 MHz.*

  The link quality of 2.4 GHZ frequency band has been thoroughly studied in [27], [28], [26] and [9]. In [24] the performance characteristics of sub 1GHz band (920-930 MHz) is studied. The 868 MHz is widely used by Btnode3, Mica2, Mica2dot and sensors based on Arduino. But the characteristics of this frequency band is not well studied. The 868 MHz frequency band uses 1 channel with data rate of 20 Kbps. The modulation scheme is binary phase shift keying (BPSK). The study by Woehrle et al. [25] shows that 868 MHz band is prone to lesser noise compared to 2.4GHz band. There are not many devices which cause external interference to sensors working in this frequency range. So we can consider the external interference as null in the studies. Physiological sensors in 868 MHz are used for studying the user experience [2], [3], [4]. Those researches were focused on the physiological measurement of engagement of users in different scenarios like E-learning, theater play etc. In my work I am focusing on the network characteristics and performance of physiological sensors in crowded events. Woehrle et al. conducted a study on link quality estimation of 868 MHz frequency band [25], by which they stated that 868 MHz is noise free. Boano et al. [5] studied the effect of temperature on the link quality and signal strength by conducting experiments in an outdoor oilfield. In my work I am using this noise free band which has no external interference to analyze the performance of physiological sensors which have high data rate and are time constrained. The user case I am considering is to study user experience in crowded environment while most of the previous works were done for environmental sensors. For studying the user experience the data from the users have to be collected continuously at a high sampling rate. The number of sensors needed to measure data from a big crowd is high. As we need the information about the response of each participant the data cannot be aggregated and averaged from closely located sensors as we do for temperature or humidity measurement. Packet loss cannot be tolerated as the signal might lose its characteristics. For example, if only 10 packets are received out of 25 packets sent per second, the ECG signal might not show the regular shape. Time synchronization between the performance and user's data is important. Then only, by data analysis we could correctly map the stimuli and the response. Delay cannot be tolerated for giving real-time feedback about the user's response. In order to reduce the effect of delay, the protocols we used in the study were designed without retransmissions and acknowledgment.

In order to study the performance of physiological sensors, extensive experiments were done with open source pulse sensors and Jeenode using two MAC protocols ALOHA and Polling. To understand the scalability, we studied packet loss variation when increasing the number of sensors from 10 to 60. The number of sensor nodes that can be connected to a sink is restricted (maximum 30 for Jeenode), so to connect more sensors we used more sink nodes. We use "group" to refer to a sink node and its associated sensors. The results show a decrease in performance with an increase in the number of nodes. This is similar to the result obtained in [31] for slotted and unslotted CSMA. There was a rapid increase in packet loss for polling when the number of sensor nodes were increased to 60. This is because, to connect 60 sensors we used 3 groups, which introduced collision in the system. Overall, Polling had lesser packet loss compared to ALOHA as expected. In a theater performance, it won't be always possible to keep the sink node near to sensors. To learn how far the sink could be placed from the sensors, experiments were conducted by placing the sensors and the sink at different distances. The obtained results shown the general trend of efficiency reduction with increase in distance. This is similar to the result obtained in [31] for experiments in 2.4 GHz. But those sensors had a maximum range of 80m and the packet loss was sharp beyond 70m. Our sensor had a maximum range of 60m and the increase in packet loss was gradual with increased distance. In an auditorium there will be many hindrance on the communication path between the sink and the sensors. The effect of hindrance was studied by introducing hindrance. This was done by placing sensors in a closed room and data was collected by keeping the sink outside the room. The result of the study shown a small decrease in performance when hindrance was present. But the cumulative effect of human hindrance and hard hindrance (walls) increased the packet loss. To understand the effect of using more than one group in the same area, experiments were conducted by using more than one group of sensors. In an auditorium the sink node can be placed in different locations. Experiments were conducted by keeping the sink node in different positions to study the influence of position of the sink node on the network performance. The results show that the position of the sink node is not significant for experiments using a single group of sensors. For a single group of sensors the average efficiency was 97% for all the positions of sink node. With 2 groups of sensors the efficiency reduced to 50%, 43% and 63% when the sink nodes were placed on the edge, corner and center of the sensor deployed area. Here the position had greater influence on the performance. The efficiency reduction was due to the collision arose when sensors from two groups start data transmission simultaneously. There was further reduction in efficiency when the number of groups become three. The probability of collision increase with increase in number of groups. This is because the polling of the three sink nodes were not managed one after another to avoid collision. To manage the polling in such a method requires strict time synchronization. The result obtained for the arrangement of three group of sensors favors the sink node placement on the edge to obtain maximum efficiency. But the value obtained even for this arrangement was only 35%.

## 1.3 Research Goals

The research questions I am trying to answer in this thesis are as follows.

- *Q1. How the performance of the physiological sensors varies with distance in 868 MHz? What is the maximum range for the sensors used ?*

  In order to understand the effect of distance on performance, extensive experiments were conducted by separating the sink and sensor nodes from 10m to 60m. The sensors and sink node were placed in line of sight path. The data sent by the sensor nodes to the sink were collected for each distance. The packet loss is calculated for each distance. The packet loss increased with distance. The maximum range attained for sensors with ALOHA as MAC Protocol is 50m and for Polling it is 60m.

- *Q2. What is the receiving rate of the sink node in practice ?* In order to find the practical receiving rate of the sink node, an experiment was conducted by keeping the sensor node very close to the sink node. The data was collected for a duration of 1 minute. The experiment was repeated with GSR and ECG sensor. The average number of packets received from a single sensor node in 1 second was 160 packets. The receiving time is 6.25 ms per packet.

- *Q3. How does the location of placement of sink node influence the packet reception efficiency ?* To study the effect, experiments were conducted by keeping the sink node in the edge, corner and center of the sensor deployed area. The experiments were repeated with two and three groups of sensors. depending on the arrangement of the sensors different positions shown better efficiency. For a single group of sensors, the position of the sink node was not significant as there was no collision in the network.

- *Q4: Does the coexistence of more than one group have any effect on network performance?*
  In order to study this, experiments were conducted with two and three groups of sensors. There was an increase in packet loss with the introduction of a new group. Even though the sensor in one group communicates only to its sink node, all the groups are using the same physical layer. Hence there is an increased in congestion in the channel.

## 1.4 Outline

This document is organized as follows.

- Chapter 2 begins by defining bio-sensors and their applicability in different fields. Then it provides background information about the challenges in wireless communication. The Related Works in this field is discussed.
- Chapter 3 gives details about the sensors used. It explains the hardware and the software. The networking methods and MAC layer protocols used by the sensors are explained in detail.
- Chapter 4 discusses the different experiments performed to answer each of the research questions. This chapter answers the research questions Q1 and Q2.
- Chapter 5 details and analyzes the results obtained from the experiments and its analysis. This chapter answers the research questions Q3 and Q4.
- Chapter 6 concludes the thesis.

# Chapter 2

# Background Theory

To understand how the physiological sensors work, first we should know the characteristics and applicability of bio-sensors. Then we should better understand the challenges regarding wireless transmission.

## 2.1 Bio-sensors

Bio-sensors or physiological sensors are used to detect information from the human body like heart rate, brain wave or breathing rate which reflect changes in a person's physiological patterns. Doctors placing the ear on the chest of the patient to hear the heart beat pattern could be considered as an early form of physiological sensing [11]. The advancements in technology resulted in the invention of many physiological sensors capable to measure heart beat patterns or complex brain signals. The current sensor devices are capable to detect activity from the Central nervous systems (CNS), Somatic Nervous systems (SNS) and Autonomic Nervous Systems (ANS).

Commonly used physiological sensors measure the following signals.

- Electroencephalogram (EEG) is the measure of electrical activity in the brain surface. These signals are measured by placing electrodes on the scalp of the user.

- Electrocardiogram (ECG) is the measure of electrical activity associated with the contraction of the heart muscle. This measurement is done by placing electrodes at different positions of the chest.

- Skin conductance (SC) or Electro-dermal Activity (EDA) is measured by using two electrodes placed on the fingers. It measures the conductivity of the skin which is a function of sweat gland activity and pore size [12].

- Electromyogram (EMG) is the measure of kinesthetics activity of muscles. This signal is measured by placing two or three electrodes on the bulb of the muscle.

- Blood Volume Pressure (BVP) is the relative measure of the amount of blood flowing in a blood vessel. Heart rate and heart rate variability can be measured from BVP.

- *Gaming*

  In [13] physiological sensors like BVP, SC, respiration etc are used to find the emotional level of a player. The level of game difficulty is modified in order to keep the level of engagement [14]. The level of motivation of the player is evaluated in [15].

- *Learning Activity*

  Physiological sensors are used to study the efficiency of different learning methods. In [16] the authors evaluate the efficiency of e-learning methods with the help SC, Heart rate and BVP. In [17] a game based learning method is used for autistic students to help them coordinate limbs, vision and hearing.

- *User Experience Study*

  The bio-sensors are used to study user experience while watching movies [19]or using a web page [18] etc. The knowledge about how user feels while using a product is of great commercial interest. In [2], Galvanic skin response (GSR) sensors are used to compare the correlation of user's response in a theater performance and video consumption . In [3] and [4], GSR sensors are used to measure the engagement of people in e-learning and a theater performance.

- *Health Monitoring*

  This is one of the major current research areas. In [20] and [21] two types of heart rate monitors are proposed which do not need direct physical attachment for taking the readings. Apple watch, Epson's Pulse sense, BACtrack S30 Breathalyzer are few health monitoring products currently available in the market.

## 2.2 Challenges in Wireless Transmission

Wireless transmission has many advantages over wired communication. It has low installation cost compared to wired communication and it is suitable for mobile applications and remote applications.

### 2.2.1 Environmental parameters

**Temperature**

Temperature affects the data delivery and link quality in wireless communication [5]. The link quality and signal strength of wireless sensor networks decrease with an increase in temperature irrespective of the sensor platform and radio chip. Temperature rise affects the performance of power amplifier and low noise amplifier negatively. So when the transmitting node is exposed to an increased temperature, the signal strength will decrease. Similarly when the receiver is exposed to a temperature increase, the received signal strength indicator (RSSI) also decreases. So in order to get the same signal strength at higher temperature, the transmitter should transmit at higher power than when the temperature is lower.

**Humidity**

The variation in humidity affects radio wave propagation. In [6] the authors found an improvement in radio wave propagation when a relative increase of humidity happens. This experiment was conducted in the potato fields using mica2Dot sensors in 433 MHz. But the results in [7] shows a reduction in transmission range in presence of fog and rain. In the later case the experiment was conducted with mica2 and mica2dot sensors.

**Foliage**

Foliage losses are common in wireless transmission in forest or cultivation areas. Foliage losses usually increases as a function of frequency [6]. When the height of the canopy is less, propagation is dominated by the lateral wave over the top of the canopy [6], [8]. The attenuation varies depending on the characteristics of the foliage.

### 2.2.2 Fading

The Radio Frequency (RF) signal reaches the sink through multiple paths. The transmission through multiple paths can result in constructive or destructive interference. Constructive interference enhances the signal whereas destructive interference degrades it. The reason for fading could be following.

- *Scattering* - It is the deviation of signal from the straight line when the signal hits an object whose size is in the order of wavelength or less.
- *Reflection* - It occurs when the signal hits a surface that is larger compare to the wavelength of the signal.
- *Diffraction* - occurs when the signal is obstructed by sharp edges.
- *Refraction* - occurs when the signal propagates through air. Refraction is the bending of the radio wave, while propagating through the atmosphere.

### 2.2.3 Path Loss

The strength of the transmitted signal decreases with distance. The free space model predicts that the received signal strength is inversely proportional to the square of the distance.

$$P_r(d) = \frac{P_t G_t {G_r}^2}{4\pi d^2 L} \tag{2.1}$$

In the above equation, $P_r(d)$ is the received power at distance $d$, $P_t$ is the transmitted power, $G_t$ is the gain of the transmitter antenna, $G_r$ is the gain of the receiver antenna, d is the distance separation between transmitter and receiver and L is the system loss factor dependent on filter loss, antenna loss and does not depend on propagation. The gain of the antenna, $G_t$ and $G_r$ is calculated as

$$G = \frac{4\pi {A_e}^2}{\lambda} \tag{2.2}$$

where $A_e$ is the effective aperture of the antenna and $\lambda$ is the wavelength of the signal. The Path Loss of the signal due to the attenuation in wireless channel can be measured from the received power and the transmitter power of the signal. It is given by

$$PL(dB) = 10log\frac{P_t}{P_r} \tag{2.3}$$

### 2.2.4 Interference

Interference can be either internal interference or external interference. These interferences cause reduction in the performance of the wireless communication system.

**Internal Interference**

Internal interference can occur when more than one sensor node transmits simultaneously in the same channel. The transmission in an adjacent channel can also cause interference. Both these interferences degrade the performance of the sensor networks. Hidden nodes are those nodes which existence is unknown to the second node. When the hidden node and the second node communicate simultaneously to a third node which is in the range of both these nodes, interference occurs. This is known as the hidden node problem.

#### External Interference

The external interference [9] is caused by coexisting networks that operate in the same frequency. For 802.15.4, the coexisting band is 802.11. Wireless Sensor Networks (WSN) operates in these unlicensed bands. The sensor node working in 2.4 GHz, is affected by communication of Wi-Fi and Bluetooth devices. Microwave ovens and cordless phones work in the same frequency. The transmission in these bands influence the data transmission of the sensor nodes and vice versa. Interference from microwave ovens cover almost half of the 2.4 GHz band [10]. This is an example of external interference which spreads to adjacent channels [10], [9]. The co-location of Bluetooth and 802.15.4 mainly affects the transmission in 802.15.4. Bluetooth use Frequency Hop Spread Spectrum (FHSS) which is hopping to a new frequency after reception or transmission of a packet. Hence Bluetooth data transmission is unaffected by interference from Wi-Fi or other electrical signals.

## 2.3 Related Works

There has been various prior works in the field of 802.15.4 and a few using the 868MHz frequency band. The state of the art is detailed in this section.

### 2.3.1 MAC Protocol: Polling

In this [29], the authors developed a embedded based wireless sensor network based on Arduino. They used star topology, in which the coordinator collects data from all the sensor nodes using the polling method. Different Polling methods like slot preemptive polling and NACK (Negative acknowledgment) preemptive polling is compared to TDMA in [30]. The focus is on on how different re-transmission methods affect the efficiency of data transmission. A study about the performance of various MAC schemes for WSNs which are powered by energy harvesters is done in [31]. Wireless Sensor networks powered by ambient energy harvesting (WSN-HEAP) can only be active for a short duration and the charging period is unpredictable. The probabilistic polling model shows high throughput and fairness and it is suitable for WSN-HEAP. In Periodic terminal initiated polling (PTIP), polling is done by the sensor node in order to get the data from the access point [34], [35].

### 2.3.2 Link quality Estimation in 802.15.4

In [27], empirical measurements of packet delivery performance of Micaz and Telos nodes are presented. The study was focused on the 2.4 GHz band. The studies show that 802.15.4 has fewer intermediate links (a pair which receives 10-90%). A variation in the received signal strength indicator (RSSI) by 2dB could make a good link poor and vice versa. The studies show that RSSI is stable over short time spans and varies over long time spans. 802.15.4 is vulnerable to interference from 802.11 and Bluetooth systems. Different Link Quality Estimators use different metrics like RSSI, PRR, RNP, ETX etc for estimating the link quality [9]. Each of these metric will evaluate only certain link properties and none of them provide a complete characterization of the network. The efficient LQE should be reactive to persistent changes and ignorant to transient changes. Short term link quality estimations help in using intermediate links which become temporarily stable to be used for packet forwarding and therefore by improving the efficiency of the network [32], [33].

### 2.3.3 Works on 868 MHz

Woehrle et al. [25] characterize the properties of low power wireless links in 868 MHz through extensive experiments using 108 GNode sensors in a sensor network test-bed called Rack. The radio configuration was 2-GFSK. Their observation is that the 868 MHz channel is less noisy compared to 802.15.4. Their experiments show that most links are symmetric over a long time span, but human activity and multi-path interference can result in time varying lossy links.

In [5] the impact of temperature on transmitting power to sensors working in 868 MHz is explained. In [2], [3] and [4] use physiological sensors working in 868 MHz for measuring the user's engagement.

# Chapter 3

# Sensor Technology

This chapter discusses the sensor technology used for the experiments in this thesis. The signals measured by the sensor are explained in section 3.1, followed by the hardware and software details and networking methods used by the sensors.

## 3.1 Basis

The physiological signal we aim at measuring is electrocardiogram (ECG). This is the measure of the electrical and muscular functions of the heart. From the ECG signal it is also possible to measure the speed at which heart beats usually expressed as beats per minute. This signal can be measured by various method like using electrodes attached to the body and by optical detection of the blood volume. The second method is used by our sensors which is known as photoplethysmography

### 3.1.1 Photoplethysmography

Recently wearable pulse sensors are build based on photoplethysmography (PPG): optical detection of blood volume changes in the micro-vascular tissue [36]. Typically, the PPG based sensors have the following parts.

- *A light source* - The commonly used light sources were Red and Infrared LED. Green LED is used as light source in existing current sensors as it has better absorptivity for oxy-haemoglobin and deoxyhaemoglobin. So the variation in reflected light can be captured better with green light compared to red and infrared.
- *Photo Detector* - photo detector (PD) collects the reflected or transmitted light from micro-vascular tissues.

The PPG sensors can work in two modes, depending on the position of the photo detector. Figure 3.1 shows the arrangement of the PD and the light source in both modes.

- *Transmission mode*- In this mode the light source and the photo detector are located in opposite directions. The light transmitted through the medium will be detected by the PD.
- *Reflectance mode*- In reflectance mode the PD will be located at the same side as the light source. The reflected light from the tissues, bone or blood vessels is then captured by the PD.

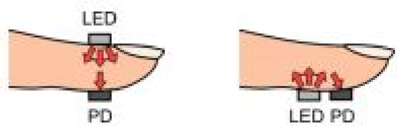


Figure 3.1: Arrangement of PD and light source in Transmission mode and Reflection mode

A cardiac cycle consists of diastole, systole and the intervening pauses. During the systolic phase arteries carry more blood volume than during the diastolic cycle. The variation of blood volume in the arteries is detected by the PPG sensor from the reflected or transmitted light from the micro-vascular tissues. Blood absorbs more light than the surrounding tissues. A decrease in the intensity of the detected light represents an increase of blood volume in the arteries. The PPG waveform and attenuation of light by the tissues is shown in figure 3.2. The reflected optical signal from the tissue corresponds to the steady component. The variation in blood volume occurring between the diastolic and systolic phase is reflected in the pulsatile part.

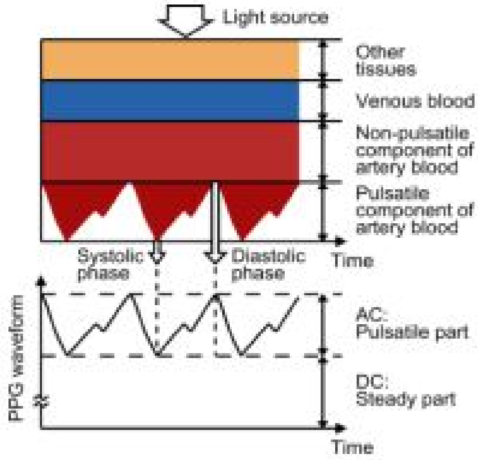


Figure 3.2: Light attenuation by tissue and PPG wave form

## 3.2 Hardware and Software

The sensors used for the study are open source Pulse sensor and the BITalino ECG sensor. The open source pulse sensor built by me and uses photoplethysmography to measure the ECG signal, where as BITalino uses the electrode method to find variation in the electrical functions of heart.

### 3.2.1 Open source sensor

The open source sensor used in the study is shown in figure 3.3. This sensor has green LED as the light source and a photo detector to collect the reflected light from the tissue. The sensor works in reflectance mode. The sensor can be connected to the finger tip, ear lobe or wrist. In our experiments the finger tip of the index finger is used as the mode of connection as it is more stable and comfortable to the user. Initially, the development board for developing the sensor was Arduino-UNO. Later the development board was changed to Jeenode as it is smaller and compact. Another advantage is that it has an inbuilt wireless communication module. Both these boards can be programmed using Arduino-IDE software. ATMEGA328 is the microcontroller in both these boards.


Figure 3.3: Pulse Sensor

**Arduino**

Figure 3.4 shows the Arduino-UNO board. The configuration included:

- *Microcontroller* - ATMEGA328
- *Operating Voltage* - 3.3V to 5V
- *Analog Input pins* - 6
- *digital Input/Output pins* -14
- *Memory* - 32 bytes Flash memory, 512 bytes EEPROM, 2 KB SRAM.

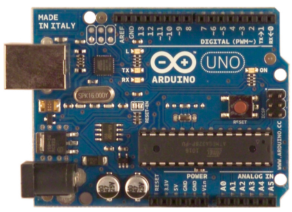


Figure 3.4: Arduino UNO Development Board

The ground and power pins were connected to GND and to the 5V pin of Arduino-UNO. The signal pin of the sensor was connected to the analog input pin A0. The board can be battery powered or can be connected to the computer through USB. A code was written in AVR C programming language to collect the data from the analog pin (A0) of the Arduino UNO board. An interrupt function was used to get the data every 2ms. The required data frequency is controlled by using a delay function. The baud rate for communication also has to be specified in the code. The code was updated to the microcontroller through the USB serial port to make the sensor measure the ECG signal.

### Jeenode

The specification of Jeenode v6 [37] is detailed below. The Jeenode Development board is shown in figure 3.5

Figure 3.5: Jeenode V6 Development Board

- *Microcontroller* - ATMEGA328
- *Operating Voltage* - 3.5V to 13V
- *Number of ports* - 4
- *digital Input/Output pins* -4
- *Analog I/O /Digital I/O pin* - 4
- *Wireless module* - RFM12B

The ground and power pins were connected to GND and to the 5V pin of the Jeenode board (port 1). The signal pin of the sensor is connected to the analog input pin (AIO1) of port 1. The jeenode board was powered from a Lithium 9-volt battery. The code used in Arduino, with slight changes to include wireless communication was uploaded to the Jeenode board using USB BUB 2, which is a USB to TTL serial adapter. RFM12B is the wireless module used by Jeenode. This works in 433 MHz, 868 MHz and 915 MHz ISM band. A short wire is used as antenna. The length of the antenna is one-fourth of the wavelength. It uses 165mm, 82mm and 78mm length wire for 433 MHz, 868 MHz and 915 MHz respectively. In Europe the frequency used is 868 MHz.

### 3.2.2 BITalino ECG Sensor

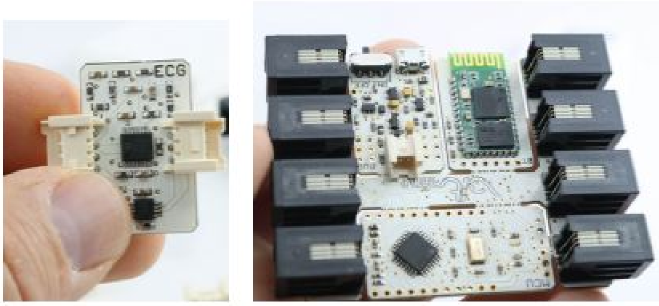


Figure 3.6: ECG sensor and BITalino Plugged board

The BITalino ECG sensor is the commercial ECG sensor used to validate the open source pulse sensor. The BITalino plugged board (figure3.6) is used for the validation of our experiments. Accelerometer, ECG, EMG, EDA and light sensor could be attached to the BITalino plugged board using RJ22 plugs. The board was powered from a Li-Po Battery (320 mAh). The wireless communication protocol used by the BITalino board is Bluetooth. Our study was restricted to sensing ECG. The ECG sensor is connected with an electrode cable. The electrical signals generated by the heart are monitored by the electrodes placed on the skin. In our study the electrodes were placed on the palm of the left and right hand.

## 3.3 Networking

The different network topologies commonly used for sensor networks are Point to Point topology, Mesh topology, Tree topology etc [39]. Point to point topology is a high capacity single channel between two sensor nodes. There is only a single path of communication between the sensors. Mesh topology is a multi-hop system in which all the sensor nodes in the network can directly communicate with each other. The sensors have more than one route to communicate with another sensor. In the tree topology the sensors form a logical tree. There are two types of nodes in a tree topology, parent node and child node. The child node senses the data and sends them to its parent node. The parent node collects the data sent by the child and send to its parent node along with the data it has sensed [40]. In the star topology all the sensors communicate to a central hub. If a sensor node needs to communicate to another sensor, it has to communicate through the central hub, so direct communication is not possible. In our system we need a bidirectional communication between the sensors and the sink. Hence we have chosen a star topology.

Medium Access Control (MAC) protocol plays a major role in the performance of the system. The MAC scheme should establish a reliable communication link between the nodes in the system. The MAC protocol ensures fair resource sharing between the sensor nodes in the network. Carrier sense multiple access (CSMA), Barkeley media access control (B-MAC), Time division multiple access (TDMA), Frequency division multiple access (FDMA) are some of the common MAC layer protocol used. CSMA is a probabilistic MAC protocol which checks the shared medium to ensure absence of traffic before transmitting the data. If a transmission is in progress, then the sensor back off from communication for a random time period and try again. B-MAC is a CSMA based protocol with clear channel assessment. It has the benefit of low power processing and collision avoidance [44]. In TDMA, each node is allocated a particular time slot to communicate. In FDMA, each node is allocated one or more frequency bands. It requires high efficiency filters in the radio hardware. ALOHA is a commonly used random access MAC protocol which is simple with low computation and overhead, but this protocol suffers from collision [43]. Polling is a collision free protocol with comparatively less overhead. In the sensor development, Polling is the MAC protocol used and it is compared against ALOHA through extensive experiments.

## 3.4 Network Topology and MAC protocol used in the system.

### 3.4.1 Star Topology: Networking Topology used in the study

The network topology used in the study is a Star Topology. The reason for selecting a star topology is that time synchronization of data becomes easy when all the sink nodes are connected and data is gathered in one laptop. Similarly, in user experience studies delay is not advisable, so the use of relay nodes in not recommended as it introduces delay to the transmission. The preference is for a one hop network. Energy is not a constraint as the sink node is connected to the laptop. The problem of single point of failure is not a concern here as the user can ensure that the sink node is working at any time. If the sink fails, it can be easily replaced with another sink by uploading the code to collect data. The sink node connected to the laptop acts as the centralized communication hub. In the star topology, all communication is routed through the sink node [40]. In the network used in the experiments, the sensor nodes do not communicate to each other directly or indirectly. The sensor nodes only communicate to the sink node. Depending on the MAC Protocol, the communication mode changes from unidirec-

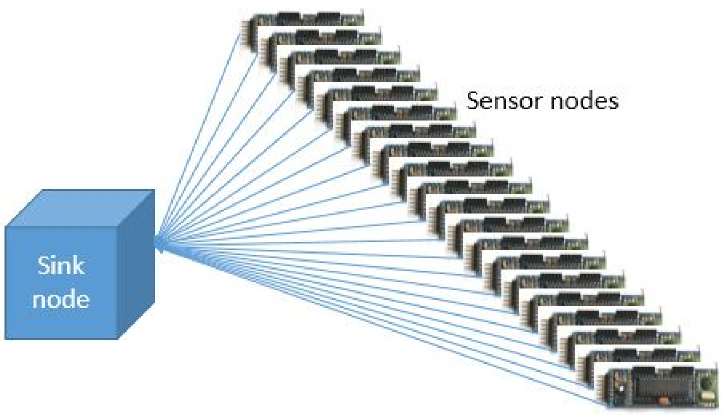


Figure 3.7: Star Topology: 1 Sink nodes and 20 clients

tional to bi-directional. The communication is unidirectional in experiments with sensor nodes using ALOHA as MAC protocol and bidirectional when the MAC Protocol is Polling.

In our system thirty sensor nodes can be connected to a single hub. The pilot study has been conducted with thirty sensors and we found that the number of packets received by the sink node is reduced when thirty clients are used. So the maximum number of clients connected to a hub in our network is twenty, as shown in Figure 3.7 . When the number of sensor nodes was increased, three star networks were created with 20 sensors in each.

### 3.4.2 MAC Layer Protocol

The MAC protocols used by the open source sensors in this study are detailed in this section. Polling is the MAC layer protocol used by the sensors. In order to understand the efficiency and performance of Polling, it is compared against ALOHA, a random access MAC protocol.

**ALOHA**

The ALOHA protocol was developed by Norman Abramson and his colleagues at the University of Hawaii in the 1970s [49]. Initially it was used in Satellite Communication [48]. Later it began to be used as a MAC layer protocol in local area networking. The major features of ALOHA are the following.

- The nodes use a shared medium for communication
- Fixed length frames are used
- A node starts transmission when it has a frame to send regardless of the state of the channel. The sender has to listen to the channel to understand whether the transmission was successful. The sender retransmits the packet after backing off for a random time if the previous transmission suffered from collision. In our study we are not using retransmissions to send the lost packet. Time of occurrence of an event is important for our application. Retransmitted packet will reach the sink at a later point of time than the response time. Also, retransmissions introduce congestion to the network. Hence the MAC protocol used is pure ALOHA without retransmissions.

### 3.4.3 Polling

In Polling the sink node allocates time slots for each node to send data. The sensor nodes will transmit data only in the allocated time slot. Time allocation is done by the sink node using a Polling message. If there are 10 sensor nodes say *S1* to *S10*, the sink node will send a polling message to S1 first and wait for 4ms. On receiving the polling message, the sensor node *S1* sends data to the sink node. Then the sink node will send polling message to S2 and wait for 4ms for the data. Similarly, the sink node will poll one by one till it reaches the last node *S10*. After sending polling messages to all the sensors, the sink will start to poll the first sensor again and repeat the round. In this way only one sensor node will send data at a time, which will reduce collision which may occur when more than one node try to send packets simultaneously.

Let's say that the Sink node sent a polling message to *S1* and waited for 4ms. The sink node has not received any packet from sensor node *S1*. Then the sink node will poll *S2* without waiting for the packet from *S1*

In this method, there are two possibilities for unsuccessful packet delivery.

- The sensor node does not receive the polling message from the sink node.
  In this case the sink node will wait for 4ms to get the packet. The sink node will send the polling message to the next sensor node irrespective of whether it received or missed the packet.

- The sink node missed the packet sent by the sensor on receiving the polling message from the sink. The sensor node send the data, but the sink node did not receive the packet within the 4ms. The sink node does not wait for the packet delivery from the sensor node and the sink will not resend the polling message to that sensor node again. The sink node will send a polling message to the next sensor node and wait for the packet delivery.

# Chapter 4

# Experiments

The experiments conducted to validate the performance of the open source sensor are explained in section 4.1. The experiments conducted to find the maximum range of the sensors is explained in section 4.2. Section 4.3 discusses the experiments done to find the receiving rate of the sink node. Theoretically the time for receiving a packet by the sink node is said to be 2ms to 4ms. Here through a set of experiments we find the practical receiving rate of the sink node which is important for real life experiments. The result is also explained in this section. In section 4.4 the impact of location of placement of the sink node on the network performance is being studied. In an auditorium while conducting experiments the sink node can be placed in different locations. The sink node can be placed on the outer edge, in a corner or in the middle of the sensors deployed area. A set of experiments were done to study the influence of each of this location on the packet reception efficiency of the sink node. Initially the experiments were conducted with a group of 20 sensors and a sink nodes. Later the experiments were repeated with two and three groups of 20 sensors and a sink node. Polling was the MAC protocol used by the sensors in these experiments. The experiments were conducted in a big hall on the ground floor of the office building. The results from these experiments will help the researchers to place the sink node in the appropriate position to get maximum efficiency as per the sensor deployment pattern.

## 4.1 Validation Test of Open source sensor

Figure 4.1: Image of a subject taking part in validation test.

In order verify our open source pulse sensor, the result it provides are validated against the commercial BITalino ECG sensor. To conduct the validation test five participants were recruited, they are all researchers at the Distributed and Interactive systems group at Centrum Wiskunde & Informatica. The electrodes of the BITalino ECG sensor were connected to the palm of the left and right hand of the participants. The pulse sensor was connected to the finger tip of the left hand index finger. After connecting the sensors, the participants watched a video of 88s. In order to get the beginning time and end time of the video, a screen recorder was run in the laptop in which the video was played. The image of a participant taking part in validation test is shown in figure 4.1.

The sampling rate of both sensors were 100 Hz. The communication protocol of the BITalino sensor was bluetooth, while the data from the open source sensor was collected through serial communication. Python code was used to collect the data from both sensors. Spearman's correlation is used to measure the statistical relationship between the collected data from both

| Subject id | ECG Signal from BITalino | | ECG signal from Pulse sensor | |
|---|---|---|---|---|
| | Skewness (SE) | Kurtosis (SE) | Skewness (SE) | Kurtosis (SE) |
| 1 | 0.682 (0.026) | 6.216 (0.053) | 1.562 (0.026) | 2.507 (0.053) |
| 2 | 0.473 (0.026) | 1.958 (0.053) | 1.662 (0.026) | 2.607 (0.053) |
| 3 | 0.499 (0.026) | 0.719 (0.053) | 0.999 (0.026) | 1.102 (0.053) |
| 4 | 1.895 (0.026) | 10.047 (0.053) | 1.609 (0.026) | 2.545 (0.053) |
| 5 | 0.441 (0.027) | 1.863 (0.054) | 1.596 (0.026) | 2.662 (0.053) |

Table 4.1: Result of the normality Test for each subject. Standard error is shown in braces.

sensors. Spearman's correlation coefficient gives the strength of monotonic relationship between a pair of data [41]. Correlation between the collected data is measured using SPSS tool.

### 4.1.1 Result of the validation test

The data collected from the sensors were aligned according to the timing of the video. The Pulse sensor received 8636 packets in 88 second from each subject. The BITalino sensor received 8800 packets from each subject in 88 second. The missing values in the ECG signal from the open source pulse sensors were manually inserted by finding the average of the ECG signal value obtained in the previous and later time. Then the correlation was calculated for the 8800 data points. The ECG signal obtained from both BITalino sensor and the open source pulse sensor were tested for normality. SPSS tool was used for the normality test. The visual inspection of their histograms, normal Q-Q plots and box plots shown that the signals are not normally distributed. The skewness and kurtosis of the ECG signal obtained from the two sensors for each subject is shown in table 4.1. The standard error is shown in the braces. When the skewness and kurtosis value were divided with the standard error, the result should be within -1.96 to +1.96 for the signal to be normally distributed [47]. But for the values shown in the table the result does not fall in that interval. So the ECG signals are not normally distributed. So Pearson's correlation method cannot not be used to find the correlation between the ECG signals. Since the signals had monotonic relationship, we used Spearman's correlation to measure the correlation between the two ECG signals.

The $r$ and $pval$ obtained for each subject's data is shown in table 4.2. The $r$ value obtained is greater than 0.59. So there exist strong correlation between the ECG signals obtained from the pulse sensor and BITalino sensor. *Pval* is obtained from the significance test. This test checks the null hypothesis $H_0$ which suggest that there is no monotonic correlation in the population against $H_1$ which says that there exist a monotonic correlation between the population.

$H_0 : r = 0 \quad H_1 : r \neq 0$

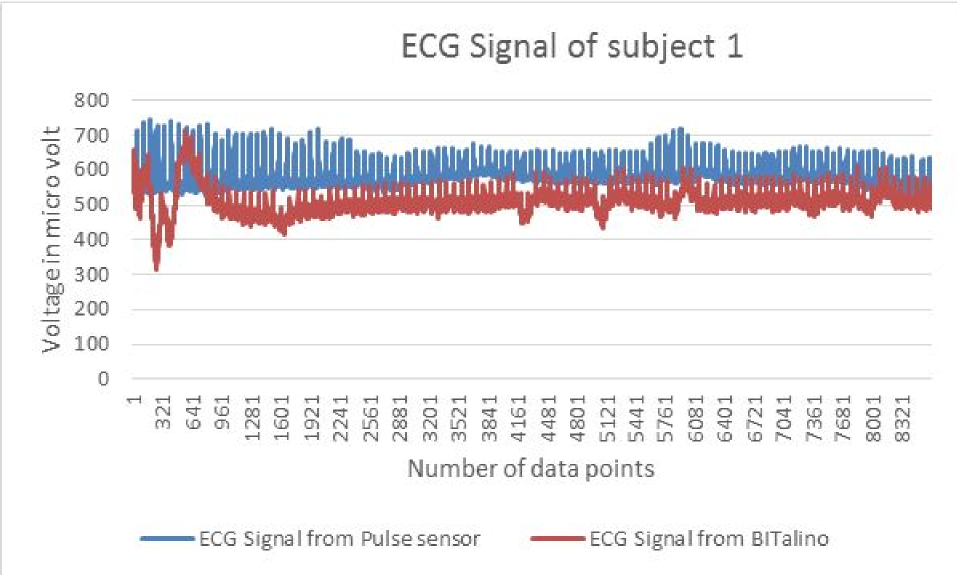


Figure 4.2: ECG Signal obtained from Pulse sensor and BITalino for subject 1.

The *pval* obtained for the tests are very small (lesser than 0.000), hence the null hypothesis is not valid. So there is a monotonic correlation between the ECG signals obtained from the open source pulse sensor and the commercial BITalino sensor. The correlation is significant at the level of 0.01 (2 tailed). The ECG signal obtained from the pulse sensor and BITalino sensor for subject 1 is shown in figure 4.2. The error in the ECG signal obtained by the BITalino sensor is due to the movement of hand.

| Subject id | $r$ | *pval* |
|---|---|---|
| 1 | 0.710 | 0.000 |
| 2 | 0.609 | 0.000 |
| 3 | 0.690 | 0.000 |
| 4 | 0.637 | 0.000 |
| 5 | 0.597 | 0.000 |

Table 4.2: $r$ and *pval* obtained in correlation test of ECG Signal from BITalino and Pulse sensor

## 4.2 Range of the open source pulse sensors

A set of experiments were performed to find the maximum range of the open source pulse sensors. The sensors were kept at a distance of 10 m, 20m, 30m , 40m, 50m, 60m and 70m from the sink node. The experiments were done with 1 sensor, 10 sensors and 20 sensors. The experiment was conducted initially with ALOHA as the MAC protocol of the sensors. The experiment was repeated with Polling as the MAC protocol. Some experiments were conducted by keeping the sensors in a closed room and the sink node outside the room. This experiment was conducted to study the impact of hindrance on the network performance. The experiment was conducted for a duration of 14s.

When ALOHA was used as the MAC protocol by the sensors, the sink node received no packets from the sensors beyond 50m distance. For Polling the maximum range attained was 60m. The maximum range of the sensors was 50m for ALOHA and 60m for Polling. When the number of sensors were increased the packet loss increased greatly for ALOHA. For Polling, there was a slight increase in packet loss with increase in number of sensors. The hindrance between the sensor and the sink node increased packet loss greatly. The number of packets received from each sensor was almost equal for Polling. For ALOHA the number of packets received from each sensors varied greatly.

## 4.3 Experiment to find the receiving rate of the sink node.

As per the theory the sink node takes 2ms to 4ms to receive one packet. One minute is 60000ms. So in 1 minute the sink node should receive 30000 to 15000 packets. We conducted a pilot study with polling as MAC protocol for 10 sensors for 14s duration. The sensors were placed at 10m distance from the sink node. The efficiency was calculated using 4ms as the receiving time. Then the efficiency we got was only 61% which was close to the 50% efficiency we got for ALOHA with same arrangement. We did not expect such huge packet loss for a collision free

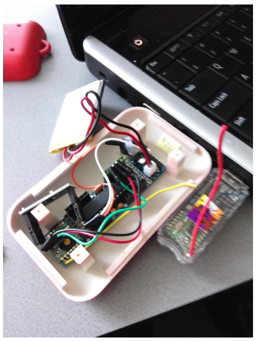

Figure 4.3: The arrangement of the sensor closer to the sink node.

protocol like polling. Hence we conducted an experiment with one sensor node and one sink node to find the exact receiving rate of the sink node.

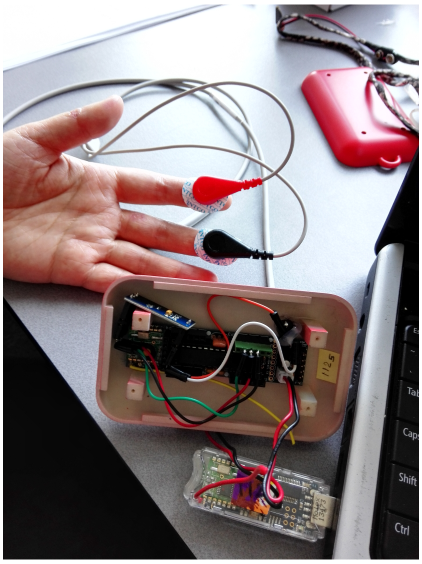

Figure 4.4: The arrangement of GSR sensor closer to the sink node

In this experiment the sink node and sensor node were placed very closer to each other. The sensor node (Jeenode) was programmed to send noise when the sink node polls. The sink node was connected to a laptop. The sink node received packets from the sensor node for a duration slightly more than 1 minute. Then the same experiment was repeated with GSR sensor and ECG sensor. The data was cut for exact 1 minute duration. The figures 4.3 and 4.4 shows the arrangement of the jeenode sensor and the GSR sensor closer to the sink node.

In one minute, 9719 packets, 9599 packets and 9600 packets were received from the Jeenode sensor , GSR sensor and ECG sensor respectively. That is in 1 second 162 packets, 160 packets and 160 packets were received from Jeenode sensor, GSR sensor and ECG sensor. From the results, the average receiving rate of the sink node is 160 packets/ second. On an average, the sink node will receive 9600 packets in 1 minute. Lets say **T** is the time for the sink node to receive one packet. From the results of the experiments $\mathbf{T} = 60000/9600 = 6.25ms$. Even though theoretically the receiving time for 1 packet is maximum 4ms, the result from the experiments shows 6.25ms as the receiving time.

## 4.4 Experiment 1: Placement of the sink node

The experiments were conducted to study the influence of location of the sink node on the performance of the sensor network. The experiments were conducted in a large hall. Three groups of sensors were used in this experiment. Each group had 20 sensors and a sink node. The sink node can be placed at different location like on the edge of the sensor deployed area, on the corner of the sensor deployed area, at the center of the sensor deployed area etc. From the pilot study we found that Polling had much better performance than ALOHA with increase in number of sensors. So Polling was used as the MAC Protocol by the sensors.

### 4.4.1 Placement of the sink node in different locations with a group of 20 sensors

The group 1 consisted of a Pulse sensor, a GSR sensor and 18 sensors programmed to send noise. The pulse sensor was connected to the finger tip of the index finger of a subject. The GSR sensor was connected to the tip of the middle finger and the index finger of another subject. The figure 4.5 shows the arrangement of 20 sensors in the hall. The numbers represent the node id of the sensors. The node id 1 and 2 were pulse sensor and GSR sensor respectively.

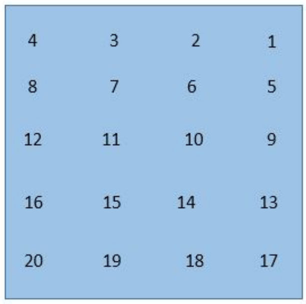


Figure 4.5: Arrangement of a group of 20 sensors

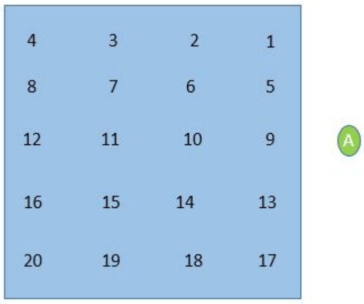


Figure 4.6: Sink node is placed on the edge of the sensor deployed area.

**Case 1: Sink node placed on the edge of the sensor deployed area**

Here the sink node was placed on the edge of the sensor deployed area. In the figure 4.6, $A$ represents the position of the sink node. Placing the sink node in the other three edges are not considered as they are equivalent to placing the sink node in the position $A$. The sink node placed at the position $A$ collected the data from the sensors for a duration above 1 minute . Timers were used to monitor the duration of each experiment. The experiment was repeated thrice in this arrangement.

**Case 2: Sink node placed on the corner of the sensor deployed area**

In this case, the sink node was placed in one of the corners of the sensor deployed area. This position is equivalent to placing the sink node in any of the other three corners. The experiment was repeated thrice by keeping the sink node in position $B$.

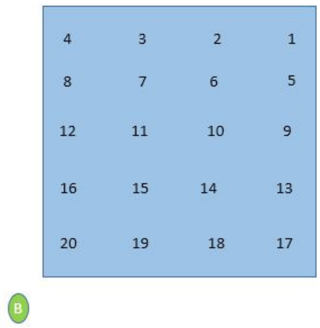


Figure 4.7: Sink node is placed on the corner of the sensor deployed area.

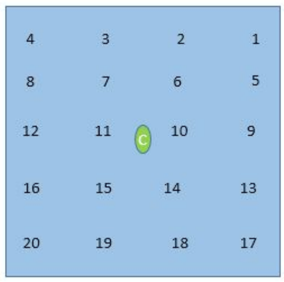


Figure 4.8: Sink node is placed on the corner of the sensor deployed area.

**Case 3: Sink node placed on the center of the sensor deployed area**

The sink node is placed in the center of the sensor deployed area as shown in figure 4.8. The position of the sink node is represented by $C$. In this arrangement the sink node is closer to sensor nodes in the center and farther from the sensor nodes in the outer edges. The experiment was repeated thrice in this arrangement.

### 4.4.2 Placement of the sink node in different locations with two groups of 20 sensors

In this experiment two groups of sensors were used. Group 1 had a GSR sensor, a pulse sensor and 18 sensors sending noise data. In group 2 all the sensors were programmed to send noise. Each group had a sink node which collects data send by the respective group of sensors. The schematic representation of arrangement of two groups of sensors is shown in figure 4.9. The numbers in black colour represent the node ids of the sensors in group 1 and red numbers denote node ids of the sensors in group 2. Figure 4.10 shows the arrangement of the sensors in

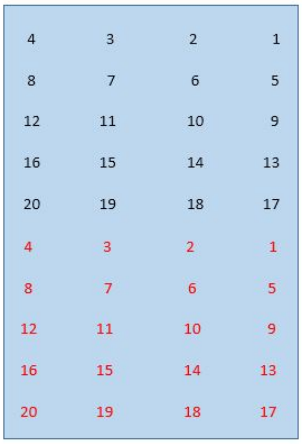


Figure 4.9: Arrangement of two groups of sensors in the hall

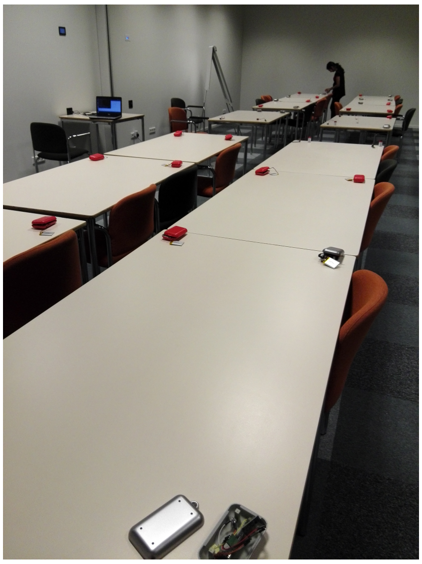

Figure 4.10: Arrangement of 40 sensors in the hall

the hall. In these experiments, data was collected by placing the sink nodes in three different locations.

Figure 5.4 shows the schematic representation of arrangement of the sink nodes in different location in the sensor deployed area. The placement of sink nodes on the outer edge of the sensor deployed area is shown as $A$. $B$ represents the placement of the sink nodes on the corner of the sensor deployed area. The sink nodes placed in the center of the deployed area is shown by $C$ in the figure. The experiment was repeated thrice in each of these arrangement.

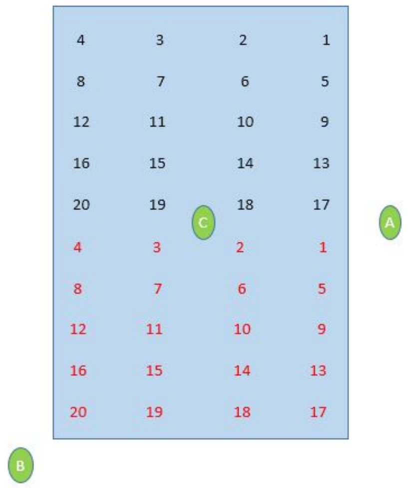


Figure 4.11: Arrangement of the sink nodes in different location in sensor deployed hall

### 4.4.3 Placement of the sink node in different locations with three groups of 20 sensors.

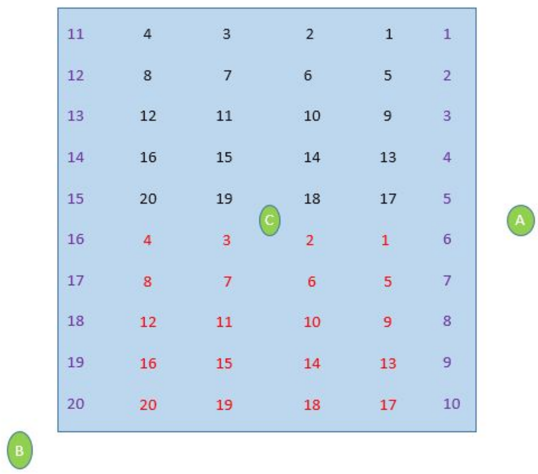


Figure 4.12: Arrangement of the sink nodes and sensors in the hall

In these experiments there were three groups with 20 sensors each. Group 1 had 20 sensors which included a GSR sensor, a pulse sensor and 18 sensors sending noise data. In group 2 and group 3, all the 20 sensors in each group were programmed to send noise. In figure 5.5, the numbers in black, red and violet represent node ids of sensors in group 1, group 2 and group 3 respectively. The sink node placed on the outer edge of sensor deployed area is shown by *A*. The sink nodes placed in the corner is shown by *B* and sink node placed in the center of the sensor deployed area is shown by *C*. The sink nodes of group 1 and group 2 were connected to a laptop and sink node of group 3 was connected to another laptop. Experiments were conducted by keeping the 3 sink nodes in any one of this position at a time. Each experiment was conducted for more than 1 minute duration. The experiments with sink node placed in the edge and corner of the sensor deployed area were repeated two times. The experiment with sink node placed in the center of the sensor deployed area was conducted only once.

# Chapter 5

# Results and Discussion

In this chapter we discuss the results obtained from the experiments conducted. The experiments were detailed in chapter 4. The experiments were conducted for a duration slightly more than 1 minute. The recorded data was cut according to 1 minute duration. Each of the experiments were repeated three times to get more accurate data. The data analysis was done using python script. The polling is done from 1 to 20, so the packet received will also be in that order. The script was used to find the packet loss by counting the number of packets not received by the sink node from each sensor node in the entire duration.

## 5.1 A group of 20 sensors and a sink node.

The result of the experiments conducted with 20 sensors and a sink node is discussed here. The 20 sensors were arranged in the hall. The sink node was placed in different locations to find the impact of the sink node placement on the network performance. The experiment was repeated thrice with the sink node placed in each of this location. Sensors with node id 1 was a pulse sensor and node id 2 was a GSR sensor. Other sensors were programmed to send noise. Polling was the MAC protocol used by the sensors.

| Test | Total no. of packets send by 20 nodes | Total no. of packets received by the sink | No. of Packets lost | Total Packet loss % | Efficiency % |
|---|---|---|---|---|---|
| Test 1 | 9482 | 9256 | 226 | 2.39 % | 97.61 % |
| Test 2 | 9444 | 9193 | 251 | 2.66 % | 97.44 % |
| Test 3 | 9444 | 9199 | 245 | 2.59 % | 97.41% |

Table 5.1: The network performance table of a group of 20 sensors with the sink node placed on the outer edge.

### 5.1.1 Sink node placed in the outer edge of the sensor deployed area.

Here we discuss the result of experiments conducted with 20 sensors and sink node placed in the outer edge of the sensor deployed area. The experiments were repeated three times. The table 5.1 shows the total number of packet send, received and lost during the entire experiment duration for the three tests. The average packet loss for the three tests was 2.55 %. The average efficiency was 97.45 %. The least number of packets were received from sensor node 11. The average packet loss for sensor node 11 was 43.19 %. The sensor node 1 also had an average packet loss of 6.35 %. For all other sensors the packet loss was close to 0%.

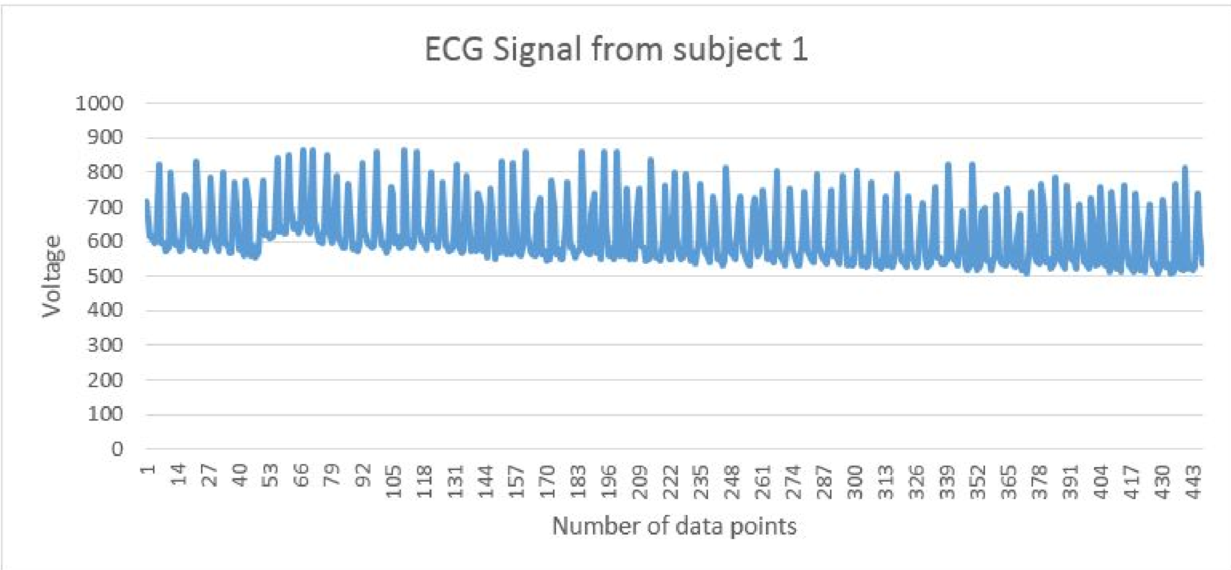


Figure 5.1: The ECG signal obtained by the sensor node 1 from subject 1.

The ECG signal and GSR signal obtained from subject 1 and 2 for test 2 is shown in figures 5.1 and 5.2. The GSR signal was very good as there was no packet loss. The ECG signal was

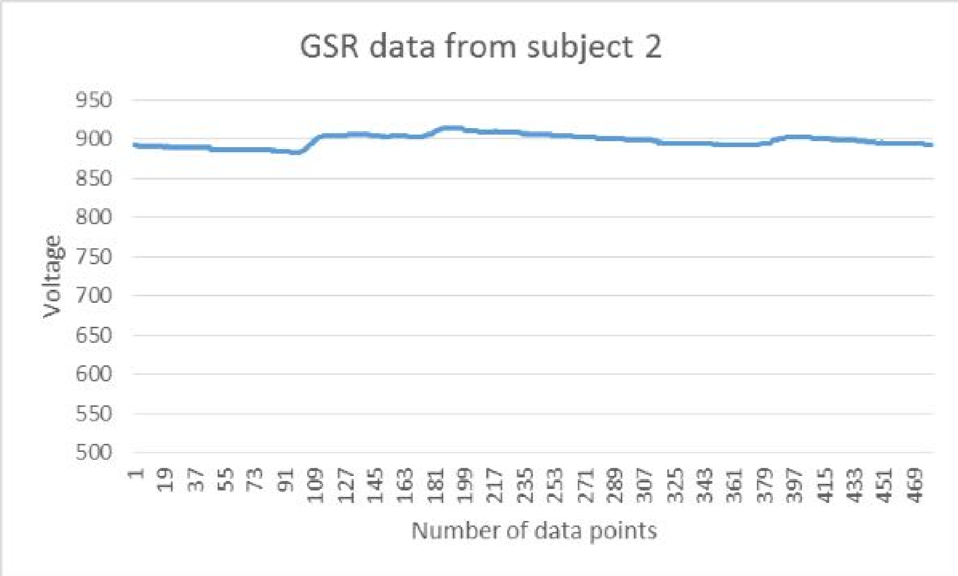


Figure 5.2: The GSR signal obtained by the sensor node 2 from subject 2.

| Test | Total no. of packets send by 20 nodes | Total no. of packets received by the sink | No. of Packets lost | Total Packet loss % | Efficiency % |
|---|---|---|---|---|---|
| Test 1 | 9426 | 9165 | 261 | 2.77% | 97.23% |
| Test 2 | 9436 | 9202 | 234 | 2.48% | 97.52% |
| Test 3 | 9397 | 9093 | 304 | 3.24% | 96.77% |

Table 5.2: The network performance table of a group of 20 sensors with the sink node placed on a corner of the hall.

also good even though there was a packet loss of 6.35 %. All the details of the ECG signal were visible from the obtained ECG signal. The packet loss was not severe.

### 5.1.2 Sink node placed in a corner of the sensor deployed area.

The table 5.2 shows the number of packet send, received and lost during the three experiments. The average efficiency of the sensor network when the sink node was placed in a corner was 97.17 %. The average packet loss in this arrangement was 2.83 %. The packet loss was highest for sensor node 11 (43.17 %) followed by node id 1 (4.89 %). Sensor nodes 3, 4, 6, 8 and 9 had an average packet loss 2.13 %, 0.78 %, 2.26 %, 1.35 % and 1.49 % respectively. The packet loss for other sensor nodes were almost zero.

All the packets send by GSR sensor were received by the sink nodes. There was an average packet loss of 4.89 % for ECG sensor. This packet loss doesn't effect the characteristics of the

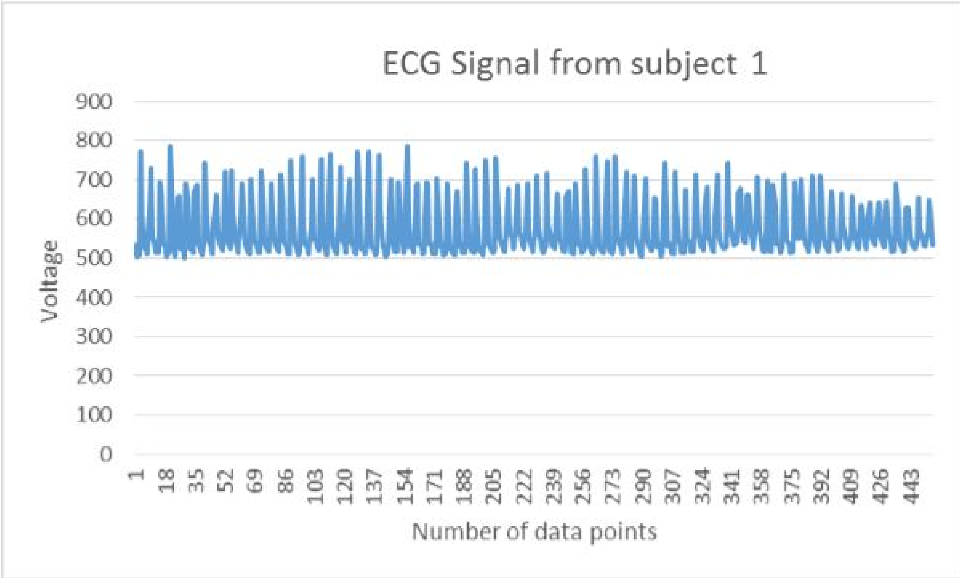


Figure 5.3: The ECG signal obtained by the sensor node 1 from subject 1 when sink node was placed in a corner of the hall.

ECG signal. The ECG signal obtained by sensor nodes 1 is shown in figure 5.3.

### 5.1.3 Sink node placed in the center of the sensor deployed area.

| Test | Total no. of packets send by 20 nodes | Total no. of packets received by the sink | No. of Packets lost | Total Packet loss % | Efficiency % |
|---|---|---|---|---|---|
| Test 1 | 9427 | 9172 | 255 | 2.70 % | 97.30 % |
| Test 2 | 9429 | 9177 | 252 | 2.67 % | 97.33 % |
| Test 3 | 9429 | 9187 | 242 | 2.57 % | 97.43 % |

Table 5.3: The network performance table of a group of 20 sensors with the sink node placed in the center of the sensor deployed.

The sink node was placed in the center of the sensor deployed area. The number of packets send by the 20 sensors, the number packets received by the sink node, packet loss and efficiency for the three tests are shown in table 5.3. The average efficiency of the sensor network was 97.35 %. The average packet loss was 2.65 %. There was a packet loss of 46.39 % and 5.66 % for sensor node 11 and sensor node 1. The packet loss for all other sensors were nearly zero. The GSR sensor had no packet loss and ECG sensor had a packet loss of 5.66 % which is tolerable as it does not effect the characteristics of the signal.

The placement of the sink node was not significant for one group of sensors. The average efficiency was 97% for all the arrangement of the sink node. The packet loss of sensor node 11 was high. That may be due to fault in the node. The packet loss for other sensors were limited. Overall the efficiency was very good for all the location of placement of the sink node.

## 5.2 Two groups with 20 sensors and a sink node in each group

This section discusses the result obtained with 40 sensors and 2 sink nodes. A group of 20 sensors were placed in one side of a hall and the other 20 sensors on the other side of the hall. The sink nodes were connected to a single laptop. We have also tried collecting data by connecting one sink node to one laptop and connecting the second sink node to another laptop. This did not show any difference in the packet reception efficiency compared to the sink node connected to the same laptop. So further experiments were conducted with both sink nodes connected to the same laptop.

| Position of the sink node | Efficiency % | | | Packet Loss % | | | Total Packet loss % | Efficiency % |
|---|---|---|---|---|---|---|---|---|
| | Test 1 | Test 2 | Test 3 | Test 1 | Test 2 | Test 3 | | |
| Edge | 45.85% | 54.92% | 50.63% | 54.15% | 45.08% | 49.37% | 49.54% | 50.46% |
| Corner | 45.18% | 45.54% | 39.83% | 54.82% | 54.46% | 60.17% | 56.48% | 43.52% |
| Center | 65.58% | 65.45% | 59.75% | 34.42% | 34.45% | 40.25% | 36.41% | 63.59% |

Table 5.4: The network performance table for 40 sensor network with different arrangements for sink nodes

The table 5.4 shows the percentage packet reception efficiency and packet loss for the three tests for different sink node arrangements. The rows 1, 2 and 3 shows the packet loss and efficiency when the sink node was placed on the edge, corner and center of the sensor deployed area respectively. The packet reception efficiency is almost 20% and 10% more when the sink node was placed in the center compared keeping it in the corner or edge of the sensor deployed area. This is because when the sink node was placed in the center, the two groups form two halves of the rectangular sensor deployed area. The upper half corresponds to group 1 and lower half corresponds to sensors in group 2. Here the chance of collision is lesser compared


Figure 5.4: The arrangement of sensor nodes in the hall and the sink node placed in the center of the deployed area.

to the other arrangement as the transmission path between sensors and sink nodes does not overlap much. In this arrangement the packet loss was least for sensor node 1 of each group. The average packet loss was 9.14 % for ECG sensor (node id 1 of group 1) and the packet loss was 3.34% for sensor node 1 of group 2. The least packet loss for node id 1 of group 2 may be because of the closer location of the sensor to the sink node. When the sink node was placed in the corner and edge of the sensor deployed area, the packet loss for ECG sensor was 31.38% and 39% respectively. The figure 5.5 shows the ECG signal obtained from the subject 1 when the sink node was placed on the center of the sensor deployed area. The sink node received 417 packets in one minute, that is almost 7 packets/second. A packet loss of nearly 10% is not suitable for ECG signal as all the deflections or the details of the ECG waveform is not visible from the obtained signal. The GSR sensor had a packet loss of 49.15%, 47.01% and 12.54% when the sink node was placed on the edge, corner and the center of the sensor deployed area respectively. The GSR signal obtained from subject 2 when the sink node was placed in the center of the sensor deployed area is shown in figure 5.6. The packet loss was 11.50%. The sink node received 406 packets per minute, that is nearly 7 packets/second. For obtaining a good GSR signal this data rate is good enough. For both the physiological sensor the packet loss was least when the sink node was deployed in the center of the two groups of sensors. So the

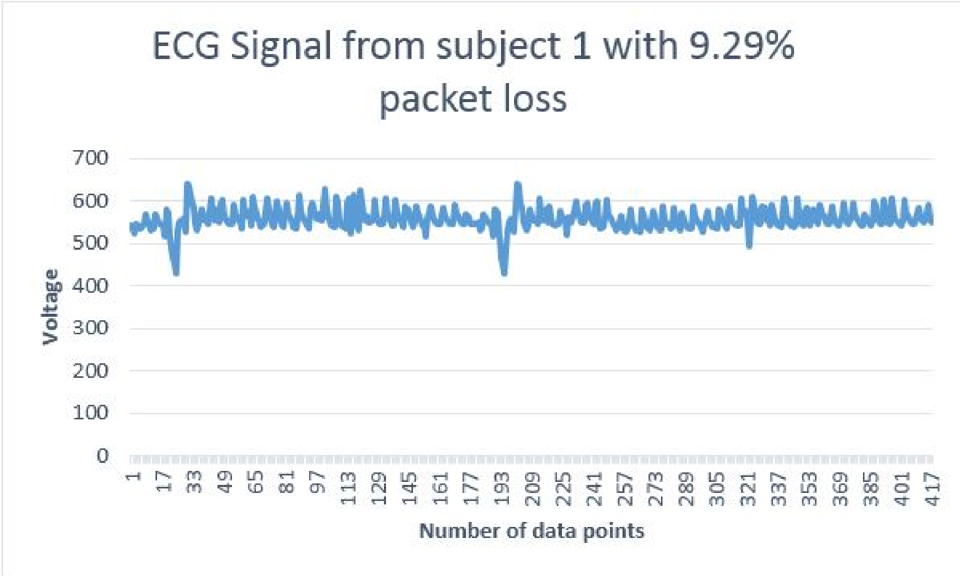


Figure 5.5: The ECG signal obtained from subject 1 when the sink node was placed in the center of the deployed area.

| Position of the sink node | Efficiency % | | Packet Loss % | | Total Packet loss % | Efficiency % |
|---|---|---|---|---|---|---|
| | Test 1 | Test 2 | Test 1 | Test 2 | | |
| Edge | 34.60% | 35.92% | 65.40% | 64.08% | 64.74% | 35.26% |
| Corner | 23.91% | 25.05% | 76.09% | 74.95% | 75.52% | 24.48% |
| Center | 23.04% | - | 76.96% | - | 76.96% | 23.04% |

Table 5.5: The network performance table for 60 sensors network with different arrangements for sink nodes

experiment results shows that when two groups of sensors are arranged in opposite sides of a hall, it is better to keep the sink node in the center of the two groups.

## 5.3 Three groups with 20 sensors and a sink node in each group

This section discusses the result obtained from experiments conducted with 60 sensors and three sink nodes. In this arrangement data was collected by connecting two sink nodes in the same laptop and the third sink node in another laptop. The pilot study had shown that the use of one or more laptop did not affect the data collection efficiency. Two tests were conducted by keeping the sink nodes on the edge of the sensor deployed area and on the corner of the sensor

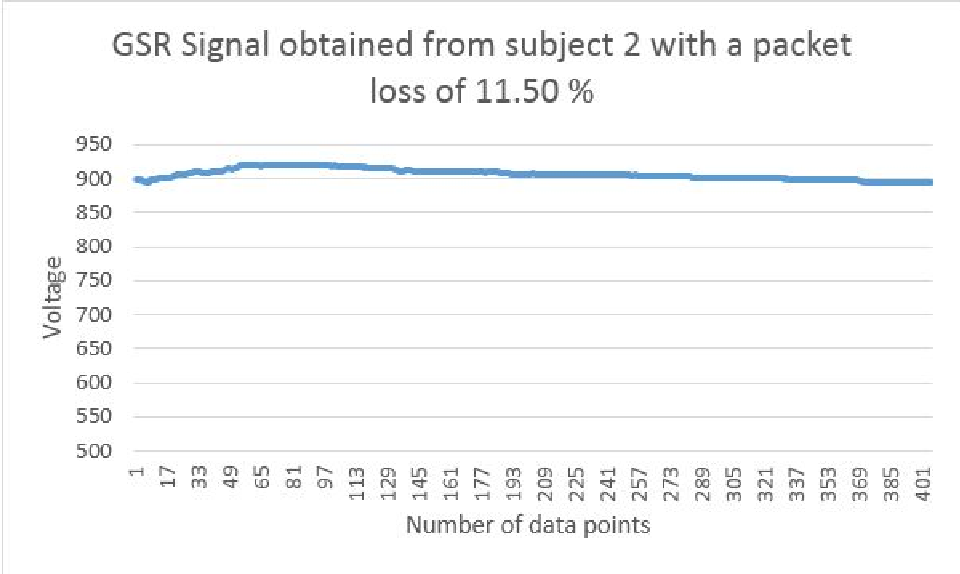


Figure 5.6: The GSR signal obtained from subject 2 when the sink node was placed in the center of the deployed area.

deployed area. Due to time limitation only one test was conducted by keeping the sink node in the center of the sensor deployed area. The table 5.5 shows the packet loss and efficiency of the group of 60 sensors when the sink node was placed in different positions. The rows 1, 2 and 3 represent the efficiency and packet loss when the sink node was placed in the edge, corner and center of the sensor deployed area respectively. In this case the efficiency was maximum when the sink node was placed in the edge of the sensor deployed area. The efficiency was minimum when the sink node was placed in the center. The ECG sensor had an average packet loss of 60.78%, 74.63% and 70.78% when the sink node was placed in the edge, corner and center of the deployed area respectively. The packet loss was 78.38%, 71.33% and 89.65% for the GSR sensor when the sink node was placed in the edge, corner and center of the sensor deployed area. Here majority of the packets send is not received by the sink node. The greater packet loss in this case is due to the collision in the network when three groups of sensors were used. When multiple group of sensors collocate more than one sensor node will be sending data simultaneously. This simultaneous data transmission results in collision.

## 5.4 Impact of collocation of groups on sensors network performance

| No. of groups of sensors | Efficiency % | | | Packet Loss % | | | Average Packet loss % | Average Efficiency % |
|---|---|---|---|---|---|---|---|---|
| | Edge | Corner | Center | Edge | Corner | Center | | |
| One | 97.45% | 97.17% | 97.35% | 2.55% | 2.83% | 2.65% | 2.67% | 97.32% |
| Two | 50.46% | 43.52% | 63.59% | 49.54% | 56.48% | 36.41% | 47.47% | 52.53% |
| Three | 35.26% | 24.48% | 23.04% | 64.74% | 75.52% | 76.96% | 72.31% | 27.59% |

Table 5.6: The network performance table for different group of sensors for various arrangement of sink nodes

In this section we discuss the effect of collocation of groups on data receiving efficiency of the sink node. The MAC protocol of the sensor nodes was Polling, which is a collision free protocol.

The table 5.6 shows the packet loss and efficiency for various arrangement of sink nodes and for different number of groups of sensors. The average efficiency decreases with increase in the number of groups. When there is only one group of sensors, the sink node polls only one sensor at a time. So at a particular time only one sensor node will be communicating to the sink node. So there is no collision in the channel. When the number of groups is increased to 2, there will be two sink nodes controlling the communication of the group of sensors. The sink node of group 1 polls one sensor node. There is a chance for the sink node of group 2 to poll a sensor node in group 2 in the same time. There is a chance for the polling message to have collision as both the groups use same physical layer for communication. Even if the polling message does not collide, there is a great chance for the data send by the sink nodes to collide. This problem is due to the random polling done by the sink nodes of each group. There is no exact timing for the sink nodes to poll. For example, if the sink node of group 2 polls only after say 7ms after sink node of group 1 polls. But such algorithms need strict time synchronization between the sink nodes which is difficult to attain.

The efficiency further reduces when the number of groups is increased to three. Here the probability of collision is more compared to the previous case as there can be a maximum of three simultaneous data transmission occurring in the channel. From the table it is clear that packet loss is more than 60 % for all the arrangement of sink nodes in the sensor deployed area.

This much packet loss is not good for physiological sensors as the signal characteristics will be lost.

For a single group of sensors, the arrangement of sink node in different location had not much importance. From the result of the experiments it is clear that the efficiency was 97% for all the three arrangements. This is because there was no collision in the network, hence the sink position doesn't had any impact. But when 2 groups of sensors were used, the packet loss was minimum when the sink node was placed in the center of the sensor deployed area. This might be due to sensor arrangement. The two groups of sensors were arranged to the two sides of the hall. When the sink node was placed in the middle of the hall, one group was towards the left side of the sink node and the other group on the right side of the sink node. The results show that this arrangement reduces collision between the two groups. The results show that for three group of sensors with two groups arranged to the two sides of the hall and the third group of sensors arranged to the outer edges (10 each in two edges) the packet loss was minimum when the sink node was placed on the edge of the sensor deployed area. But still the packet loss was very high and not suitable for physiological sensors.

# Chapter 6

# Conclusion

The main goal of the thesis was to understand the performance of physiological sensor in wireless networking. The study was done using the 868 MHz frequency band, which has little external interference as there are not yet many devices working in this frequency. The use case considered was to study user experience in crowded environments like a theater play or a movie show. In user experience studies data loss is not advisable as it will change the characteristics of the signal. Before selecting a MAC protocol for studying user's experience we should do extensive testing to see how suitable it is for the application. Extensive experiments were done in order to understand the effect of hindrance, number of sensors and distance on the network performance. The protocols used were ALOHA and Polling without acknowledgments and retransmissions in order to make them suitable for time constrained application like user experience study, gaming, health monitoring etc.

The results of the experiments show that the packet loss for Polling was less where as ALOHA had great packet loss. Both protocols shown the efficiency reduction due to distance and number of sensors. Polling shown better fairness for a group of sensors whereas in ALOHA the fairness was low. In a user experience study having fairness is very important. The experience of the entire group is considered for inferring the general response. It is not good if the data we get have few data points for a set of sensors and more data points from 1 or 2 sensors. Our results show that it is better to use 1 sink node and a maximum number of sensors instead of using more sensors with more sink nodes in the same area. Otherwise the auditorium should be divided into non interfering locations and use 1 sink node and optimum number of sensors in each of these areas, by which the performance and scalability can be increased. The location of the position of the sink node plays an important role in the efficiency of the network when multiple group of sensors were arranged. When the two groups of sensors were arranged to the two side of the hall, it is better to keep the sink node in the center as it has better efficiency.

Consulting these result, researchers can design the arrangement of the sensors in the experimental environment considering hindrance, human interference etc. The grouping of sensors in the hall can be planned to avoid two groups being in an overlapping zone. This knowledge is useful when conducting user experience studies like pre-release film review, theater performance, dance shows etc. For example when two group of sensors are used, it is better to arrange the sensors in two sides of the hall and keep the sink in the center of the two groups. Similarly for the arrangement of three groups of sensors, it is better to place the sink node on the edge.

## 6.1 Future Work

In our study, we conducted the experiments with only 60 sensors and the duration of each experiment was 1 minute. Future studies should focus on conducting the experiments with more sensors and for longer duration to get a better understanding. They could also consider measuring the humidity, temperature and air condition in the experimental area to understand whether these parameters affect the network performance in indoor environments. During the experiment we found that some sink nodes perform better than other sink nodes due to some hardware properties. When a sink node was used for group 1, more packet were received from sensors in group 1. But when the same sink node was reprogrammed to be the sink node of group 2, more packets were received from group 2. This need further studies to explain the reason for such behavior.

# Bibliography


[1] ISO FDIS 9241-210 (2009) Human-centred design process for interactive systems. ISO.

[2] Chen Wang and Pablo Cesar, *Do we react in the same manner?: comparing GSR patterns across scenarios*, In Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational, NordiCHI '14, Pages 501-510.

[3] Chen Wang, Erik N. Geelhoed, Phil P. Stenton and Pablo Cesar, *Sensing a live audience*, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '14, Pages 1909-1912.

[4] Chen Wang and Pablo Cesar, *Physiological Measurement on Students Engagement in a Distributed Learning Environment.*, Proceedings of the International Conference on Physiological Computing Systems, (PhyCS 2015), Angers, France, February 11-13, 2015.

[5] Carlo Alberto Boano, Nicolas Tsiftes, Thiemo Voigt, James Brown, and Utz Roedig, *The Impact of Temperature on Outdoor Industrial Sensornet Applications*, IEEE Trans. Industr. Inf. 6, 3, 4551-459.

[6] John Thelen, Daan Goense and Koen Langendoen, *Radio Wave Propagation in Potato Fields*, In proceedings of the $1^{st}$ workshop on Wireless Network Measurements, 2005.

[7] G. Anastasi, A. Falchi, A. Passarella, M. Conti and E. Gregori, /emphPerformance Measurements of Motes Sensor Networks,in $7^{th}$ ACM symposium on Modeling,

Analysis and Simulation of Wireless and Mobile Systems (MSWiM04), Venice, Italy, 2004, pp. 174181.

[8] K. Sarabandi and I. Koh,*Effect of canopy-air interface roughness on hf-vhf wave propagation in forest*, IEEE Transactions on Antennas and Propagation, Vol. 50, No. 2, February, 2002.

[9] Nouha Baccour, Anis Kouba, Luca Mottola, Marco Antonio Ziga, Habib Youssef, Carlo Alberto Boano and Mrio Alves *Radio link quality estimation in wireless sensor networks: A survey*, ACM Transactions on Sensor Networks (TOSN), Volume 8 Issue 4, September 2012 .

[10] Zhou. G., Stankovic J. A., and Son S. H.*Crowded spectrum in wireless sensor networks.* In Proceedings of the $3^{rd}$ Workshop on Embedded Networked Sensors (EmNets '06).

[11] Jennifer Allanson and Stephen H. Fairclough *A research agenda for physiological computing* Interacting with Computers,Volume 16, Issue 5, October 2004,Science Direct Pages 857878.

[12] Christian Martyn Jones and Tommy Troen, *Biometric Valence and Arousal Recognition*,In Proceedings of the $19^{th}$ Australasian conference on Computer-Human Interaction: Entertaining User Interfaces,OZCHI '07, Pages 191-194.

[13] Cristina Conati, Romain Chabbal and Heather Maclaren, *A study on using sensors for monitoring user emotions in educational Games*,In proceedings of Workshop on Modeling User Affect and Actions: Why, When and How. Proc. of UM'03, Pittsburgh, PA, 2003.

[14] Guillaume Chanel, Cyril Rebetez, Mireille Btrancourt and Thierry Pun, *Boredom, Engagement and Anxiety as Indicators for Adaptation to Difficulty in Games*, In Proceedings of the $12^{th}$ international conference on Entertainment and media in the ubiquitous era, MindTrek '08, Pages 13-17

[15] Lotfi Derbali and Claude Frasson *Prediction of Players Motivational States using Electrophysiological Measures during Serious Game Play*, In proceedings of $10^{th}$ International Conference on Advanced Learning Technologies (ICALT),IEEE 2010.

[16] Nikos Tsianos, Zacharias Lekkas, Costas Mourlas, Panagiotis Germanakos, Anna Saliarou and George Samaras, *A Preliminary Study on Learners Physiological Measurements in Educational Hypermedia*, $10^{th}$ International Conference on Advanced Learning Technologies (ICALT), IEEE 2010.

[17] Kun-Hsien Li, Shi-Jer Lou, Huei-Yin Tsai and Ru-Chu Shih, *The Effects of Applying Game -Based Learning to Webcam Motion Sensor Games for Autistic Students Sensory Integration Training.*

[18] R.D Ward and P.H Marsden, *Physiological responses to different WEB page designs*, International Journal of Human-Computer Studies - Application of affective computing in humanComputer interaction.Volume 59 Issue 1-2, July 2003,Pages 199 - 212.

[19] Eva Oliveira, Mitchel Benovoy, Nuno Ribeiro and Teresa Chambe. *Towards Emotional Interaction :Using movies to automatically learn Users Emotional states.*, In Proceedings of the $13^{th}$ IFIP TC 13 international conference on Human-computer interaction, INTERACT'11 - Volume Part I, Pages 152-161.

[20] Everlyn Chiang Hai Yin and V.Muthukumar, *Intelligent Pillow for Heart rate monitor.*, International Journal for Electrical and Computer Engineering. Volume 3, no:6.

[21] Chacko John Deepu, Chen Zhihao, Teo Ju Teng, Ng Soon Huat, Yang Xiufeng and Lian Yong *A Smart Cushion for Real-Time Heart Rate Monitoring*, IEEE Biomedical Circuits and Systems Conference (BioCAS), 28 Nov 2012.

[22] *Top 10 Sensor Trends to Watch*, `http://www.eetimes.com/document.asp?doc_id=1320763`

[23] Abhijit Mitra, *Free Space radio Wave Propagation, Mobile Communication*, http://www.iitg.ernet.in/scifac/qip/public_html/cd_cell/chapters/a_mitra_mobile_communication/chapter4.pdf

[24] Stefan Herbert Aust, *Advanced Wireless Local Area Networks in the Unlicensed Sub-1GHz ISM-bands*, Doctoral Thesis, Techniche University, Delft, June 2014.

[25] Matthias Woehrle, Martin Bor and Koen Langendoen, *868 MHz: A noiseless environment, but no free lunch for protocol design*, Ninth International Conference on Networked Sensing Systems (INSS), 2012.

[26] Zhi Ang Eu, Hwee-Pink Tan and Winston and K.G. Seah *Design and performance analysis of MAC Schemes for Wireless Sensor Networks Powered by Ambient Energy Harvesting*,Published in Journal Ad Hoc Networks, Volume 9 Issue 3, Pages 300-323 , May 2011 .

[27] Kannan Srinivasan, Prabal Dutta, Arsalan Tavakoli and Philip Levis *An empirical study of low-power wireless*, Published in Journal ACM Transactions on Sensor Networks (TOSN), Volume 6 Issue 2, February 2010, Article No. 16.

[28] Paolo Baronti, Prashant Pillai, Vince W.C. Chook, Stefano Chessa, Alberto Gotta and Y. Fun Hu *Wireless sensor networks: A survey on the state of the art and the 802.15.4 and ZigBee standards*,Science Direct, Computer Communications 30 (2007) 16551695.

[29] Vongsagon Boonsawat, Jurarat Ekchamanonta, Kulwadee Bumrungkhet, and Somsak Kittipiyakul, *XBee Wireless Sensor Networks for Temperature Monitoring.*

[30] Romano Fantacci and Massimo Scardi, *Performance Evaluation of Preemptive Polling Schemes and ARQ Techniques for Indoor Wireless Networks*

[31] Zhi Ang Eu, Hwee-Pink Tan and Winston K.G. Seah, *Design and performance analysis of MAC Schemes for Wireless Sensor Networks Powered by Ambient Energy Harvesting*

[32] Muhammad Hamad Alizai, Olaf Landsiedel and Alexander Becher, *Challenges in Short-term Wireless Link Quality Estimation*,

[33] Alexander Becher,Olaf Landsiedel and Georg Kunz, Klaus Wehrle *Towards Short-Term Wireless Link Quality Estimation*, HotEmNets08, June 2-3, 2008, Charlottesville, Virginia, USA

[34] A. El-Hoiydi, J.-D. Decotignie and J. Hernandez, *Low Power MAC Protocols for Infrastructure Wireless Sensor Networks*

[35] Amre El-Hoiydi and Jean-Dominique Decotignie, *Low power downlink MAC protocols for infrastructure wireless sensor networks*,Published in:Journal Mobile Networks and Applications Volume 10 Issue 5, October 2005 ,Pages 675-690

[36] Toshiyo Tamura, Yuka Maeda, Masaki Sekine and Masaki Yoshida, *Wearable Photoplethysmographic sensors: Past and Present*, Wearable Electronics, Journal:Electronics Volume 3, Issue 2

[37] Jeenode V6 - Hardware Reference, `http://jeelabs.net/projects/hardware/wiki/JeeNode`

[38] Arduino-UNO, `https://www.arduino.cc/en/Main/ArduinoBoardUno`

[39] Divya Sharma, Sandeep Verma and Kanika Sharma, *Network Topologies in Wireless Sensor Networks: A Review*, International Journal for Electronics and Communication technology, IJECT Vol. 4, Issue Spl - 3, April - June 2013.

[40] Shamneesh Sharma, Dinesh Kumar and Keshav Kishore, *Wireless Sensor Networks- A Review on Topologies and Node Architecture*,International Journal of Computer Science and Engineering, Volume 1, Issue 2, October-2013.

[41] Spearman's Correlation `http://www.statstutor.ac.uk/resources/uploaded/spearmans.pdf`

[42] P.P. Parikh, M.G. Kanabar and T.S. Sidhu, *Opportunities and challenges of wireless communication technologies for smart grid applications*, Published in Power and Energy Society General Meeting, 2010 IEEE.

[43] Yi Chu, Paul D. Mitchell and David Grace, *ALOHA and Q-Learning Based Medium Access Control for Wireless Sensor Networks*,Published in: International Symposium on Wireless Communication Systems (ISWCS), 2012.

[44] Jennifer Yick, Biswanath Mukherjee, Dipak Ghosal, *Wireless sensor network survey*, Computer Networks, Volume 52, Issue 12, 22 August 2008, Pages 22922330.

[45] Kemal Akkaya and Mohamed Younis *A survey on routing protocols for wireless sensor networks*, Ad Hoc Networks, Volume 3, Issue 3, May 2005, Pages 325349.

[46] Peng Jiang, Hongbo Xia, Zhiye He and Zheming Wang, *Design of a Water Environment Monitoring System Based on Wireless Sensor Networks*, Published in open access journal: Sensors, ISSN 1424-8220.

[47] Kolmogrov-Smirnov, Lilliefors and Anderson-Darling tests, Journal of Statistical Modeling and Analytics, 2(1), 21-33.

[48] Lam S. S, *Packet Broadcast Networks; A Performance Analysis of the R-ALOHA Protocol*, IEEE Transactions on Computers, (Volume:C-29 , Issue: 7 ),596 - 603.

[49] 1 Fahimeh Goodarzi Masoumi, Majid Rahiminasab, *Improvement of Hybrid ALOHA with simultaneous data transmission for 5 users*, European Journal of Applied Engineering and Scientific Research, 2013, 2 (3):33-37