AN APPLICATION PROTOCOL FOR WIRELESS NETWORKS AND FUNCTIONAL BRAIN SPECTROSCOPY

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ABSTRACT

AN APPLICATION PROTOCOL FOR WIRELESS NETWORKS AND FUNCTIONAL BRAIN SPECTROSCOPY

This thesis presents research that created an application protocol for wireless networks and functional brain spectroscopy. The proposed protocol was tested through the integration of several types of networks, devices, and sensors to facilitate functional brain spectroscopy. The need for reliability and speed to transmit medical data in near real time can make medical application uniquely challenging. This research addresses one of the main challenges faced when building medical solutions that monitor the human brain. The findings proposed a protocol that was implemented using an architectural model for a solution that provides full mobility in an everyday environment using a near-infrared light sensor designed to monitor brain function in humans. Moreover the study showed it is possible to use heterogenic networks and heterogenic devices to provide useful data that can be used for medical purposes [103]. A system implemented the proposed protocol was built to allow the possibility of testing subjects to be monitored in their real environment [104]. To test this hypothesis, heterogenic communication software was developed to allow for the collection of physiological data from a mobile near-infrared sensor via a mobile telephone that had Bluetooth support and Global Standard for Mobile Communications (GSM) support. The result of this work introduced Medical Data Transfer Protocols (MDTP) [106], an algorithm [103], and an architectural model (Four-node Model) [105].

ACKNOWLEDGEMENTS

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NOMENCLATURE

C_i:	Blood Chromophores Concentration
d	Distance Between the Light Source and the Light Detector
DPF_λ	Differential Path Length Factor
$\varepsilon_{i,\lambda}$	Extinction Coefficient of Blood Chromophore for Wavelength λ
I_{out}	Detected Light
I_{in}	Source Light
L_λ	Path Length of Light at λ
OD_λ	Optical Density for Wavelength λ
$\mu_{a,\lambda}$	Absorption Coefficient at Wavelength λ
$\mu_{s',\lambda}$	Reduced Scattering Coefficient at Wavelength λ

ABBREVIATIONS

BOLD	Blood Oxygen Level Dependent
CSF	Cerebrospinal Fluid
CT	Computed Tomography
CWS	Continuous Wave Spectroscopy
DOT	Diffuse Optical Tomography
EEG	Electroencephalography
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Optical Brain Spectroscopy Using Near-infrared Light
FDS	Frequency Domain Spectroscopy
GSM	Global Standard for Mobile Communications
GPRS	General Packet Radio Services
Hb	deoxyhemoglobin
HbO_2	oxyhemoglobin
IDE	Integrated Development Environment
J2EE	Java Enterprise Edition
J2ME	Java Micro Edition
J2SE	Java Standard Edition
MDTP	Medical Data Transfer Protocols
MRI	Magnetic Resonance Imaging
NIRS	Near-infrared Spectroscopy

NIRI Near-infrared Imaging

PET Positron Imaging Tomography

RFCOMM Radio Frequency Communications

SDK Software Development Kit

SPECT Single Photon Emission Computed Tomography

SPP Serial Port Profile

TRS Time-Resolved Spectroscopy

URL Unified Resource Locator

TCP Transmission Control Protocol

UDP User Datagram Protocol

DEFINITIONS

Wireless System A system used wireless signal to transmit data

Mobile System A system that can be moved from one location to another location with minimum effort

Wireless Mobile System
A system used wireless signal to transmit data and can be moved from one location to another location with minimum effort

CHAPTER 1 – INTRODUCTION

1.1 Overview

The purpose of this research is to create an application protocol for wireless networks and functional brain spectroscopy. The protocol was tested using an architectural model [105] that was used to build mobile medical solutions that provide quality medical data within an acceptable time duration (event-to-action: in real-time or near real-time) simulating full mobility in everyday environments. The system utilized heterogenic nodes and a near-infrared light sensor designed to monitor brain function in humans.

One of the secondary contributions in this research was the proposal of an architectural model that can be used to build mobile medical solutions that provide full mobility in everyday environments (real-time health monitoring).

A combination of wireless networks and devices employing several different protocols were used for data processing and data transmission to provide the full mobility. A fully mobile functional brain Spectroscopy system was developed [103] to allow the possibility of testing subjects to be monitored in their real environments. The developed application introduces a model (four-node-model) to build fully mobile medical applications that support quality medical data and acceptable time duration (event-to-action time) for medical purposes.

The system introduces a newly created application level protocol to increase data quality and reduce event-to-action time duration. Moreover a new algorithm was created to minimize data loss. Finally a mathematical model was used to calculate the acceptable event-to-action time for particular physiological data based on the number of nodes and the type of nodes that data will go through.

To test this hypothesis, communication software was developed to allow for the collection of physiological data from a mobile near-infrared sensor via a mobile telephone. This system was then used to track changes in concentrations of oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) during various activities and send data to a computer at a monitoring site using the protocol and algorithm created. The resulting data's accuracy was compared with other methods [98] where the medical data collection was local to the test subject and observer.

Data was captured using a wireless near-infrared light sensor (Node 1: Client), transmitted to a mobile phone (Node 2: Mobile Server) using Bluetooth. The mobile phone sent the data to a central server (Node 3: Central Server). Finally the data was displayed on a monitoring station (Node 4: Monitoring Client).

Large amounts of data and small amounts of data can be captured from biological tissues for different purposes in different situations. The amount of data, the type of data, the type of tissues, and the event-to-action requirements can influence the quality of

captured data. Three data types were tested in this research and three biological event-to-action responses were used to ensure enough sample scenarios to test the hypothesis. The first data type was the effect of cigarette smoke on the human brain duirng 5 minutes of smoking. The second data type was the effect of breathing on the human brain during a 2-minute time period. The third data type was the response of a Canine when presented with its favourite toy 1 minute after detecting explosives. The responses from the activities can be inferred from the changes in concentration of HbO_2 and Hb. The data types used in this research have a direct relationship with the acceptable time duration of event-to-action and a direct relationship with the acceptable data quality that has been gathered. As a result, this has a direct effect on the packet size that is needed to be transmitted and on the acceptable time of transition.

The need to deal with different biological data that have variable timing requirements led to the introduction of a new algorithm to provide acceptable data quality. Sending and exchanging data over multiple nodes with acceptable quality and time durations (event-to-action) requires a protocol that can ensure these requirements are met despite the lack of control over these heterogenic nodes. Medical Data Transfer Protocol (MDTP) was introduced to address this challenge.

The specific aims of this research are the following: create a protocol to provide quality medical data; transmit data within acceptable time durations (event-to-action); and create a model that can be used to represent the minimum number of nodes while building

a fully mobile medical system that uses heterogenic nodes to monitor human physiological data in near real-time. As a result this model might also allow health care providers to take effective action within acceptable time frames when possible. Moreover this may lead to a better understanding of tissue pathologies and increase the quality of service over heterogenic networks.

1.2 Heterogenic Networks

Networks – whether infrastructure based or non-infrastructure based – play an important role in our lives [1, 2, 3]. Wired networks, such as the Internet, provide us with global data access, while wireless networks such as the Global Standard for Mobile Communications (GSM) give us mobility. Non-infrastructure-based networks (ad-hoc networks), such as Bluetooth networks, give us the freedom to communicate at no cost over short ranges [4].

Bluetooth devices utilize the unlicensed frequency, 2.4 GHz that offers a 10- to 100-metre range and a data transfer rate of up to 1 Mbps [5]. Bluetooth technology offers point-to-point and point-to-multiple-points communication [6]. It performs communication through a protocol stack divided into hardware and software layers [7]. Bluetooth standards were created to provide guidelines to device manufacturers to facilitate interoperability between devices from different vendors. Moreover, Bluetooth standards specify profiles that determine the usage of the device and the services offered

by it [8]. Standardization, low cost, minimum hardware, low power requirements, and the free use of the unlicensed band all contributed to widespread use of Bluetooth devices [9].

GSM is widely used in more than 200 countries around the world, having an estimated subscriber base of over two billion users [10]. Roaming is one of the value-added features introduced by the GSM standard. This capability allows mobile users to travel the world and still be able to use their phones to connect with local operators. The introduction of data communication has also helped GSM standards to become more and more popular. GSM networks currently offer wide varieties of services, ranging from basic voice services to more advanced capabilities such as allowing Internet access.

GSM's many features make it possible to use this type of network to assist in the monitoring of people's physiological parameters in everyday life regardless of their location [11, 12]. GSM networks use different frequencies for upload and download links, which offer various data transfer rates between the network and the device. The data transfer rates can reach up to 9.6 kbps, which allows the networks to offer basic data services to their users [13]. The introduction of General Packet Radio Services (GPRS) – data services to GSM networks – has made it possible to run more varieties of applications than before at a lower cost and faster speed [14]. GPRS was added on top of the traditional GSM network to allow network operators to offer better data communications. GPRS is a packet-switched communication method where the communication channel can be employed by other users, unlike other data communication methods such as circuit switched data. With GPRS download rates

reaching 236 Kbps and upload transfers reaching up to 118 Kbps, GPRS offers enhanced speed over the traditional GSM network [15].

1.3 Functional Optical Brain Spectroscopy

Functional brain imaging using fMRI (Functional Magnetic Resonance Imaging) and Positron Imaging Tomography (PET) have increased our understanding of the neural circuits that support cognitive and emotional processes [16, 17]. However, these methods are expensive, uncomfortable, and may have side effects such as exposure to radioactive materials (with PET) or loud noises (with fMRI) [18, 19]. Such disadvantages make these imaging methods inappropriate for many uses that require the monitoring of brain activities under daily, real-life conditions.

Functional Optical Brain Spectroscopy Using Near-infrared Light (fNIRS) is another method to conduct functional brain analysis. fNIRS is a non-invasive method that uses infrared light reflection to gather changes in the concentration of HbO_2 and Hb in the blood [20]. The main advantages of fNIRS are the ability to measure the concentration of chemical substances, the device's low cost, low power requirements, non-invasiveness, and portability. Low cost and portability have made it possible to use fNIRS to monitor patients in their homes for an extended period of time, allowing health care providers to monitor slowly developing diseases in patients. The non-invasive nature of fNIRS has also made it possible to perform as many tests as needed without worrying about side effects [21].

1.4 Summary

Combining mobile network technologies with fNIRS introduces a new way to monitor human brain activities under real-life conditions. This research contributes an application protocol and a model that can be used to combine heterogenic technologies to provide a novel, cost-effective, and mobile means to monitor human brain activities with acceptable event-to-action time duration.

CHAPTER 2 – LITERATURE REVIEW AND BACKGROUND MATERIAL

2.1 Communications

A communication system consists of a transmitter and a receiver connected by a communication channel (Figure 2.1). The channel is the medium that carries the signal from the transmitter to the receiver. Several physical media are in existence today, for example wire, radio frequency, and fibre cable. Each type of media has its own characteristics. The performance, the bandwidth, and the reliability of communication systems depend heavily on the characteristics of the channels. For example, when considering multicellular systems, such as cellular networks like GSM or CMDA system, we can see the effect compared to wire-based networks.

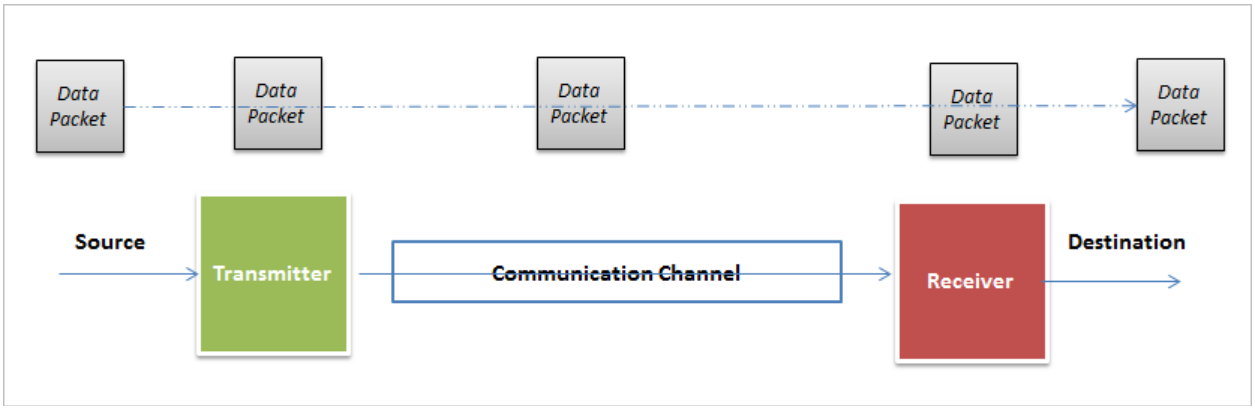

Figure 0.1: Point-to-Point Communication

A universal communication system that is effective for all communication needs does not exist [95]. Cost, coverage, bandwidth, and transfer rate are all factors that make such a universal system impossible to construct yet. Even wireless networks and 3G

networks operating at bit rates as high as 54 Mbps for IEEE 802.11 systems and 2 Mbps for UMTS systems are still not enough. The cost of UMTS is high but the coverage is wide. The cost of IEEE 802.11 is cheap and the bit rate is high, but the coverage is limited. Wi-Fi systems have higher bit rates than UMTS systems but they are designed to function well in a limited range and provide good indoor coverage while UMTS operate with a lower bit rate but with high mobility and more coverage (Figure 2.2 and Figure 2.3).

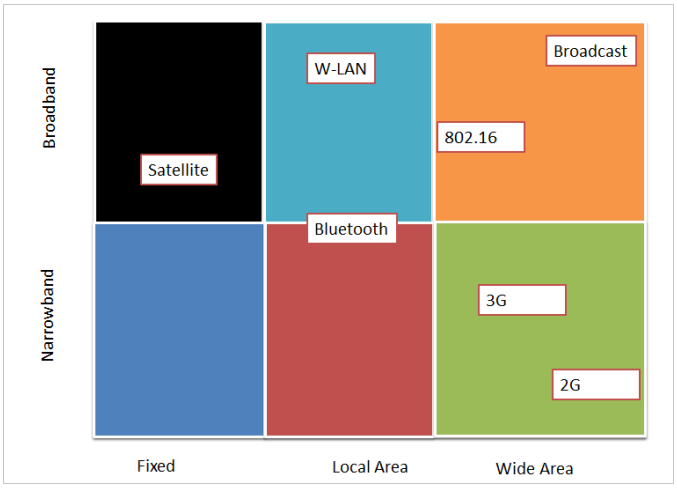

Figure 0.2: Mobility vs Transfer Rate

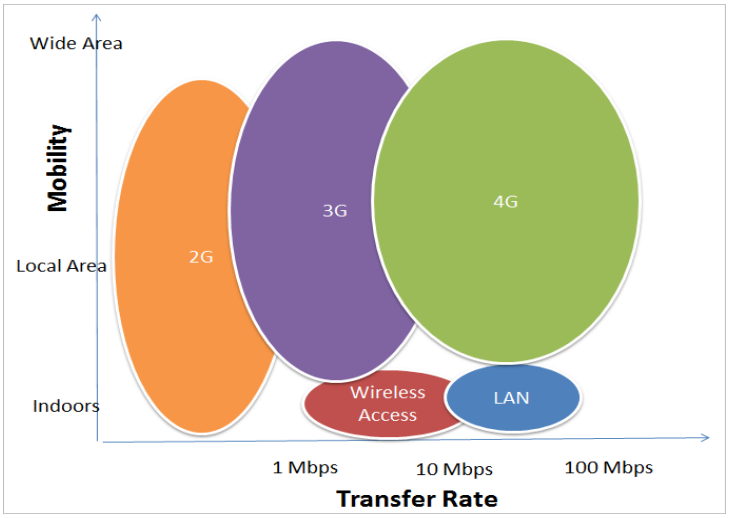

Figure 0.3: Coverage of Wi-Fi Systems and 3G Cellular Systems

Point–to-point communication between systems regardless of channel media follows the same model (Figure 2.1). The design of the transmitter and the receiver has to be compatible with the channel characteristics. When designing communication systems the designer is faced with trade-offs between cost, performance, and reliability. In digital communication performance and reliability are quantified by bit rate and bit error rate. Bit rate is defined by the number of bits sent from the transmitter to the receiver per second (bits/second or Bps). Bit error rate is qualified by the number of bits that have errors over the total number of transmitted bits. It is desirable to have a high channel bit rate and a low bit error rate to achieved good performance. Digital communication performance comes with a price; in order to achieve the desired performance, the cost of the communication will increase. The cost of the communication channel is in direct relation to the required transmission power and the channel bandwidth. (See Figure 2.4.)

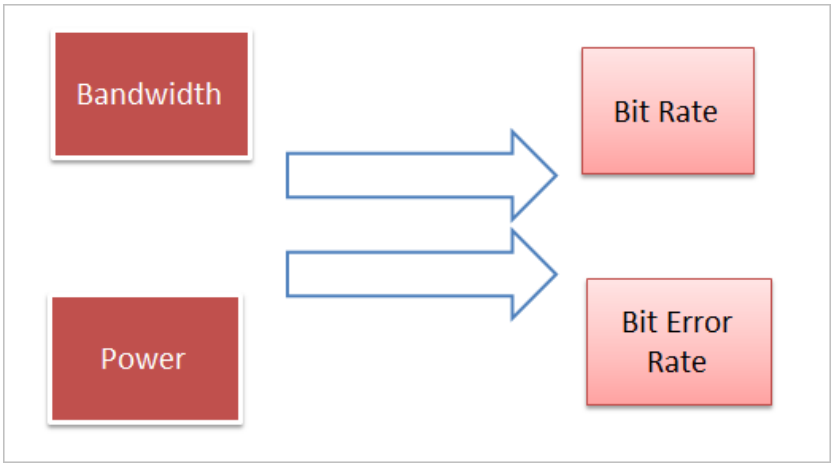

Figure 0.4: Trade-off between Cost and Performance in Communications

2.2 Networks

2.2.1 Sensor Networks

Several types of sensors have been created and used to monitor different objects, automobile functions for example [22]. These sensors can often communicate with each other to form sensor networks [23]. Moreover such networks have been used in manufacturing, telecommunication, security [24, 25, 26, 27], and the natural environment [28]. Currently there are wide varieties of sensor networks used in factories to perform different tasks ranging from monitoring machines' performance and product quality to ensuring worker safety [29, 30, 31]. Monitoring machines or products on factory floors does not require mobility or wireless connectivity since everything is in close proximity.

On the other hand, monitoring habitat [32] using multiple sensors without disturbing the surrounding environment for extended periods of time is not practical with wired networks. Wireless sensor networks are used in these cases [33, 23, 34,35].

For example, several sensors can be dropped from the air in different locations, where they can perform data collection about the environment, and then send the data back to a central location using wireless communication. Wireless sensor networks have limited mobility; they are stationary. Mobile wireless sensor networks, however, allow mobile monitoring of conditions and situations that are at least somewhat independent of location and use wireless connections to transmit their collected data [36]. This type of network is used in many fields. Health monitoring [37, 38] and telemedicine [39] utilize this type of network to monitor patients remotely [40]. Other applications of mobile wireless sensor networks include [41], but are not limited to, entertainment [42], automobile [43, 44], social studies [45], and home appliances [46].

Sensor networks differ in their technical capabilities and implementation (hardware, software, communication). For example researchers have managed to create a very small operating system that can be loaded into 178 bytes of memory [47, 33,48]. One of the most advanced sensor network platforms available on the market today is Intel Mote [36, 49]. It features an ARM 7 processor, Bluetooth transceiver [50], RAM, flash memory, and multiple IO options. It runs TinyOS, which is an open source embedded operating system that provides enhanced data acquisition functionality and control. Network layers were created on top of TinyOS to support the multi-hop functionality to allow the use of Bluetooth [36,51].

Currently, available sensors and sensor networks support long-range and short-range communication (433 MHz – 5.9 GHz) [52, 53]. Some health care sensor networks combine short- and long-range communications to monitor patients [54, 55, 40,56]. They utilize mobile phone networks and Bluetooth networks together to achieve better coverage [41,57]. Sensor networks have wide variations in data transfer rates. Some have a low transfer rate (Spike, 35 Kbps) and others have a high transfer rate (WLAN, IEE 802.11a, 54 000 Kbps). Transfer rate requirements depend highly on the type of sensor application. Some sensor applications require a high transfer rate [58] because they generate large amounts of data that must be dealt with quickly. Examples are sensors that stream video data from remote locations [59].

In summary sensor networks are an active research area with various groups focussing on different elements of sensor networks, such as networks, sensors, data acquisition, protocols, and performance [60, 61, 62, 63].

2.3 Mobile Applications

2.3.1 Wireless Near Real-Time Applications (Traditional)

Near real-time applications include applications that either send or receive text, image, audio, video, or any other binary data between two or more applications. These applications usually have tolerance for certain levels of delay. The level of delay accepted by these applications varies. Near real-time interaction applications [96] such as voice over IP (VoIP) applications or video conferencing tolerate less delay than streaming multimedia applications, such as live television, live radio, etc. In order to meet user expectations for these applications, networks have to meet the minimum level of delay

and minimum bandwidth to achieve the desired quality. In traditional wired circuit-switched networks, this level of quality can be achieved by resource reservations [95]. Currently most networks are packet-switched based. In packet-switched networks it is more difficult to control the minimum level of delay or the minimum available bandwidth. These applications over wireless networks perform even worse due to the nature of the unreliable transmission medium (wireless channel). Wireless connections are shared by multiple users, have limited bandwidth and have higher error rates than wired networks [96, 97]. Moreover, wireless users use several types of mobile devices with different capabilities (computational power, bandwidth, memory, etc.), which makes it even more difficult to provide the same level of quality that users are accustom to over wired networks.

2.3.2 Wireless VoIP – Voice Applications

In wireless communication voice transmission continues to be used more than data transmission despite the growth in the use of wireless devices for text messaging. As VoIP became popular over wired networks, users expected the same level of quality in services when using wireless networks. This provided a challenge due to the bandwidth required. Advanced encoding algorithms have been introduced to facility that requirement, but this is still an active research area. There are many problems related to the inter-operability that need to be resolved before wired networks will achieve the same level of quality. Because mainstream network (wired and wireless) operators invested large amounts of money in their networks, they have to support inter-operability between

the networks to support new services such as VoIP. To ensure inter-operability, protocol conversion, signal encoding, voice encoding, etc., is required. This conversion is achieved through adding adapters or gateways that reduce the speed of the data stream from the source to the target. Figure 2.5 shows an example of how GSM networks work with an H323 IP network to provide the user with the service. Another example, in order to provide VoIP over wired land lines using IEEE 802.11, large changes were made to the stack to make VoIP possible. In order to evaluate the performance of GSM and H.323 VoIP, a call delivery access delay and a number of mis routings, due to use mobility, can be used. For evaluating wired network performance when provide VoIP services, packet access delay and packet loss and a number of supported voice streams can be used to evaluate performance [96].

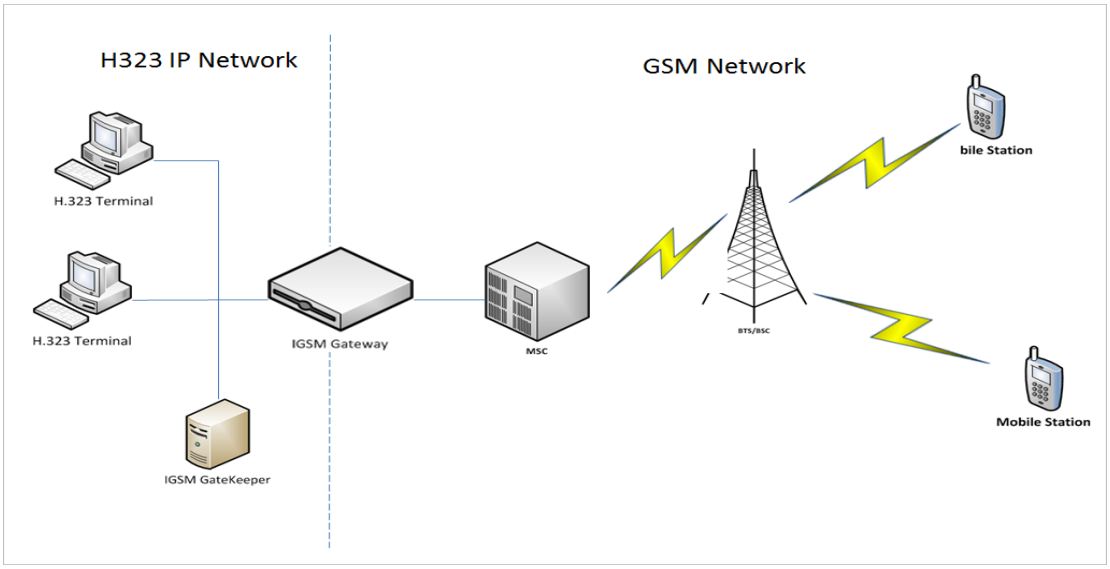

Figure 0.5: iGSM Architecture

2.3.3 Wireless Video Applications

Video streaming is commonly used over wired networks. Users enjoy good performance of these wired networks with affordable pricing. Due to the inexpensive cost, video usage increased over wired networks and started spreading over wireless networks. The performance of wireless networks is not the same as wired networks, unfortunately users expect the same. Moreover wireless networks have a higher error rate than wired networks. Error rate and bandwidth limitation makes it hard to provide users with the same level of services as wired networks in particular real-time services. Several approaches and metrics have been suggested to provide evaluation of performance of wireless networks when streaming video. Some of these metrics are frame rate, bandwidth, delay, and corrupted blocks. The suggested metrics cannot provide an effective measure of the video quality perceived by the viewer [94]. Quality is very subjective; therefore it is hard to agree on a set of criteria that can measure user perception of quality. Instead Peak Signal to Noise Ratio (PSNR) is used to evaluate quality of a decoded video. PSNR's main goal is to identify the maximum single energy to noise energy ratio, which in turn can be used to approximate the distortion of the decoding [94].

2.3.4 Wireless File System-Based Application

The concept of file and file system is fundamental for applications. Users benefit from this concept over wireless networks for several reasons. The wireless devices' connection is expensive and wireless devices do not always have connectivity. Having a local storage file in the device is useful for users especially when they cannot be connected. The concept of a file system and the synchronization of wireless files becomes important in order to keep files up to date. Replication can be used to provide local copies of files from the wired networks to the wireless devices, but at the same time these devices have limited storage. A solution to limited device storage is the assumption that the device is always connected, has access to good bandwidth, and has a low error rate. In practice this is not always possible, so instead frequent synchronization is needed to keep local storage up to date.

2.3.5 Wireless Location-Based Applications

The purpose of wireless-based application is to provide services to users or objects that are changing locations within a duration of time. These services can be categorized based on the object type and the object speed of that changing location. Currently there is common agreement that these types of services can be classified as follows: personal mobile location services and in-vehicle mobile location services [95]. Despite the difference of the purpose of these categories, they still operate the same and have similar technical components. These applications utilize map database services, spatial analyses

services, and position services. Accuracy and timing requirements for these applications vary based on the usage.

In-vehicle mobile location services are applications designed to be used inside vehicles [98]. Typically these applications are driven by the type of service the vehicle manufacturer wants to provide to their customers. A popular example of this type of services is OnStar [99]. Some of the services offered by OnStar include emergency service, air bag deployment notification service, stolen car location service, and door unlock service.

Personal mobile location services focus more on persons rather than vehicles [98]. These services provide convenient access to services located close by the person. Moreover these services can become very useful in case of a personal emergency. NTT DoCoMo [98] is one of the popular personnel location services. It provides information for users based on their location such as restaurant location, weather, attractions, etc.

To achieve the required position accuracy and time requirements for location-based services, different techniques can be used to determine the location of the person or the vehicle. Mobile positioning techniques fall into three main types: cellular based techniques, Global Positing System (GPS), and a hybrid of the two types (Figure 2.6).

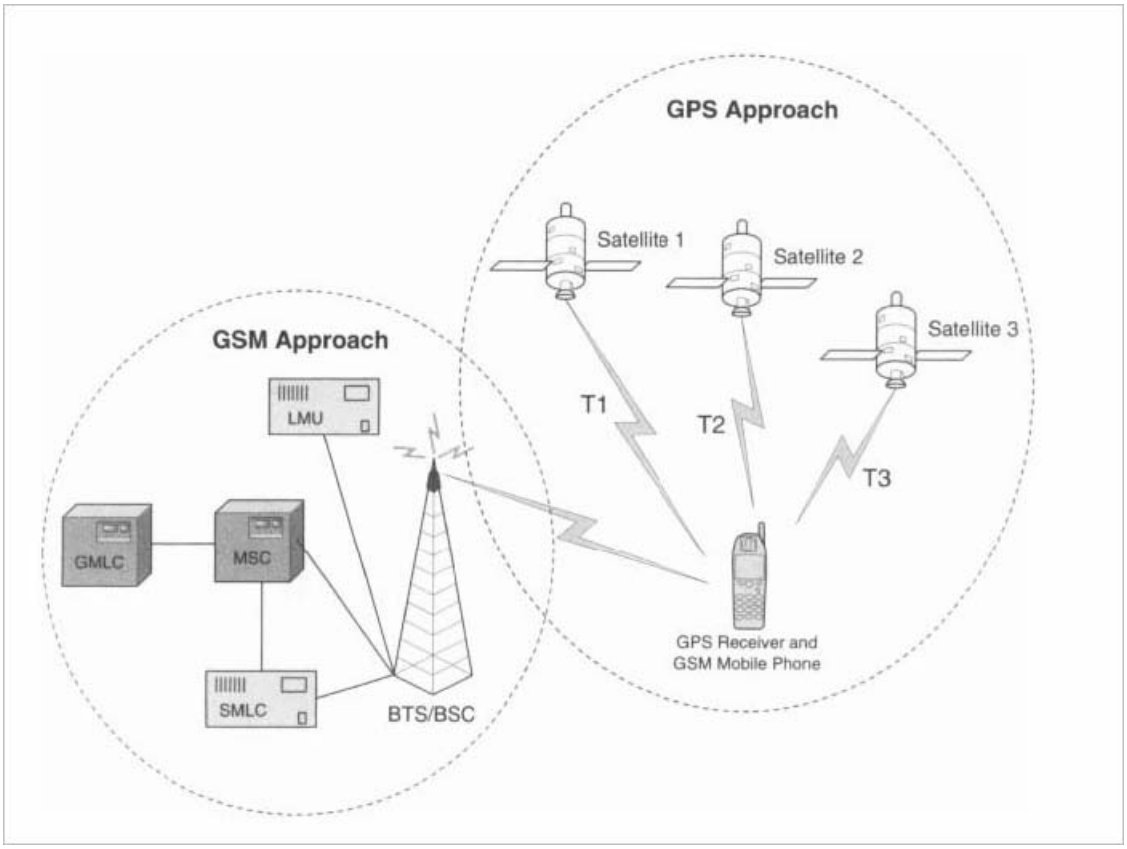

Figure 0.6: Hybrid Architecture for Positioning

2.3.6 Wireless Peer-to Peer Applications

Peer–to-Peer (P2P) computing is a trend that shares data and utilizes distributed devices. In a P2P environment devices play the same role, that is, the same device can be a server and a client. P2P is widely used for file sharing and today several service protocols have been developed. The most famous P2P applications in existence today, or existed in the past, are the following: Bit Torrent [100], Freenet [101], Gnutella [102], and Napster [102]. In P2P systems several topologies are involved such as a centralized structure and a decentralized unstructured. These topologies created un-interoperable

systems between these applications. P2P started using wired networks, which made implementing it feasible. In a wireless network context, it is more challenging due to the wireless topology. Moreover the wireless bandwidth and performance can affect the P2P applications. Other factors can play a vital role in the usefulness of these applications such as the file size, the maximum display time of files, the required bandwidth for streaming, the popularity of files, and the number of copies replicated.

2.4 Software and Protocols

Java portability allows the protocol to run on a wide range of operating systems and devices. Sun Microsystems realized that one size does not fit all; it grouped Java into three main editions, each targetted at a specific range of devices. Java Enterprise Edition (J2EE) is targetted for enterprise servers to create large scalable applications. Java Standard Edition (J2SE) is targetted for desktop applications. Java Micro Edition (J2ME) is targetted for small devices with limited hardware capabilities [64].

Eclipse [65] and Netbeans [66] are among the most popular integrated development environments (IDE) used to build and debug Java applications. Both IDEs are used in this research.

In order to make Java a portable language, Sun created a virtual machine for each specific platform where Java programs can run. The virtual machine concept made it easy to port network Java programs from one edition to another. Java has native network support. It is possible to create applications to support different kinds of networks and protocols. Java has native libraries that support wired and wireless communications. It

supports Bluetooth, WiFi, and more. Several popular network protocols and standards are also supported. By default, Java libraries support Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and binary stream communications.

TCP is a reliable protocol used in communication when a dependable connection is required [67]. It allows two hosts to communicate and exchange data streams and guarantees the data delivery [68]. Data packets are delivered in the same order they were sent. In contrast, UDP does not provide guaranteed delivery and does not guarantee packet ordering [69]. Selecting which protocol to choose for a particular application mainly depends on the application requirements. These protocols have proven their value and made their way into Bluetooth and GSM networks.

Bluetooth networks support both TCP and UDP communications [70]. Applications running on the Bluetooth networks can use any of these protocols to send and receive data. The most common way to send TCP and UDP packets over Bluetooth is using Bluetooth Radio Frequency Communications (RFCOMM) [71]. RFCOMM is a transport protocol that provides RS-232 serial port emulation. Bluetooth Serial Port Profile (SPP) is based on this protocol [72, 73].

GSM networks are similar to both Bluetooth networks and wired local area networks. They support TCP and UDP communication protocols [74-78]. Since wireless networks support the same communication protocol as wired local area networks, applications running on wireless networks can communicate and exchange data with the applications running on wired local area networks.

Application level protocols are created to support specific applications. These protocols can run on top of either TCP or UDP. Medical Data Transfer Protocols (MDTP) in this research are an example of such protocols.

2.5 Near-infrared Spectroscopy

Several methods have been devised for imaging the human brain, in particular Electroencephalography (EEG), Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT), Near-infrared Spectroscopy (NIRS), and Diffuse Optical Tomography (DOT). These methods vary in their strengths and weaknesses [82]. In recent years, researchers have started using NIRS and DOT, either alone or in combination with other methods, to image brain functions. The non-invasive nature of the NIRS is appealing to researchers to measure changes in HbO_2 and Hb during brain function activities [83].

Functional Optical Brain Spectroscopy Using Near-infrared Light (fNIRS) has been introduced as a new method to conduct functional brain analysis. fNIRS is a method that uses the reflection of infrared light to observe changes in the concentration of HbO_2 and Hb in the blood, and can provide a similar result to fMRI [84]. fNIRS takes advantage of the absorption and scattering of near-infrared light to provide information about brain activities [85]. For a long time, it was thought that it was only possible to collect information from the superficial layers of tissue (e.g., microscopy) due to light scattering. However, about 25 years ago, it was discovered that functional information

could be obtained from brain tissue using light directed at the scalp and detected from the scalp [20]. This discovery motivated the development of diffuse optics as a method for brain monitoring. This method has different names: Near-infrared Spectroscopy (NIRS), Diffuse Optical Tomography (DOT), and/or Near-infrared Imaging (NIRI). Today, several types of NIRS devices have been built to image brain functions. These devices differ in their capabilities, designs, and costs [82, 86].

The NIRS devices can be classified into three main types: Continuous Wave Spectroscopy (CWS), Time-Resolved Spectroscopy (TRS), and Frequency Domain Spectroscopy (FDS). The CWS device consists of a continuous light source, which transmits light waves with constant amplitude, and a detector that locates the attenuated incident light after it passes through the tissues. The TRS device transmits short incidents of light pulses into tissues and measures the light after it passes through the tissues. On the other hand, the FDS device transmits a sinusoidally modulated light wave into the tissue [82].

Each of these types of NIRS devices has limitations and strengths [87]. CWS has the advantage of low cost, but it is difficult to distinguish contributions of absorption and scattering to the light attenuation. FDS, on the other hand, is known for its good spatial resolution, penetration depth, and accurate separation of absorption and scattering effects. Nevertheless, FDS is significantly more expensive than CWS. As for TRS, although theoretically it can provide a better spatial resolution than FDS, it has a lower signal-to-noise ratio. Since TRS requires short laser pulses and photon counting detection, it is the most expensive type of the NIRS instrumentation. Despite the advancements in NIRS

technology, its limitations continue, including the short path length and the artifacts' movements during measurements.

2.6 Optical Properties within Tissues

Absorption and scattering are the main physical processes affecting the transmission of light photons in tissues. Light photon absorption and scattering causes the light intensity to decrease. Both absorption and scattering are wavelength dependent. The amount of absorbed light photons is also impacted by the concentration of blood HbO_2 and Hb in tissues, which vary in time, reflecting physiological changes in tissues' optical properties [84].

When light photons travel through tissues, they are scattered several times before finally reaching the receiver. Scattering increases light optical path length, causing photons to spend more time in tissues that in turn affects the tissues' absorption characteristics.

Despite the fact that both absorption and scattering play a major role in light transmission, scattering is more dominant than absorption. When light travels through tissues and blood, photon absorption leads to a loss of energy to tissues and blood chromophores, or induces either fluorescence (or delayed fluorescence), or phosphorescence. The main substances of biological tissues that contribute to light photon absorption in the near-infrared light are water, fat, and hemoglobin. While water and fat remain fairly constant over a short period of time, the concentrations of oxygenated and

deoxygenated hemoglobin change according to the function and metabolism of the tissues. Thus, the corresponding changes in absorption can provide clinically useful physiological information.

2.7 Modified Beer-Lambert Law

Near-infrared light, in the range of 700-900 Nm, can travel relatively deep into body tissues. It is also worth mentioning that such light can easily travel through soft tissues and bones, such as those of neonates and infants. Therefore, it is suitable to use near-infrared devices to monitor brain activities or other oxygen-dependent organs in this category of humans [88].

NIRS relies on a simple principle: light in the range of near-infrared light emitted on the organ of interest passes through the different layers above the organ. When it passes through the tissues, light photons go through physical interactions, such as scattering and absorption that lead to a loss of energy in the emitted light. When the remaining light exits the organ, it is measured by a detector.

In neuroimaging applications, the light is transmitted through the scalp, so the photons pass through several layers of tissue surrounding the brain, such as the scalp, skull, Cerebrospinal Fluid (CSF) and meninges. Then, the NIR light reaches the brain and the blood vessels, and backscattered light gets detected by a set of detectors. The light in this case follows the so-called “banana-shaped” path due to scattering effects caused by the tissues. Because water and lipids are relatively transparent to near-infrared light and the optical properties of the layers surrounding the brain and blood are fixed within a

given period of time, it was found that light is mainly absorbed by oxygenated and deoxygenated hemoglobin. Here, it must be noted that the scattering of the near-infrared light in the human tissues is much greater than its absorption, while absorption of this kind of light is much more significant in the blood. This leads to the belief that the optical properties of the blood, which in fact change based on the amount of oxygen in the blood, can play a vital role in determining the amount of backscattered light from the brain. The amount of blood volume and blood oxygen concentration can be an indicator of hemodynamic activities that are related to brain functions. Analyzing the amount of backscattered light during the oxygenation and deoxygenation process of the blood flow in the brain can lead to a better understanding of the brain function [89].

NIRS measures the optical properties of HbO_2 and Hb in near-infrared light. The effects of the changes in concentration levels of HbO_2 and Hb in the blood stream on light absorption can be described by the Beer Lambert's Law. A Modified Beer Lambert Law can be used to predict the amount of blood chromophores (HbO_2 and Hb) in tissues [86].

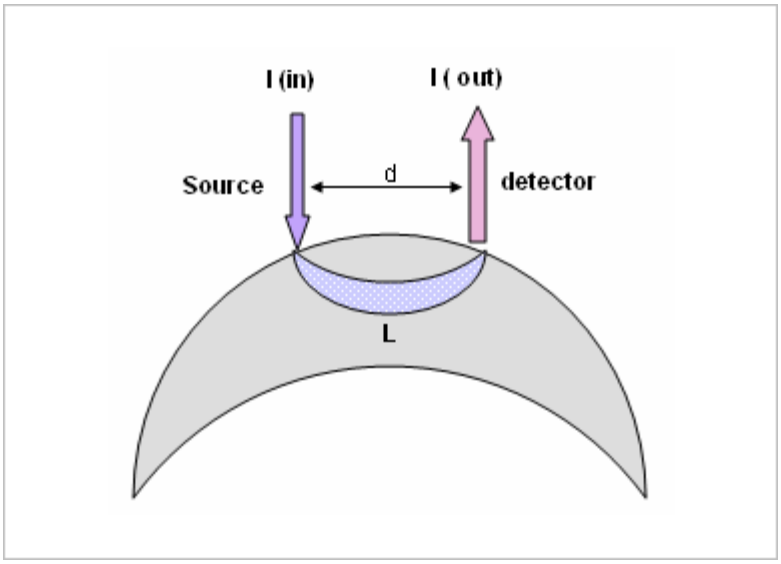

Figure 0.7: Modified Beer Lambert Law, Light Photon Propagation in Tissues between Source and Detectors

$$I_{out} = I_{in} \cdot 10^{-OD_\lambda} \qquad (1)$$

[86, 90, 91, 92, 93]

I out: detected light

I in: source light

Equation 0.1: Light Attenuation between Source Light and Detected Light

$$OD_\lambda = -\log_{10} \frac{I_{out}}{I_{in}} = \text{attenuation} = A_\lambda + S_\lambda \qquad (2)$$

[86, 90, 91, 92, 93]

ODλ: optical density for wavelength λ

Equation 0.2: Optical Density for Wavelength λ

$$A_\lambda = \sum_{i=Hb,HbO_2} \varepsilon_{i,\lambda} C_i L_\lambda \qquad (3)$$

[86, 90, 91, 92, 93]

Aλ: light absorption in blood HbO_2 and Hb [42]

εi,λ: extinction coefficient of blood chromophore for wavelength λ

Ci: blood chromophores concentration

*L*λ: path length of light at λ

Equation 0.3: Absorption of Light in Blood

$$L_\lambda = d \cdot DPF_\lambda \quad (4)$$

[86, 90, 91, 92, 93]

$L\lambda$: path length

d : distance between the light source and the light detector

$DPF\lambda$: differential path length factor

Equation 0.4: Path Length

[86]

$$DPF_\lambda = \frac{1}{2}\left(\frac{3\mu'_{s,\lambda}}{\mu_{a,\lambda}}\right)^{1/2}\left[1 - \frac{1}{1 + d \cdot (3\mu'_{s,\lambda}\,\mu_{a,\lambda})^{1/2}}\right] \quad (5)$$

[86]

μ a, λ: absorption coefficient at wavelength λ

$\mu s'$,λ: reduced scattering coefficient at wavelength λ

Equation 0.5: Differential Path Length

[86]

$$\Delta OD_\lambda = OD_{\lambda,final} - OD_{\lambda,initial} = \sum_{i=Hb,HbO_2} \varepsilon_{i,\lambda}\,\Delta C_i\, d\, DPF_\lambda \quad (6)$$

[42, 123, 124, 125, 126]

Equation 0.6: Differential Value

$$\overline{\Delta OD} = \overline{M} \times \overline{\Delta C} \qquad (7)$$

where

$$\overline{\Delta OD} = \begin{bmatrix} \Delta OD_{\lambda_1} \\ \Delta OD_{\lambda_2} \end{bmatrix}, \overline{\Delta C} = \begin{bmatrix} \Delta C_{HbO_2} \\ \Delta C_{Hb} \end{bmatrix} \text{ and}$$

$$\overline{M} = d \cdot \left(\overline{\varepsilon} \times \overline{DPF} \right)^T \qquad (8)$$

42, 123, 124, 125, 126]

$\overline{\varepsilon}$ and $\overline{DPF}$ are defined as $\overline{\varepsilon} = \begin{bmatrix} \varepsilon_{HbO_2,\lambda_1} & \varepsilon_{HbO_2,\lambda_2} \\ \varepsilon_{Hb,\lambda_1} & \varepsilon_{Hb,\lambda_2} \end{bmatrix}$ and

$\overline{DPF} = \begin{bmatrix} DPF_{\lambda_1} & 0 \\ 0 & DPF_{\lambda_2} \end{bmatrix}$

Therefore,

$$\overline{\Delta C} = \overline{M}^{-1} \times \overline{\Delta OD} \qquad (9)$$

[86]

Equation 0.7: Transformation from Light Output Change to Change in Blood Chromophore Concentrations

Equation 9 "provides a transformation from light output change to a change in blood chromophore concentrations. By using blood chromophore concentrations, we define two parameters:" [42]

$$OXY = \Delta C_{HbO2} - \Delta C_{Hb} \qquad (10)$$

and

$$BV = \Delta C_{HbO2} + \Delta C_{Hb} \qquad (11)$$

Equation 0.8: Blood Chromophore Concentration Parameters

"OXY and BV are estimates proportional to, respectively, oxygenation and blood volume changes in the tissue due to hemodynamic activation." [86]

2.8 Basic Anatomy and Physiology of the Human Brain

Blood carries oxygen and nutrients to tissues. Also, it carries carbon dioxide and other products of metabolism away from tissues, so the body can eliminate them. Red blood cells contain hemoglobin, which is the main oxygen transporter. When the red blood cells pass through the lungs, they collect oxygen where it becomes bound with the hemoglobin. Furthermore, red blood cells release carbon dioxide to the lungs. Blood vessels form a comprehensive network inside the body where they deliver blood to different tissues and organs. Arteries, arterioles, and capillaries deliver oxygenated blood to tissues whereas veins and venules collect deoxygenated blood from them.

The human brain is protected by several layers. These layers provide a safe and secure environment for the brain. Near-infrared light, used to measure changes in the blood oxygenation, has to pass through all the protective layers: scalp, periosteum, skull, and the meninges (Figure 2.2). The meninges contain three layers: dura mater, arachnoid mater, and pia mater. [94]

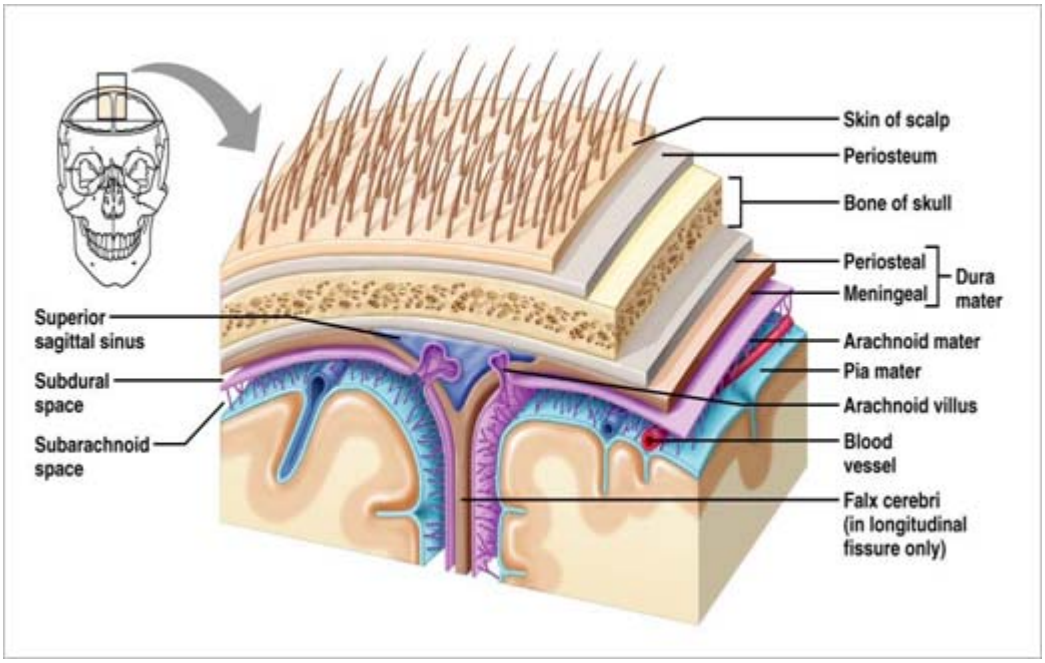

Figure 0.8: The Brain's Protective Layers [18]

CHAPTER 3 – FOUR-NODE MODEL

3.1 Four-node Model Description

The four-node model was inspired from human and animal body structure (Figure 3.1). The four-node model (Figure 3.2) depicts the minimum necessary devices and networks required to support an affordable and practical solution to monitor biological tissues with an acceptable event-to-action time duration. In the proposed model, in order to support real near-time (event-to-action) mobility monitoring of biological tissues, a minimum of four types of device and three types of networks are required.

The first node (Node 1) is a wireless sensor closely attached to the body that supports short-range communication. The sensor can be a device that implements any data collection approach (near-infrared, ECG, etc.). The purpose of this node (the sensor) is to closely monitor specific biological data in the body. Multiple sensors can be attached to the body to collect more specialized data from different types of tissues. The sensor can have different frequencies used to sample data from tissues. The system built to test this model used a sensor with 100 Hz sample rate and data accuracy of 12 bits. The sensor is equivalent to any of human body sensors (nose, eye, ear, etc.).

The second node (Node 2) is a data buffer and a long-range data communication device (a cell phone that supports data communication). The purpose of this node is to act as a data buffer for the data collected from the sensor. This node can also act as a network speed regulator between the sensor and the wide area network (WAN). The node

implements a data integrity algorithm to minimize data losses due to data transmission over multiple networks. When integrating networks with different throughputs, data loss can occur due to capacity problems. The amount of captured data from the sensor sometimes cannot be sent fast enough to the central server; this node can prepare the data and store it to be forwarded to the central server. Finally this node adjusts its receiving speed based on the sensor transition speed. In the human body an equivalent would be the lungs.

Node 1 and Node 2 provide full mobility support in this model. These two nodes can be used in several scenarios. For example, in one scenario a doctor can monitor patients in their real environment (work, home, etc). Today most people carry cell phones that can be used as Node 2. The monitored subject can move freely while carrying a light weight sensor. Depending on the data type that needs to be monitored, the subject can carry a specific type of sensor that is capable of collecting the required data type. In this scenario the data can be transmitted to a central location or stay in local storage. The data is transmitted or downloaded at a later time when the event-to-action time duration is not critical.

In another scenario, doctors can carry their own communication device and their own sensors. While administering to patients either in their clinic or in the hospital, they can collect data from their patients. The data gets stored and the doctor can analyze the collected data at a later time when the event-to-action time duration is not critical.

The third node (Node 3) is a central server that acts as a communication and long-term storage node. Node 2 communicates with Node 3 over any type of long-range network. In the implemented application in this research, a combination GSM network and the Internet were used to test the four-node model. The equivalent in the human body would be the heart.

During the communication between Node 2 and Node 3 a special consideration, based on the number of networks that are involved in the transmission process, is required. If a public infrastructure is used to transmit data, control over the priority of the transferred medical data over these networks is not guaranteed. The lack of control over the priority can cause delay or data accuracy issues.

This dependency can make the medical data less useful. The data might become less useful due to two reasons discovered in this research: event-to-action time duration and data accuracy. These issues can be addressed by introducing a combination of a new protocol and a new algorithm that can make public networks appropriate to transfer medical data with acceptable event-to-action time durations and acceptable data accuracy. This thesis will explain the proposed protocol.

The fourth node (Node 4) is a monitoring device that is used to observe the monitored subject remotely. This node can be stationary or mobile. If the node is a

stationary device then a wired network can be used to transmit data from the central server (Node 3). If the node is a mobile device, a combination of wireless and wired networks can be used to transmit the data. The equivalent in the human body is the brain.

These four nodes are the minimum required nodes necessary to support full mobility to monitor biological tissues in near real-time (acceptable event-to-action time durations with acceptable data accuracy) for most medical data types. To support this model, three network types are required: short-range wireless network; long-range wireless network; and wired network. Finally three types of protocols are required: protocol to transmit data over the short-range wireless network; protocol to transmit the data over the long-range wireless network; and finally a protocol to transmit the data over the wired network. One of the enhancements this research contributes is eliminating the need for three different protocols to transmit the data over these networks. This contribution enhances the event-to-action time duration and data accuracy. One more contribution in this research is the elimination of multiple protocols; an algorithm can take into account the speed and data priority difference between the different networks.

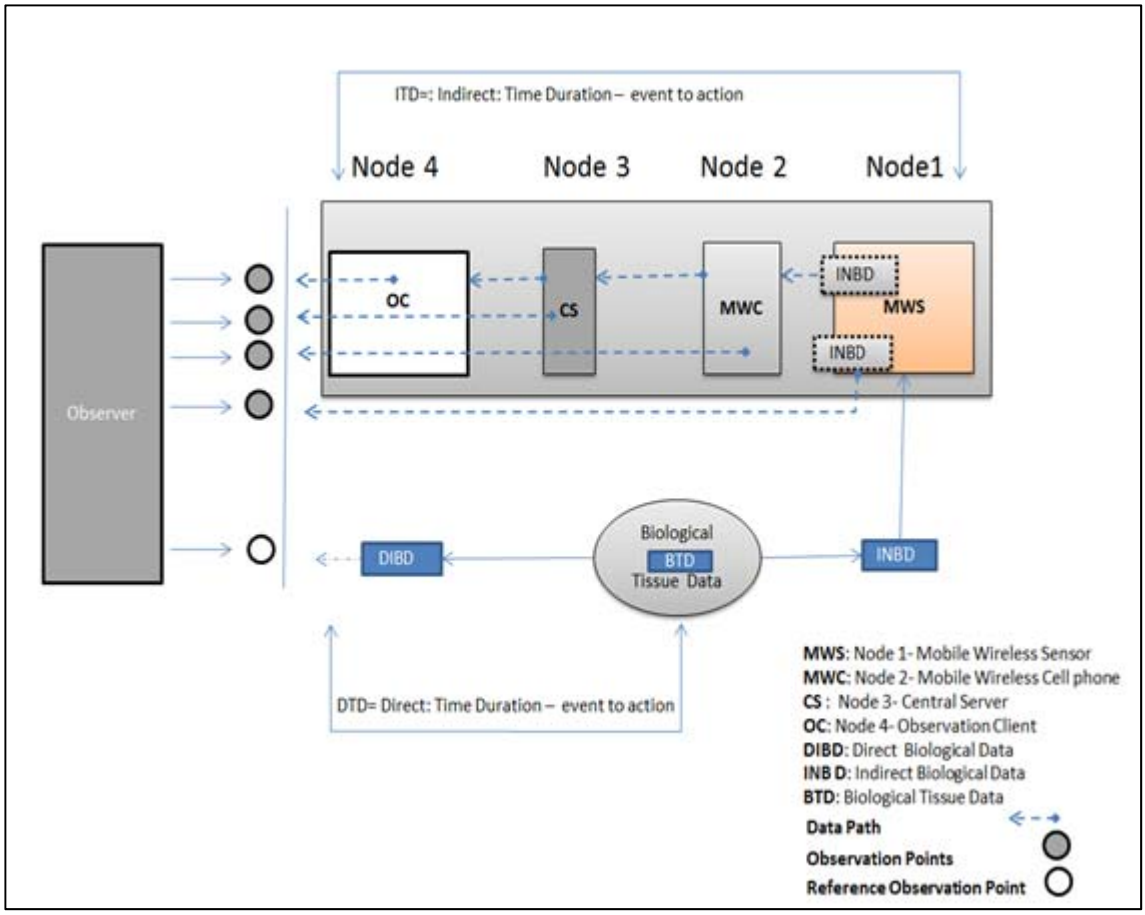

Figure 0.1: Four-Node Model

3.2 Medical Data

3.2.1 Data Types

Large numbers of data types can be gathered from biological tissues for medical purposes. The data type that can be used for medical purposes varies based on the organ that is being monitored, the parameter being collected, and the event-to-action time duration required. In this research the focus was on the brain, the amount of blood oxygenation was the parameter, and the event-to-action time duration occurred after a specific activity.

We monitored two data types – HbO_2 and Hb concentrations in the brain during three activities. Two activities dealt with the human brain and one activity dealt with the canine brain. The HbO_2 and Hb concentrations were observed in human brains during breathing and during smoking. The HbO_2 and Hb concentrations were observed in the canine brain after an explosive detection exercise.

The time duration required to observe the changes in the data was recorded during the above mentioned activities.

The first experiment was designed to generate observer data during human breathing over 120 seconds. The observed time duration during the experiment indicated that over the time duration of 20 seconds, we can see that each breath holding trial had a clear measured impact on the HbO_2 and Hb concentrations. From the experiment we can infer that an acceptable event-to-action time duration when monitoring breathing is 20 seconds. Based on this timing, the generated data were 2,000 state changes in HbO_2 and Hb concentrations during one breath (20 seconds X sensor sample rate in 100 Hz). The experiment lasted for 120 seconds. The total amount of data during this experiment was 12,000 state changes (120 X 100).

The second experiment was designed to gather data during 900 seconds when a human smoked a real cigarette (complete cigarette). The observed time duration during

the experiment indicated that over the time duration of 100 seconds, we can see that each inhalation of cigarette substances (nicotine and other chemicals) had a clear measured impact on the HbO_2 and Hb concentrations. From the experiment we can infer that an acceptable event-to-action time duration when monitoring a human smoking is 100 seconds. Based on this time, the generated data were 10,000 state changes in HbO_2 and Hb concentrations during one inhalation of cigarette substances (100 seconds X sensor sample rate in 100 Hz). The experiment lasted for 900 seconds. The total amount of data during this experiment was 90,000 state changes (900 x 100).

The third experiment was designed to gather data after rewarding a canine for detecting an explosive substance over a time duration of 180 seconds. The observed time duration during the experiment indicated that over the time duration of 20 seconds, we can see that the effect of detecting an explosive substance had an impact on the HbO_2 and Hb concentrations but was not clear. From the experiment we can infer that an acceptable event-to-action time duration when monitoring explosive discovery is 20 seconds. Based on this timing the generated data were 2,000 state changes in HbO_2 and Hb concentrations during one detection of explosive substances (20 seconds X sensor sample rate in 100 Hz). The experiment lasted for 120 seconds. The total amount of data during this experiment was 18,000 state changes (180 X 100).

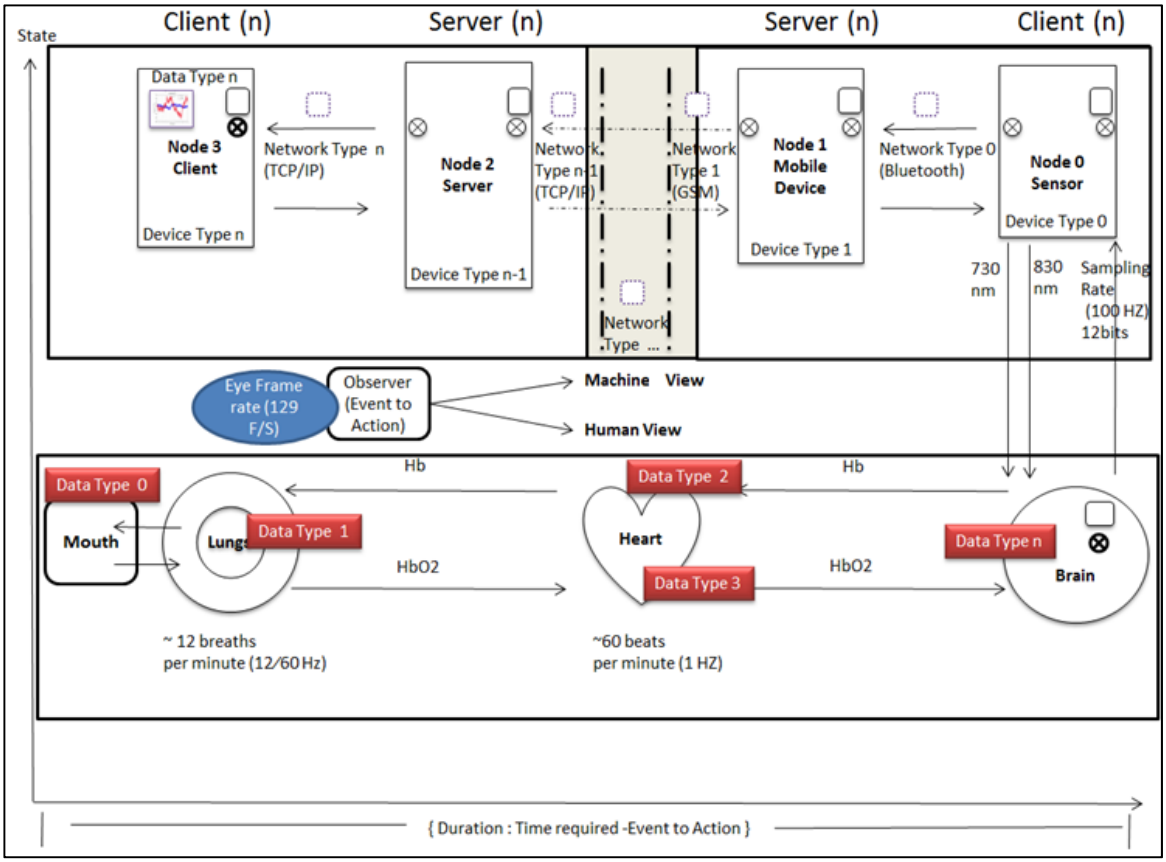

Figure 0.2: Medical Data Types

3.2.2 Data Observation Points

Medical personnel can observe biological changes through four observation points in the four-node model. The first observation point is the output data from the sensor (Node 1). The second observation point is the output data from the cell phone (Node 2). The third observation point is the central server (Node 3). The last observation point is the observation client (Node 4). At each observation point data was examined to validate data accuracy and event-to-action time duration.

In order to validate the collected data accuracy and timing requirements using this model, a reference observation point was used.

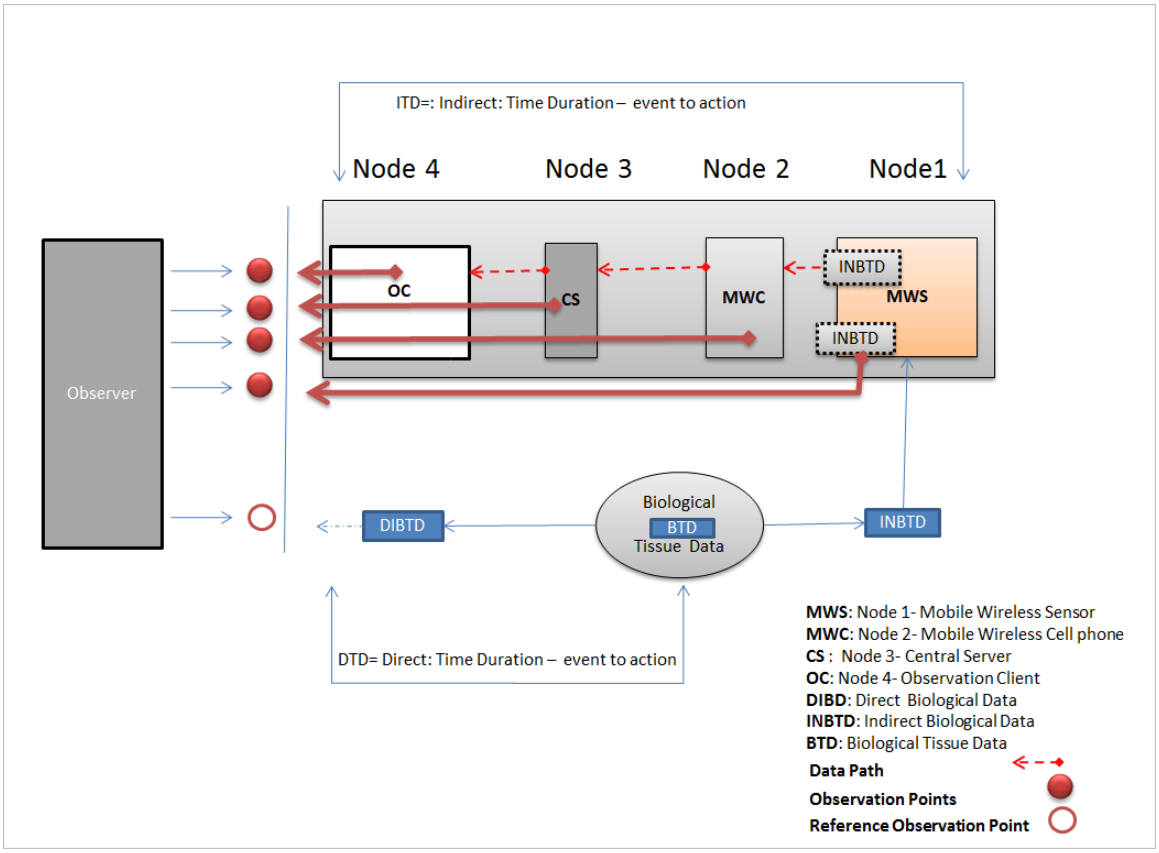

Figure 0.3: Data Observation Points

3.2.3 Data Transmission Path

Speed and throughput of networks and nodes that are involved in transmitting data need to be able to transmit data with a speed that can meet the timing requirements. Otherwise, the data might be less useful in providing acceptable event-to-action time duration results. At the same time, networks and nodes need to ensure no data loss during

transmission. Data loss during transmission can compromise data quality, which in turn may make data less useful.

Data captured by Node 1 goes through a specific path to reach Node 4. The data is passed from Node 1 to Node 2 which ensures the integrity of the transmitted data over the heterogenic networks. When data arrives at Node 3, data is checked for integrity. Once the data integrity is complete, data is passed to Node 4. In case of data integrity issues, Node 3 requests a retransmission of data from Node 2. Node 2 resends the data and goes through the same process again.

In typical situations, the longer the path the more time is taken to transmit data and the more likely data integrity can be compromised. The proposed protocol and the proposed algorithm can reduce the effect of data path length effect.

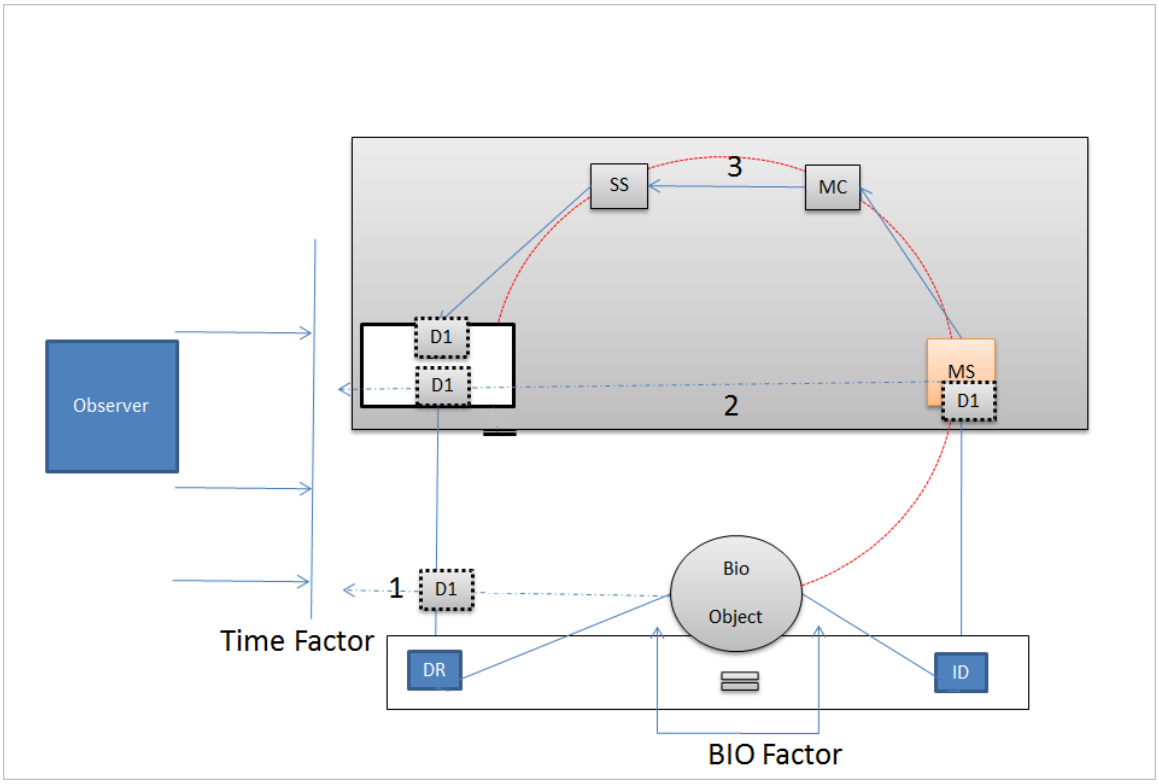

Figure 0.4: Data Transmission Path

3.3 Data Integrity and Event-to-Action Time Duration

During data transmission over heterogenic networks and heterogenic nodes, data accuracy may be compromised due to network load or node processing speed. The time duration to transfer data from Node 1 to Node 4 may not be enough to meet the required event-to-action time duration of the monitored biological data. In order to overcome the above two challenges, the research proposed a protocol to enhance the data accuracy and the event-to-action time duration. The proposed protocol is called Medical Data Transamination Protocol (MDTP) (see Figure 3.2).

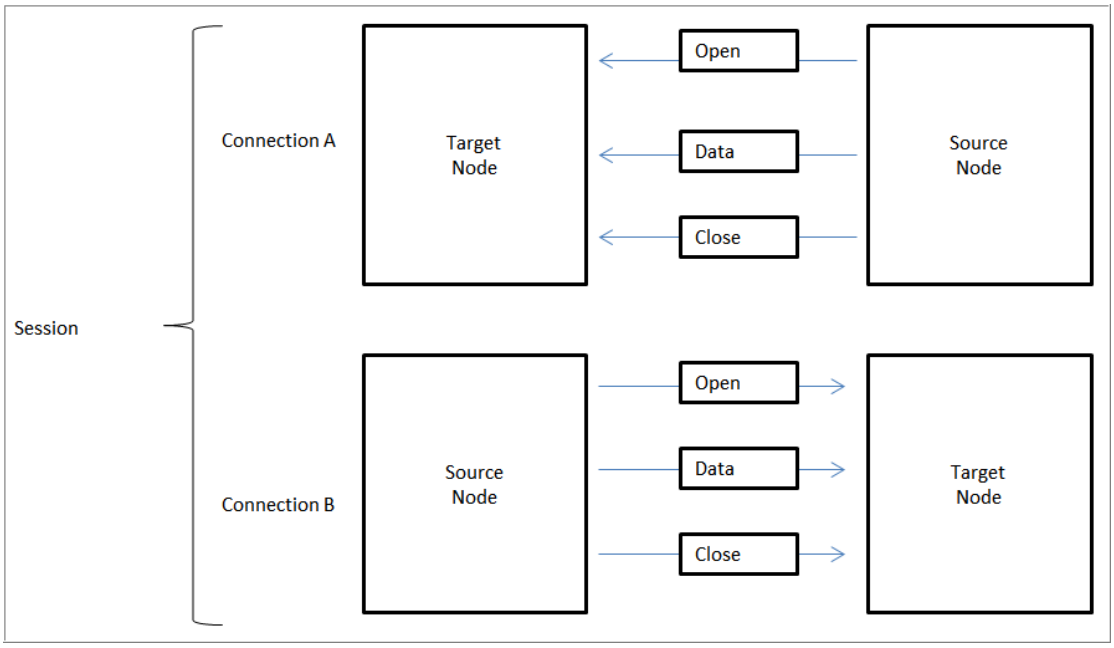

Figure 0.5: Medical Data Transmission Protocol (MDTP)

3.3.1 Data Integrity Algorithm (DIA)

To ensure data integrity it is validated at each node. The algorithm (Figure 3.6) validates the sequence number of each packet. If the data is valid, the protocol sends the data to the next node; otherwise the target node asks the source node to resend the data using the second connection. The algorithm on the target node tries to merge data after it ensures the correct sequence of packet has been received. Based on data type, the algorithm tries to reconcile the received packet or simply ignores any missed packets or compensates for it using a compensation algorithm for the specific transmitted data type.

Any packet loss, such as changes in HbO_2 and Hb concentrations during detection of explosive substances, can make the data less useful. In this case the timing requirement

for such state changes is not critical, but the data integrity is more important. On the other hand, a Data packet loss during monitoring changes in HbO_2 and Hb concentrations while smoking is not critical and neither is the data accuracy. In this case, the changes occur over a longer time period and the algorithm can establish a pattern even if data loss occurs. In the case of monitoring changes in HbO_2 and Hb concentrations during breathing, the time requirements and the data accuracy is different. Even if a packet is lost, the observer still can infer the changes. Finally there might be a case where data integrity and event-to-action time duration is short and important. In this case the algorithm might be less useful.

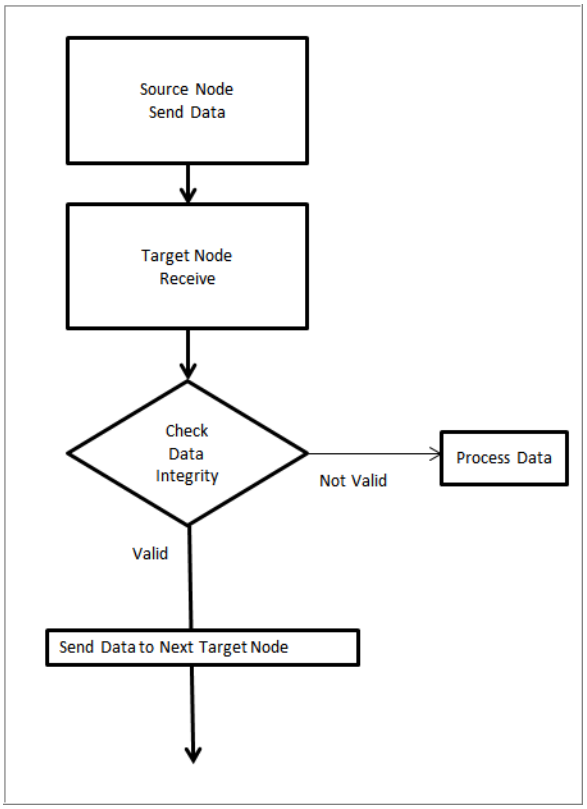

Figure 0.6: Data Integrity Algorithm (DIA)

3.3.2 Event-to-Action Time Duration

It is important to understand the event-to-action time duration and the data integrity requirements when monitoring HbO_2 and Hb concentrations during a specific activity. Based on the requirements, the proposed model, algorithm, and protocol can be useful or less useful.

In this research in order to validate the event-to-action time duration, we use the following formula to calculate time duration.

$$ITD \leq DTD$$

ITD: Indirect Time Duration – event to action

DTD: Direct Time Duration – event to action

$$ITD = \sum_{0}^{N} Tn$$

$$n \in N$$

N: Set of nodes data passes through

Tn: Processing and transfer time for node n

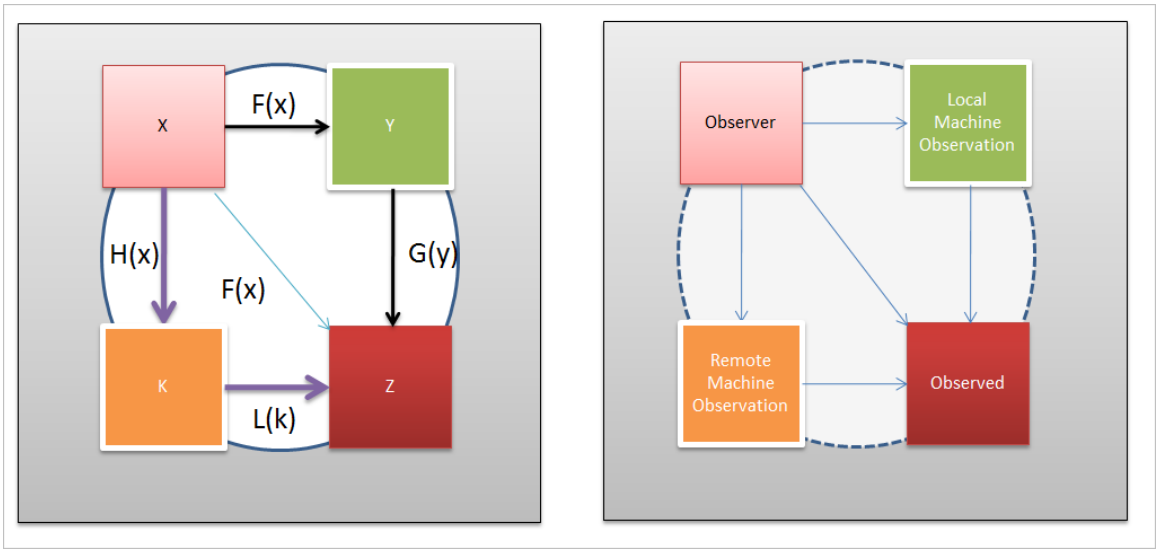

Figure 0.7: Event-to-Action Calculation Model

CHAPTER 4 – MEDICAL DATA TRANSFER PROTOCOLS (MDTP)

Medical Data Transfer Protocol (MDTP) [106] is an application level protocol designed to support medical data transfer when monitoring the human brain.

Initially we used Hypertext Transmission Protocol (HTTP) as a data encapsulation protocol. HTTP is designed to be a request-response protocol to transmit text-based data. We found that the fact it is a text-based protocol makes it unsuitable for binary transmission without adding performance overhead.

This research required continual, fast binary data upload. After reviewing existing upload protocols and approaches, we came to conclude that a new protocol needed to be created. Performance and native binary data transfer were key requirements for the protocol. Based on the requirements, the protocol was designed. The protocol satisfied the requirements by minimizing the control data and the number of overall transactions. Moreover the protocol packet was designed to hold binary data that reduced the data representation overhead.

4.1 Protocol Overview

This protocol (see Figure 4.1) for this research was created to encapsulate only the acquired data and send it to the Server. The protocol is an application level protocol. The total length of each packet in the protocol is 128 bits. Packet length is also key as the captured data required a long packet.

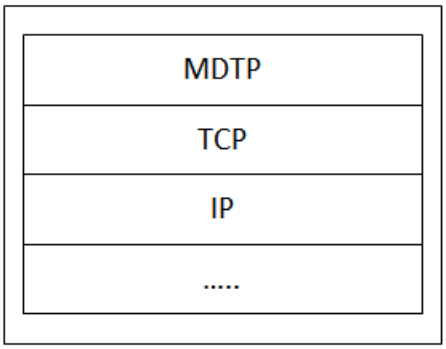

Figure 0.1: Protocol Stack

4.2 Packet Structure

Data are passed using a well-defined data structure called a packet. The packet has two sections: Head and Body. The head is 64 bits and the body is 64 bits.

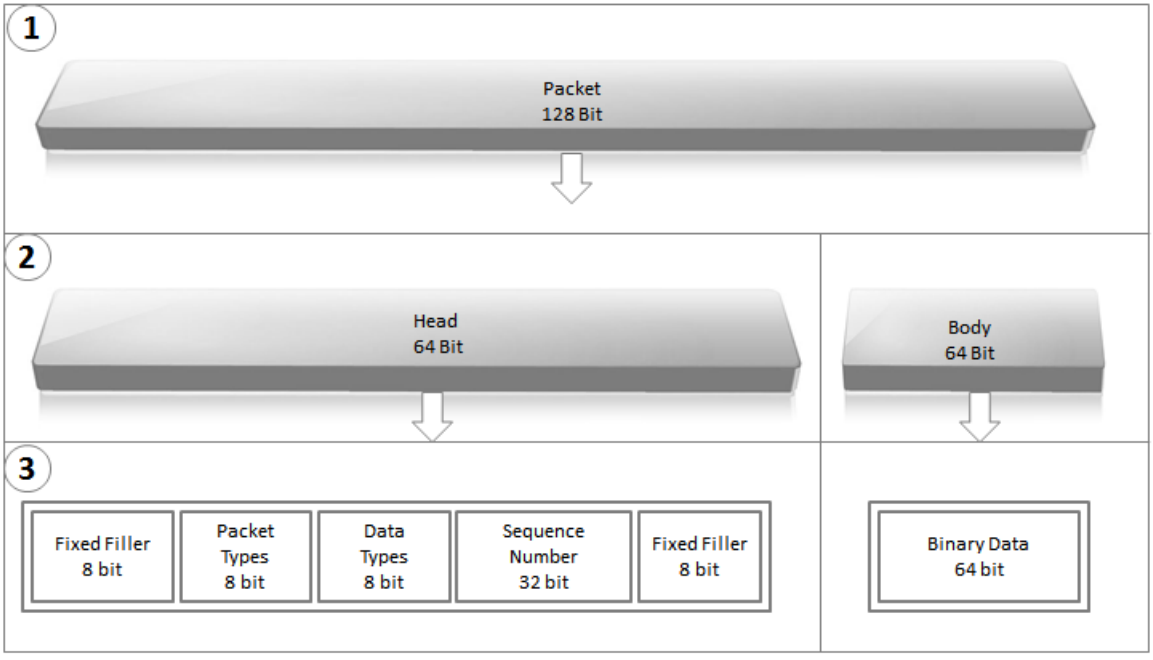

Figure 0.2: Packet Structure

4.2.1 Packet Head

The head section is 8 bytes long. The first byte contains fixed filler values to mark the boundaries of the packet. The second byte is used to describe the packet type: (Open Packet, Data Packet, Close Packet). An Open packet type is used to open a transmission session between all nodes. A Data packet type is used to transmit the actual biological data. The Close packet is used to close the transmission session.

The third byte is used to store the type of data that is being transmitted. The data type is used to identify the monitored tissues. The following are the allowed tissue types (Data Types): Command, HUMAN_BRAIN (Human Brain Tissues), CANINE_BRAIN (Canine Brain Tissues) GENERAL_TISSUES (General Tissues) and Error (Error Message). In order to support other tissues, a new data type can be added. Data types specify the type of data that is under way, such as the packet purpose (oxygen concentration in the blood stream). The four bytes after the data type contains the packet sequence number that identifies the packet number, and the last byte of the head is a fixed filler value to mark the end of the head.

There are three packet types defined in the protocol; however, more packet types can be added. The most significant packet types used are OPEN, DATA, and CLOSE. The data type can be any of the five defined values: Command, Human Brain, Canine Brain, General Tissues, and Error.

4.2.2 Fixed Filler

In a long stream of binary data it is hard to identify the start and the end of a packet in case a bit gets lost. The filler bytes create a pattern to simplify the process of reconstructing the binary stream when some bits get lost. It is easy to find the damaged packet, then ignore or reconstruct the damaged packet. The filler bytes exist at the start and at the end of the head. Such a location is chosen due to the fact that the sequence of data in the header is almost fixed, with the exception of the sequence number. This sequence of a well know order of bits makes it easy to identify a packet header in a long binary stream.

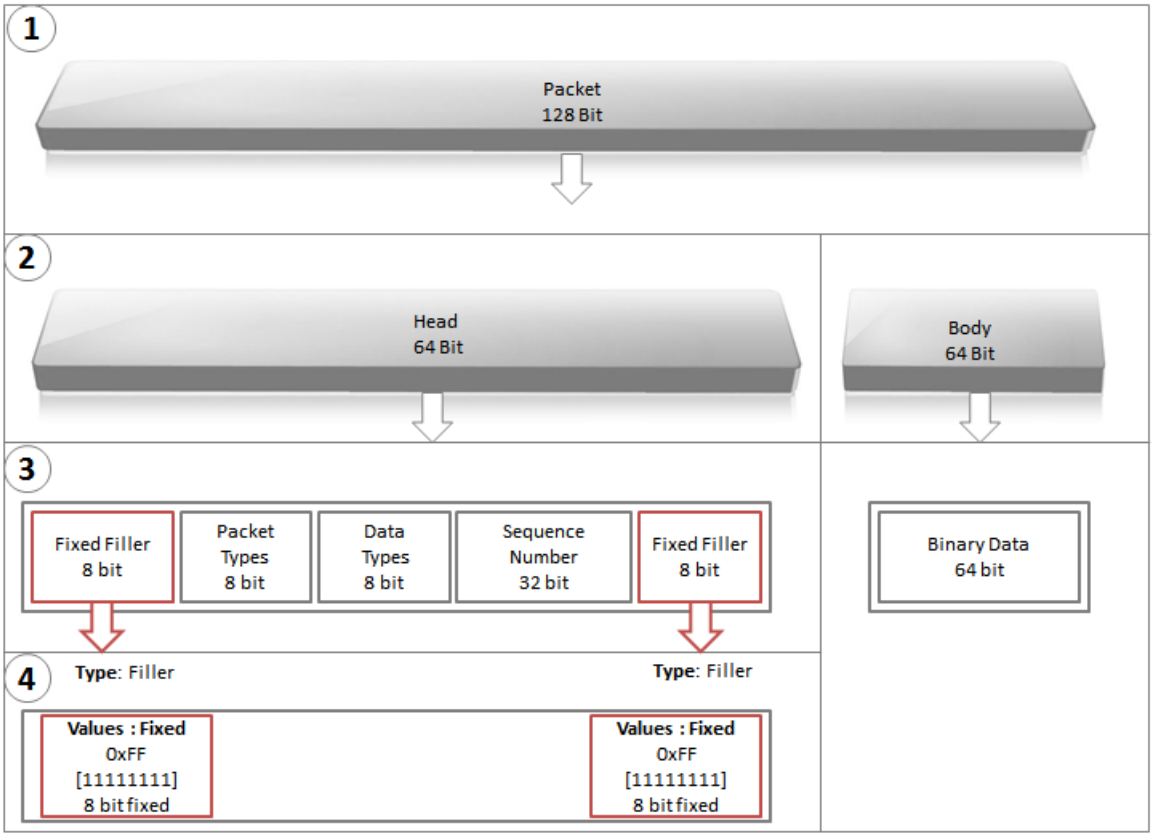

Figure 0.3: Fixed Filler and Its Values

4.2.3 Packet Types

The protocol is a lightweight protocol; it has only three packet types.

Packet type OPEN is used to signify the packet contains an indication to open connections between nodes. The value of the byte is 0x00. It is a fixed value of 8 bits.

Packet type CLOSE is used to indicate the end of transmission and that it is time to close the connections between nodes. It has a fixed value of 0xFF and it is 8 bits.

The packet type DATA is used when the source node is sending data to the target node. It is represented by 8 bits and has a fixed value of 0x01.

The value of the packet type can be set according to the type of the packet. In this instance of the protocol there are only three possible values. The possible values are: 0x00; 0x01 and 0xFF.

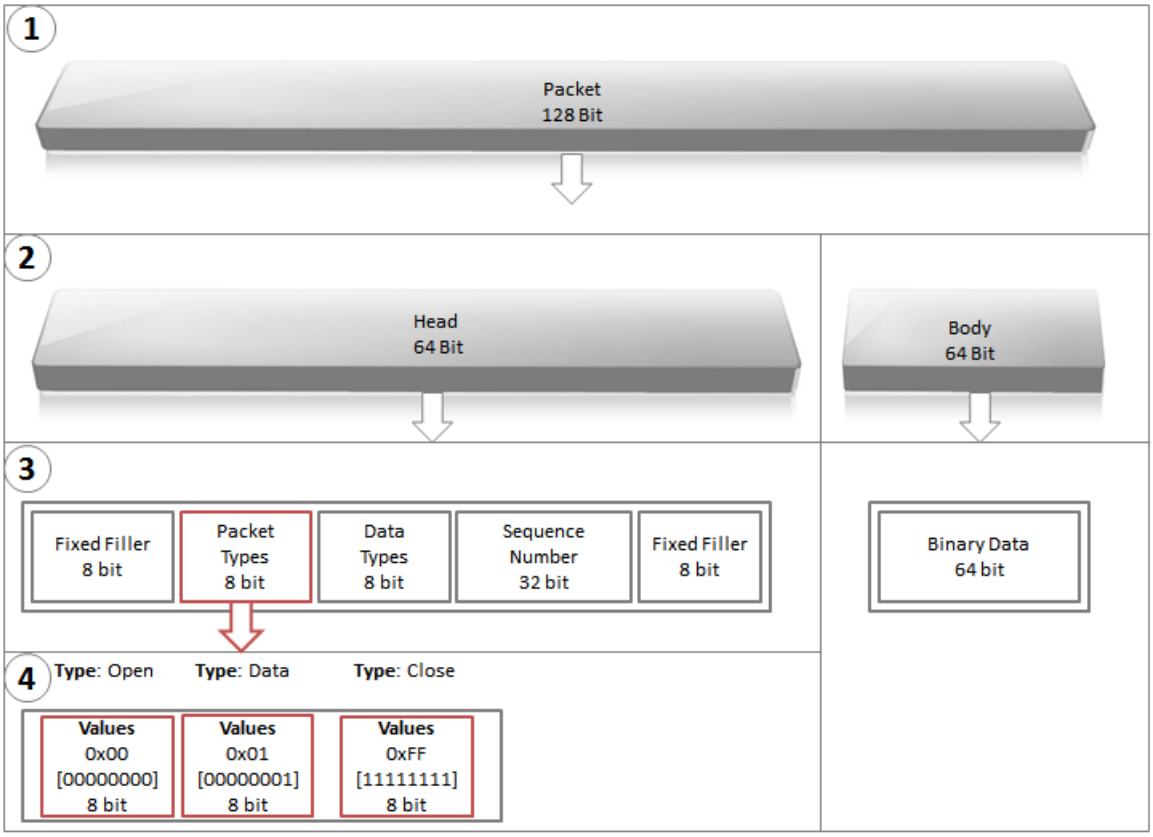

Figure 0.4: Packet Types and Their Values

4.2.4 Data Types

The data type bits indicate the type of data that is being transmitted and measurements type. The protocol was initially designed to support the monitoring of oxygen concentration in the blood stream in the human brain. Other measurements types were added later to validate the concept. The protocols support five data types: Command Data Type, Human Brain Data Type, Canine Brain Data Type, General Tissues Data Type, and Error Data Type. The data type bits get filled with value 0x00 when the packet type is either open or close. It indicates the packet contains command data.

Human Brain Data Type indicates the packet contains data related to human brain measurements. In this case the bit has value of 0x01. Canine Brain Data Type indicates that the measurements are canine brain related data. General Tissues Data Type is used when capturing tissues that are related to brain overall measurement and 8 bits will contain 0x03 as a value. The last possible value is Error (0xFF). When the data type bits has this value, it indicates the packet contains an error message.

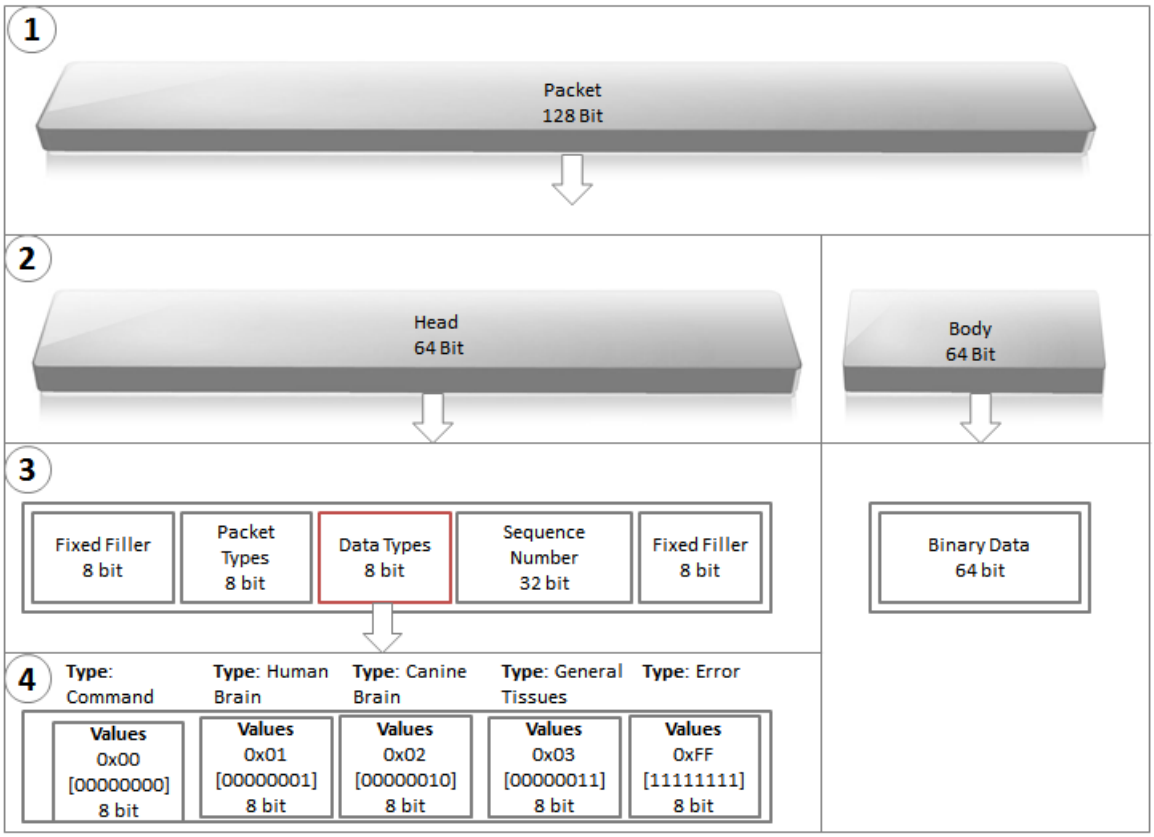

Figure 0.5: Data Types and Their Values

4.2.5 Sequence Number

The sequence number bits are used to mark the packet number and order. The packet number and order is used to detect errors and help in constructing the overall packet pattern. It starts with zero and can reach 0xFFFFFFFF. The sequence number is always increased by one. The packet sequence number is equal to the previous packet number plus one.

The volume of captured data can be large. It was the main reason to allocate 32 bits to the sequence number. Capturing data from the human brain and using a high frequency Sensor for an extended period of time can generate a large number of Data packets.

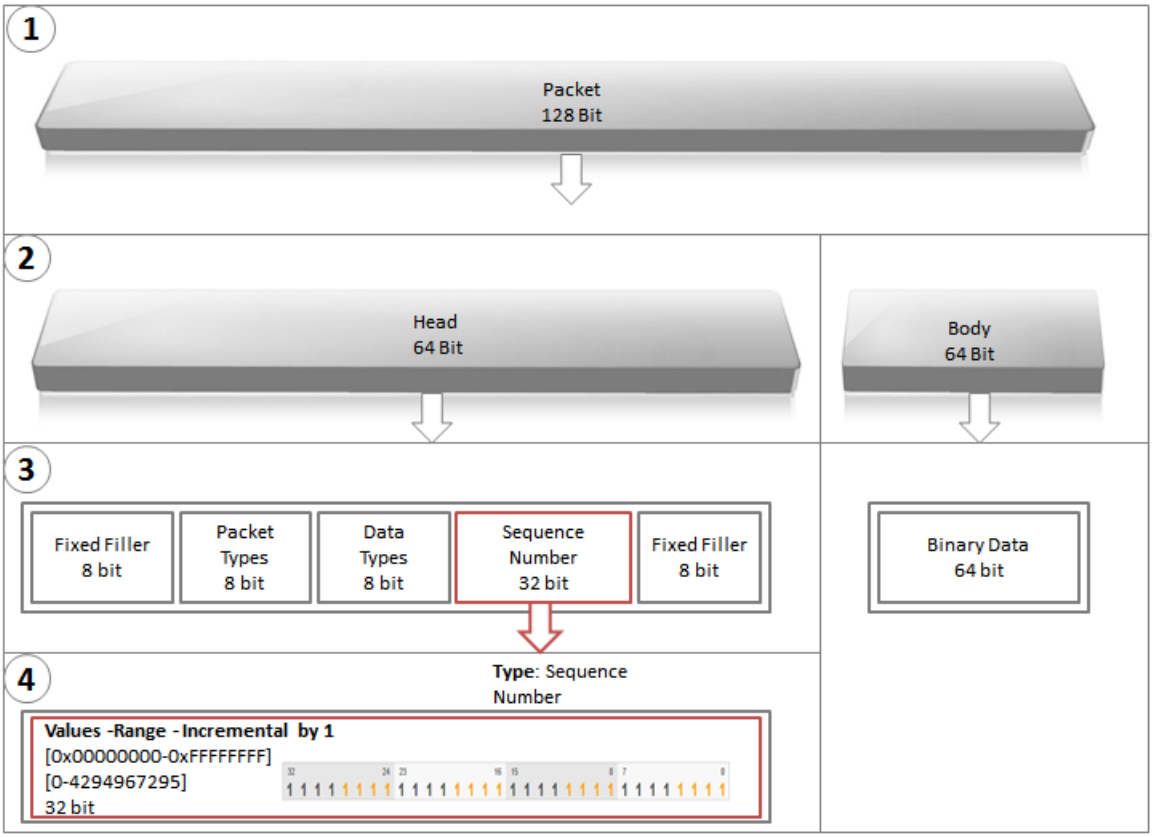

Figure 0.6: Sequence Number

4.2.6 Packet Body

The packet body bits hold the actual captured data from the target tissues. The Sensor fills this part of the packet with the binary data that represents the changes that occur in the tissues. The number of filled bits will depend on the type of data the Sensors used and its accuracy. The data is represented in a binary format to eliminate data conversion.

Values in the body will depend on the actual captured changes using the Sensor. The content of these bits will be used to represent the changes. Most likely the data in these bits will be used to create a graphical representation of the changes. A pattern can be established and used to analyze the change.

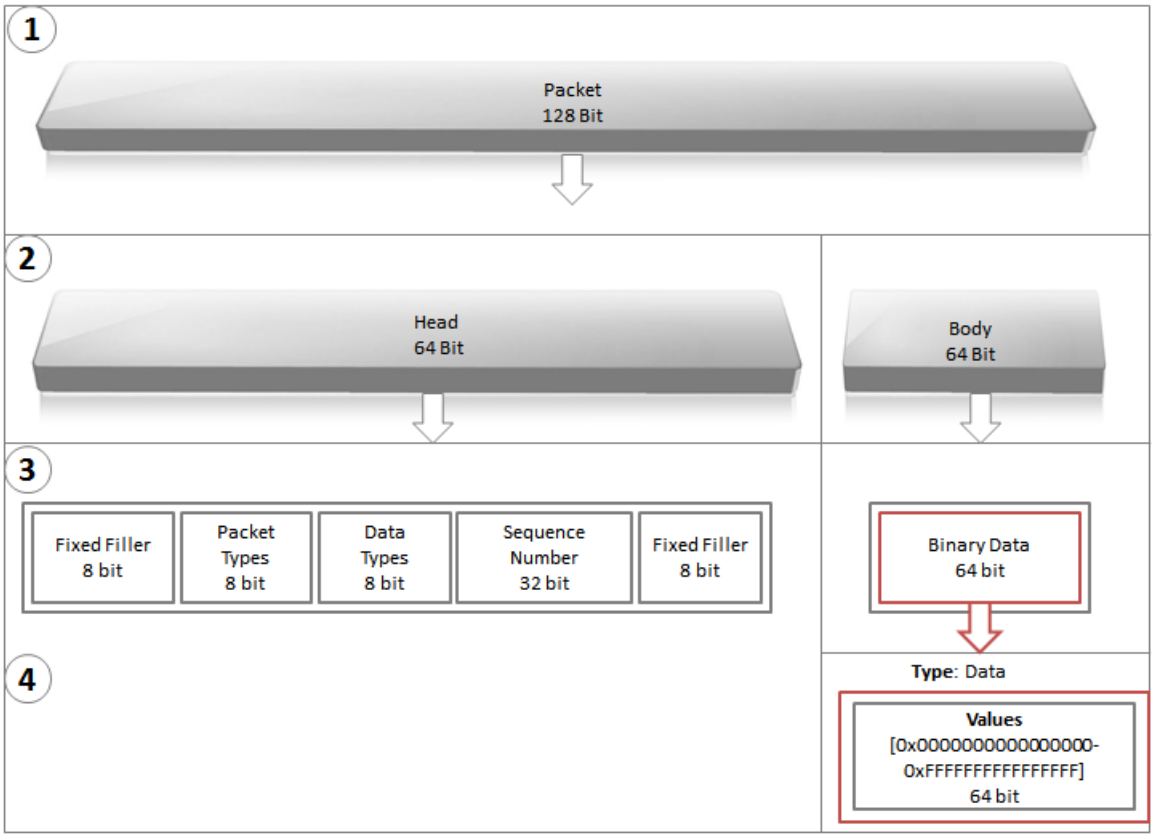

Figure 0.7: Body and Binary Data Values

4.3 Packet Creation

The packet gets populated with different data based on the roles it plays. The first main packet interaction is the Open packet. The Open packet can be issued from any node in the system.

4.3.1 Open Packet

The source node creates an Open packet and populates the head and the body of the packet with the required values. The source node needs to set values in the packet to 64 bits. First it populates the head bits. It fills the filler bits with the fixed values 0xFF (Fixed Filler). Next the packet type gets filled with the packet type “OPEN” (0x00). Data type bits are filled with 0x00 (Command) to indicate this packet is a command packet (OPEN). Sequence number bits are filled with 0x00000000 since this is the first packet in the measurements process. The value bits get filled with 0x0000000000000000 since no actual data is being transmitted.

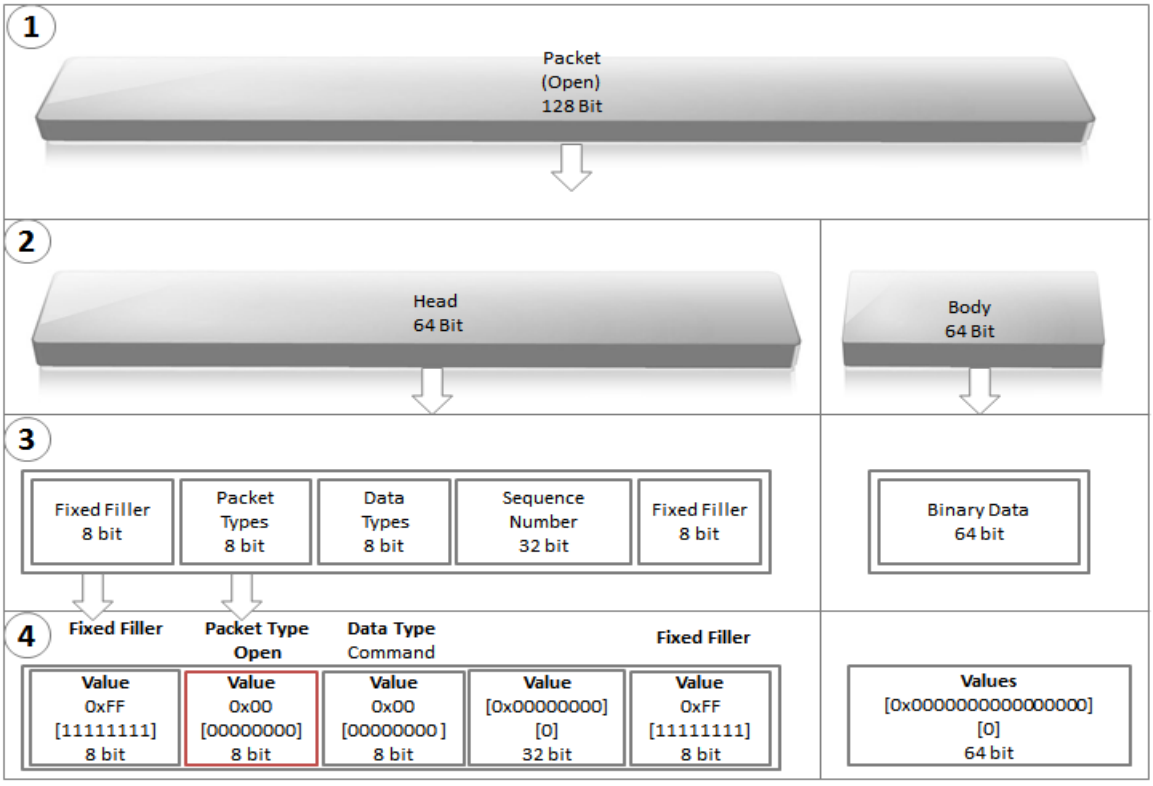

Figure 0.8: Open Packet

4.3.2 Close Packet

The source node sends a Close packet. It is used to close the connection between the different nodes. The packet gets created and the packet bits get filled with the required values.

Fixed Filler bits get populated with 0xFF. Packet type bits get populated with 0xFF (Close). Data type bits need to be filled with 0x00 to indicate this packet is a command packet not a Data packet. The sequence number bits will contain the last sequence number from the previous transaction plus one. The binary data in the body in this packet

type will contain 0x0000000000000000 since this packet does not contain any measurement data.

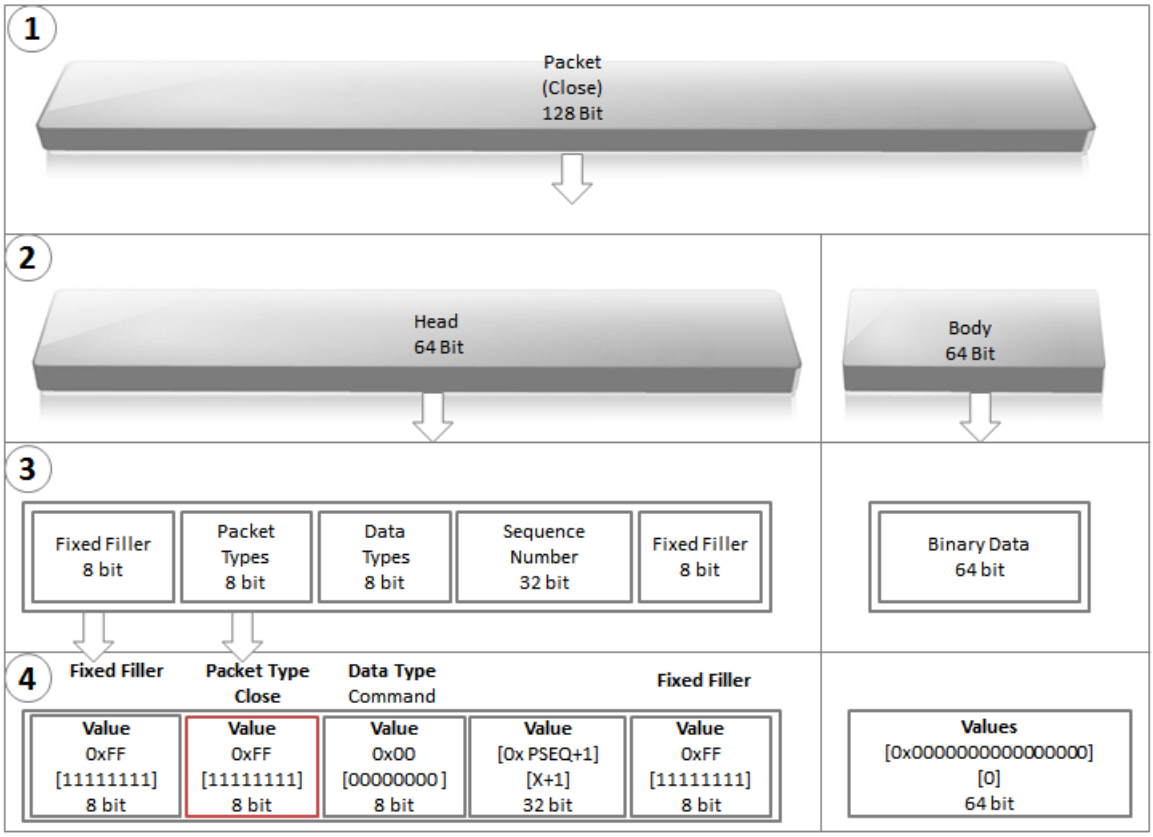

Figure 0.9: Close Packet

4.3.3 Data Packet

Packet type data gets created by the source to encapsulate measurement data. It will have the actual binary data that has been captured using the Sensor.

Fixed filler bits get filled with 0xFF values; Packet type bits get filled with 0x01 (Data) to indicate this packet is a Data packet. Data type bits can contain any of the predefined data types: Human Brain, Canine Brain, General Tissues, or Error. Human Brain Data Type value (0x01) indicates the packet contains data related to human brain activities. Canine Data Type value (0x02) indicates the packet contains data related to canine brain activities. General Tissues Type value (0x03) indicate the packet contains data related to general tissues measurements. Finally Error Type value (0xFF) indicates the packet contain an error message.

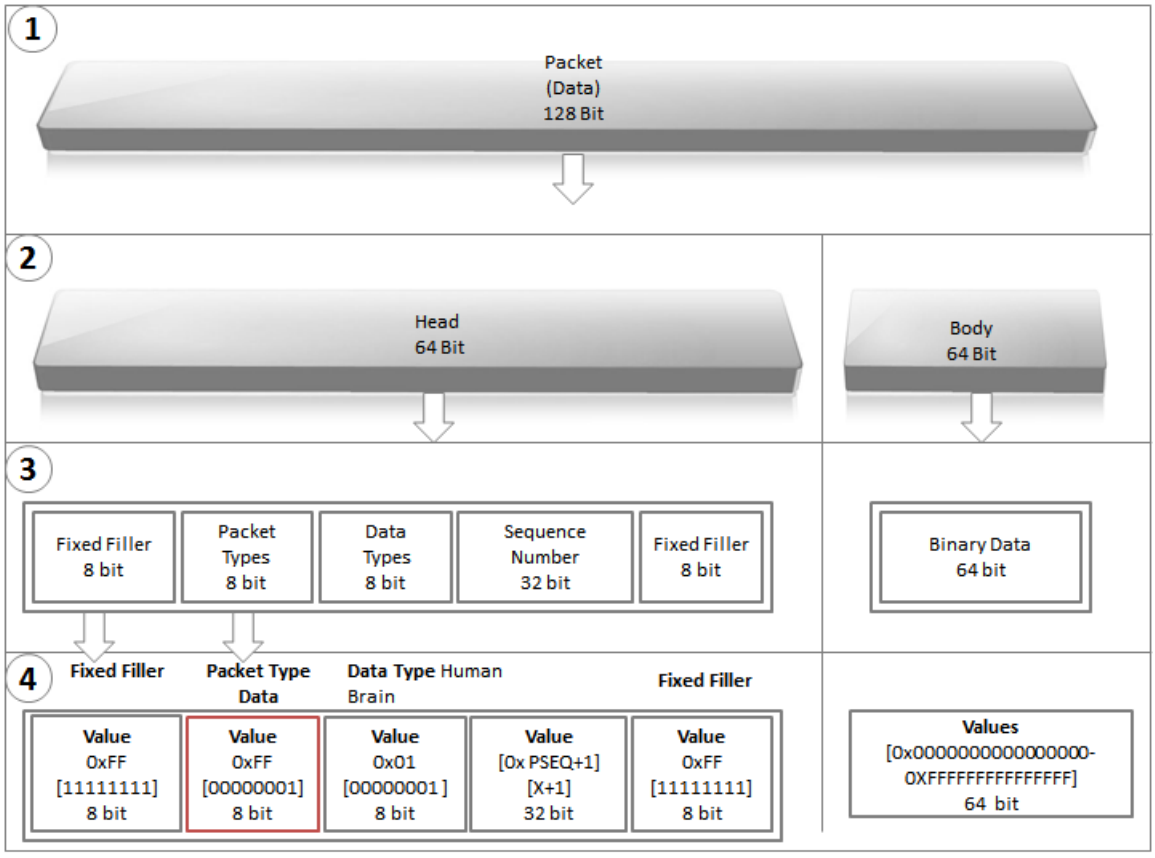

Figure 0.10: Data Packet

4.4 Packet Behaviour and Interaction

The protocol is a multi-layer protocol that ensures interaction between all nodes involved in the communication. The ultimate goal of the protocol is to facilitate the data collection process.

The data collection can start from any node that is part of a data collection process. The node initiates the data collection processes to create an Open packet and send it to the nodes that are part of the collection network. The participating nodes open two connections to form the transmission session. Two connections are open to ensure the data is transmitted through redundant connections, which are duplicated.

The data source (the Sensor) starts capturing data, creates Data packets, and sends them to the target. The data is sent over two connections that are compared at the target to ensure data accuracy.

Data capture stops when the source (the Sensor) sends a Close packet type to indicate the end of transmission.

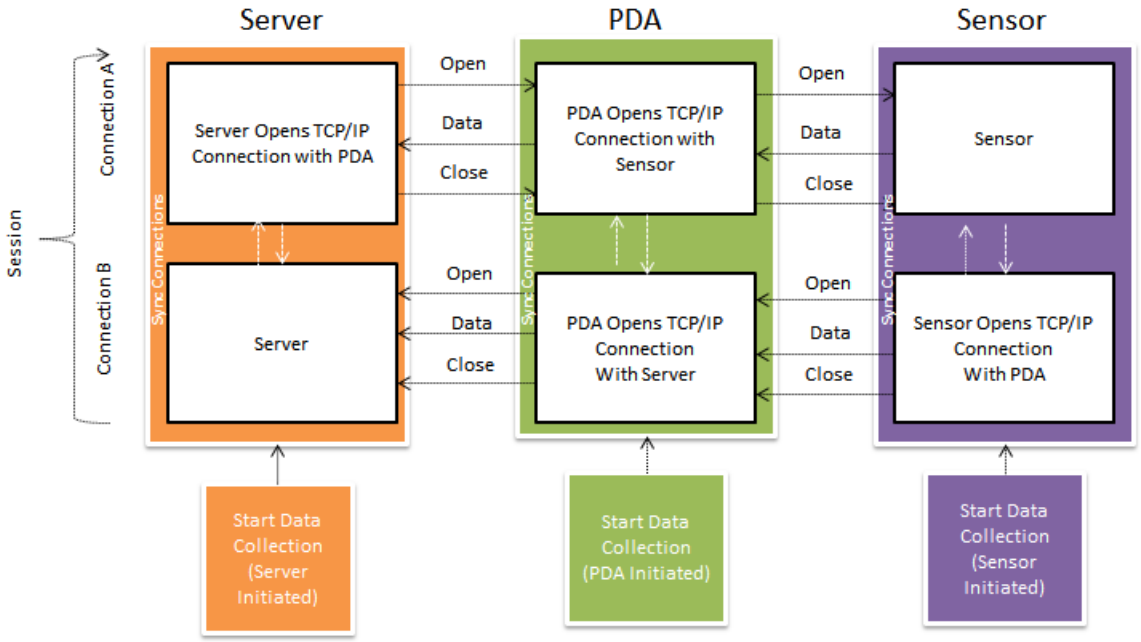

Figure 0.11: Closed System Packet Interaction

4.4.1 Session

Each session contains two connections between all data collection nodes. The data collection can be started from any node.

In the case where the collection starts from the Server, the Server sends an Open packet to the PDA. The Open packet causes the creation of a TCP/IP connection between the Server and the PDA. The PDA forwards the Open packet to the Sensor which creates a TCP/IP connection between the PDA and the Sensor. The Sensor sends an Open packet to the PDA to create the second connection between the PDA and the Sensor. The PDA sends an Open packet to the Server to open a second connection with the Server. At this

stage there are two connections between the nodes. The Sensor, after establishing the second connection with the PDA, starts sending Data packets through both connections.

The PDA receives Data packets from both connections from the Sensor and forwards them to the Server. The Server receives data from the PDA from both connections and compares them to ensure integrity and finally analyzes the data or saves it.

CHAPTER 5 - RESULTS AND DISCUSSION

We have shown that it is feasible to provide full mobility monitoring of brain functions in humans in an everyday environment using a near-infrared light sensor by employing a set of heterogeneous networks accessed using the protocol outlined. To validate the protocol's functionality, we used it to monitor brain functions during smoking outside the lab environment. Again, it was used to collect changes in oxygenation concentration levels in the brain during breath holding, and finally was used to measure the changes in oxygenation concentration levels in dogs' brains when presented with their favourite toys.

The research contributes a protocol to support a fully mobile system to monitor human brain activities outside the lab environment. To validate the system's basic data functionality, more than 100 tests were performed.

This chapter presents the results in two sections: the protocol-related results and the biomedical application-related results.

5.1 Protocol Related Results

5.1.1 Summary

The tests were focussed on performance, data integrity, availability, and the effectiveness of the developed protocol. Our results indicate that the protocol has achieved its goals.

5.1.2 Protocol Performance

The protocol worked in all cases, but different amounts of delay were experienced in the data transmission. In this section, we discuss the factors affecting our system's transmission performance and explain what we mean by "near real-time."

A real-time system can be defined as a system that can perform operations within a predefined time regardless of the system's load [96]. In this research, we define our system to be a near real-time system, because the system transmits the data with a delay that varies according to the load of the involved networks, over which we do not have control. While performing the experiments, we encountered delays in data transmission. Typically, the delays varied between 0.1 to 2 seconds, as illustrated in Table 5.1. The delay is impacted by the networks' speed during the time of day the experiments were performed. Because GSM networks give higher priority to the voice channel, and consequently lower priority to data channels, these delays are unavoidable. The Internet bandwidth and usage also impact the end-to-end transmission.

To minimize the delay, the protocol was designed to allow sending of packets continuously. This approach reduced the overall time between packets which make it possible to send the data with a very short delay (0.3 second) most of the time. Because the packet size is very small (128 bits) due to the protocol design, the network bandwidth requirements became very small. Therefore, the system required only a very few resources to transmit the data to the server making it possible to transmit the data in near real-time despite unpredictable changes in the network's load.

The system can still send data with a very short delay utilizing the available resources even when load on the network increases from other applications. Table 5.1 shows the average encountered delay during 15 days for 3 separate test locations. We ran 3 location-based tests for 24 hours at different times. Time stamps were inserted into the Sensor, PDA, and Server. The time difference between the time stamps is used to calculate the delay.

Day	Location	Average Delay Seconds	Location	Average Delay Seconds	Location	Average Delay Seconds
05/01/2011	Toronto	0.5	Vaughan	0.2	Brampton	0.7
06/01/2011	Toronto	0.5	Vaughan	0.2	Brampton	0.7
07/01/2011	Toronto	0.4	Vaughan	0.4	Brampton	0.7
08/01/2011	Toronto	0.6	Vaughan	0.2	Brampton	0.7
09/01/2011	Toronto	0.6	Vaughan	0.2	Brampton	0.4
10/01/2011	Toronto	1.0	Vaughan	0.2	Brampton	0.4
11/01/2011	Toronto	0.2	Vaughan	0.2	Brampton	0.4
12/01/2011	Toronto	0.2	Vaughan	0.2	Brampton	0.2
13/01/2011	Toronto	0.2	Vaughan	0.3	Brampton	0.4
14/01/2011	Toronto	0.5	Vaughan	0.2	Brampton	0.1
15/01/2011	Toronto	0.5	Vaughan	0.2	Brampton	0.1
16/01/2011	Toronto	1.0	Vaughan	0.2	Brampton	0.2
17/01/2011	Toronto	0.2	Vaughan	0.2	Brampton	0.3

18/01/2011	Toronto	0.1	Vaughan	0.4	Brampton	0.3
19/01/2011	Toronto	0.2	Vaughan	0.4	Brampton	2.0

Table 0.1: Average Delay Using MDTP Protocol Per Day/Location

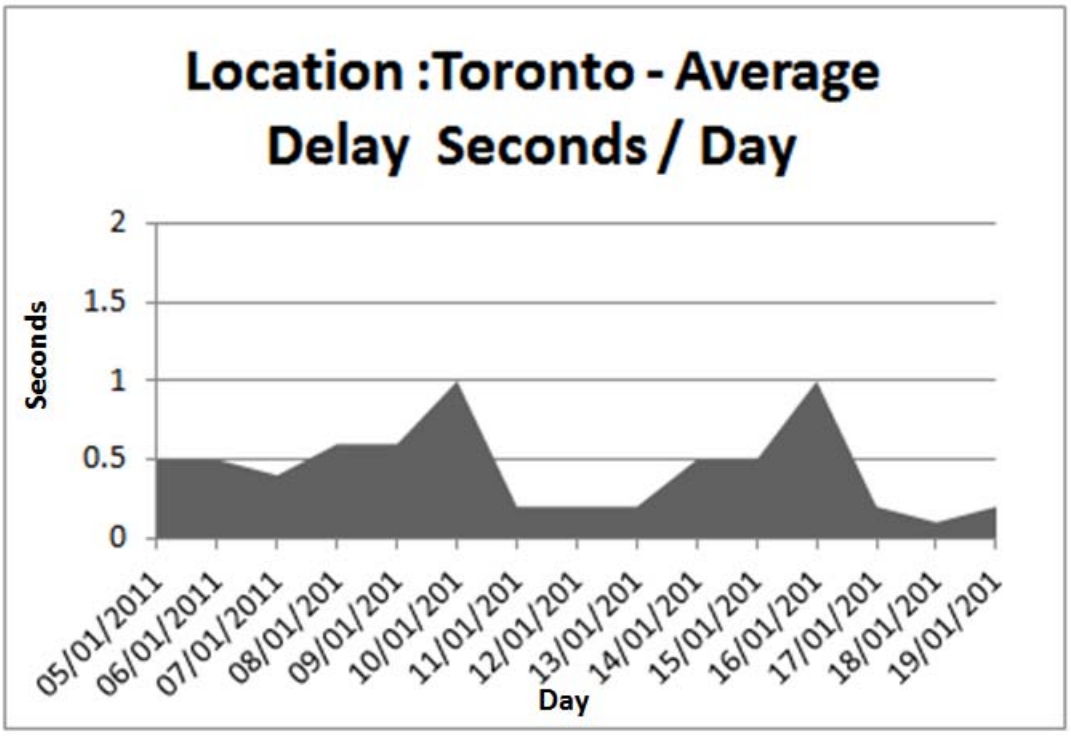

Table 0.2: Average Delay Using MDTP Protocol Per Day/Location

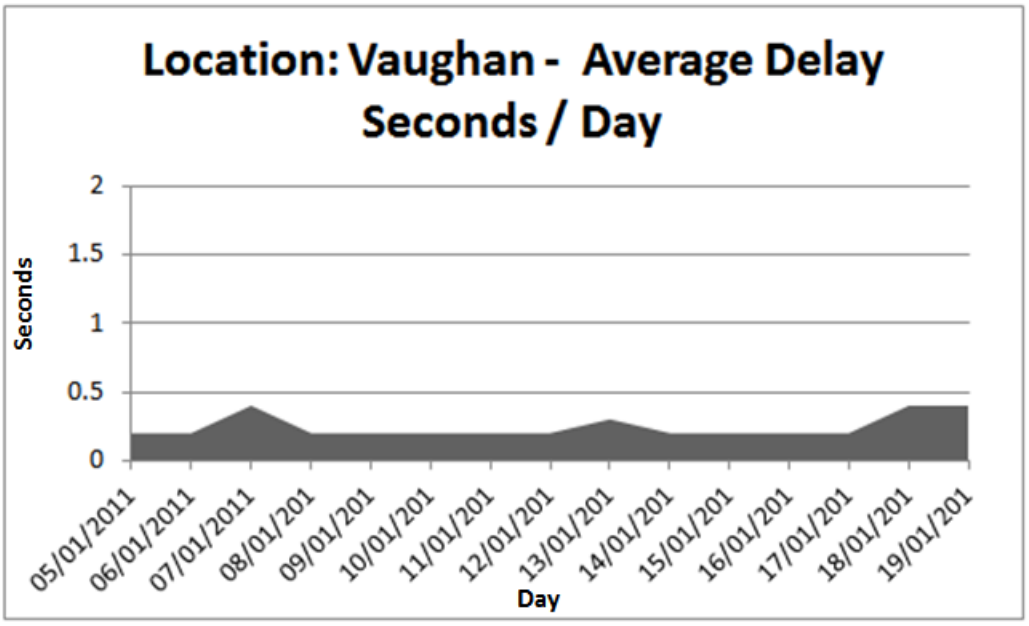

Table 0.3: Average Delay Using MDTP Protocol Per Day /Location

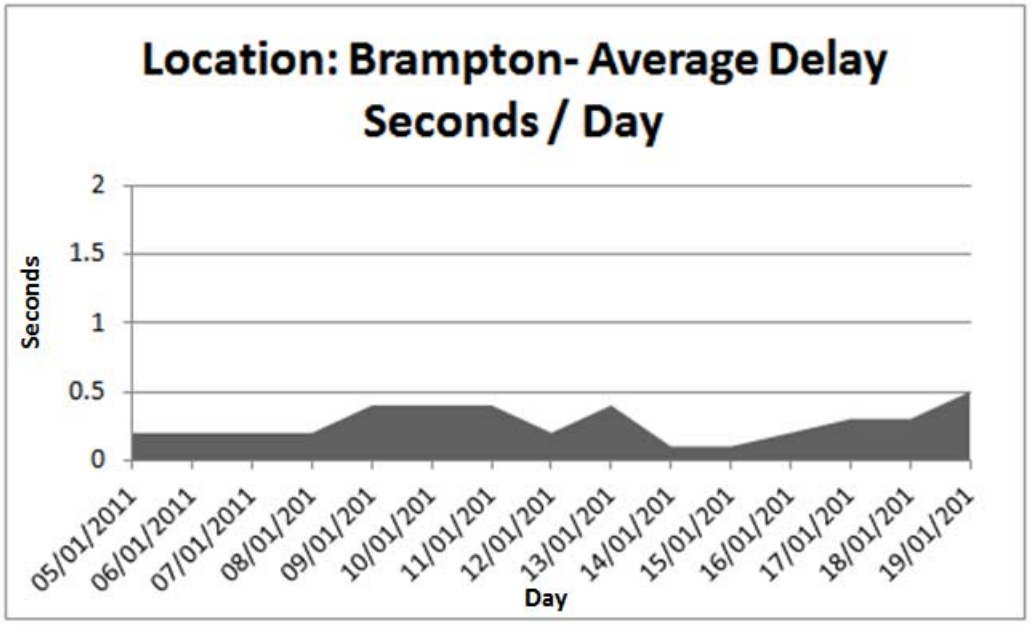

Table 0.4: Average Delay Using MDTP Protocol Per Day /Location

5.1.3 System Data Integrity

5.1.3.1 Packet Sequence Number

Packet sequence numbers are used to validate the data transmission. The system generates 100 packets per second. Each packet has a unique sequence number. The PDA tags the packet with a unique number. On the server this unique number is used to check the integrity of the data transmission.

More than 100 data integrity tests were performed. The system was used to generate continuous packets (86,400,000 packets) for a duration of 1,440 minutes (60 X 24). In each test the packet numbers were checked to ensure that the server received the complete number and the correct sequence. The result shows that the system successfully sent all acquired packets with the correct sequence. It is worth mentioning that the number of packets is proportional to the test duration. The formula (Equation 5.1) provides a way to calculate the number of packets. The sequence number is simply a sequence number starting from 0.

$$Pn = Pf \bullet T$$

Pn = Packet Numbers

Pf = Packet Frequency (the packet frequency for the sensor used is 100 Hz)

T = time in milliseconds

Equation 0.1: Total Packet Number Calculator

On the server side we detected packets without a sequnce number in some cases. We tracked the cause back to the Sensor. Occasionally and randomly, the Sensor sends packets without a sequence number. The total number of packets sent from the Sensor

without a sequence number did not exceed 10,000 packets out of 86,400,000 packets. In most of the cases, packets without sequence numbers occurred randomly in time. In the case when the packets without sequence numbers are continuous, the total number did not exceed 1,000 packets. The packets that do not have a sequence number can be ignored and this does not impact the overall result. Simple manipulation can be used to eliminate these packets or fix them and add them to the overall acquired packets.

5.1.4 System Availability

The protocol system was designed to provide full mobility. The protocol can function with or without GSM connectivity. Where there was no GSM connectivity or the GSM connection was lost during the measurement process, the system was able to save all acquired packets in the PDA's local file system as expected.

5.1.5 MDTP Protocol

The MDTP protocol was designed to support near real-time binary data streams over heterogenic networks. To compare MDTP performance versus HTTP protocol performance, two versions of the system were implemented. The first version implemented MDTP protocol and the second version implemented HTTP protocol. Performance tests were performed using time stamps. The first time stamp was added on the PDA code just before the code starts sending the data. The second time stamp was added in the server code just where the code starts receiving the data. The results demonstrate that MDPT protocol performs better than the HTTP protocol for near real-

time binary data streaming. Table 5.2 shows a comparison between the MDTP protocol and the HTTP protocol.

MDTP Average Delay second	HTTP Average Delay second
0.5	**15**
0.3	**10**
0.2	**8**

Table 0.5: MDTP Protocol Versus HTTP Protocol

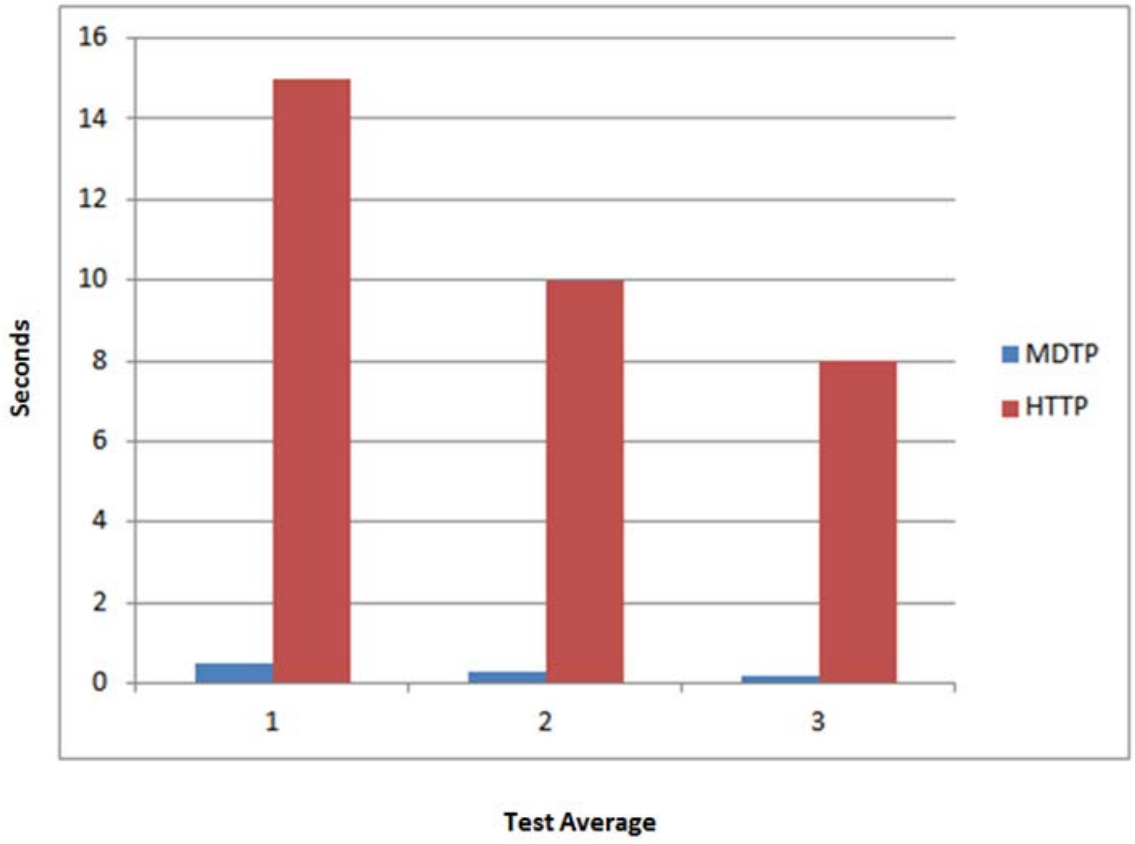

Table 0.6: MDTP Protocol Versus HTTP Protocol

5.2 Biomedical Application Results

5.2.1 Summary

Our protocol was designed to support a wide range of measurement activities. We wanted to ensure that a variety of data would be available for testing. In order to achieve this goal we performed tests on both humans and trained dogs with tests being conducted both inside and outside lab environments. HbO_2 and Hb changes in brain and tissue were collected for both species in different circumstances. In total, three major types of biomedical experiments were conducted using the protocol.

The first experiment was a breath holding experiment. The test was used as a validation experiment in order to ensure that our system worked correctly and could collect biological data. The second experiment was related to smoking and it was conducted entirely outside the lab. This experiment was performed to understand the effect of smoking on the brain in a real environment away from the distractions and unrealities of a rigid laboratory environment – an environment where smoking actually takes place. The third experiment was conducted to attempt to monitor a trained canine's brain activities. The experiment was conducted in order to determine if it was possible to monitor the brain activity of animals.

We found the second and third test to be particularly compelling. Smoking is an addictive behavior that occurs in the real world. In order to more accurately understand the factors that cause this behavior we believe that any measurement must occur in the true circumstances of the activity. The third experiment, involving trained canines, was motivated by both the need for data outside the human realm but also because we believe it may be possible to determine elements of mental activity within working animals – specifically canines – that directly relate to the activity that the animal is about to engage in. This is significant because it implies a certain level of predictability. Whether this is actually feasible is beyond the scope of this thesis, however, Helton et. al. have run a similar test in a lab environment but without the benefit of our system. [97] If testing is ever to be done in a real world setting, there must be a mechanism for allowing it.

5.2.2 Breath-Holding Experiment Results

To validate that the system was functioning as expected a breath-holding experiment was performed on humans. The result was compared with a lab method [98]. Test subjects were asked to rest for 20 seconds, then to hold their breath for 20 seconds, and thereafter exhale and breathe normally for 20 seconds. The trial for each test subject lasted for 120 seconds. The rest duration between trials for each test subject was approximately 2 days.

We performed 15 breath-holding trials. We asked three different test subjects (two males and one female) to hold their breaths. The first test subject was a 23-year-old, healthy, female non-smoker; the second test subject was a 46-year-old, healthy, male non-smoker; and the third test subject was a 36-year-old, healthy, male smoker. During the lab trials, the test subjects were asked to wear the sensor on their foreheads near the hair line and lay down on their backs on the test bed; they were asked not to move and not to speak. Instructions to inhale and exhale were communicated to them by the person running the trials. In the outside trials, the test subjects were asked to wear the sensor on their foreheads and sit on a chair in the open; they were asked not to move or speak while performing the breath-holding trial.

Figure 5.1 shows the test subject wearing the sensor during the breath-holding experiment.

Figure 0.1: Test Subject Wearing the Sensor During the Breath-Holding Experiments

After analyzing the collected data using our system, we can see that each breath-holding trial had a measured impact on the HbO_2 and Hb concentrations. The result was compared to a result obtained from a similar experiment using fMRI [98]. This experiment proved that the system can provide results similar to the ones previously obtained by other test methods, such as fMRI [98]. Clearly the system worked as expected.

Figures 5.2 and 5.3 show two examples of data obtained during the breath-holding trials. The graphs show that HbO_2 increases during the breath holding. The arrow indicates when this increase occurs due to breath holding. The brain compensates for the lack of oxygen by increasing the blood flow [98]. Then the HbO_2 level goes down after breathing was resumed.

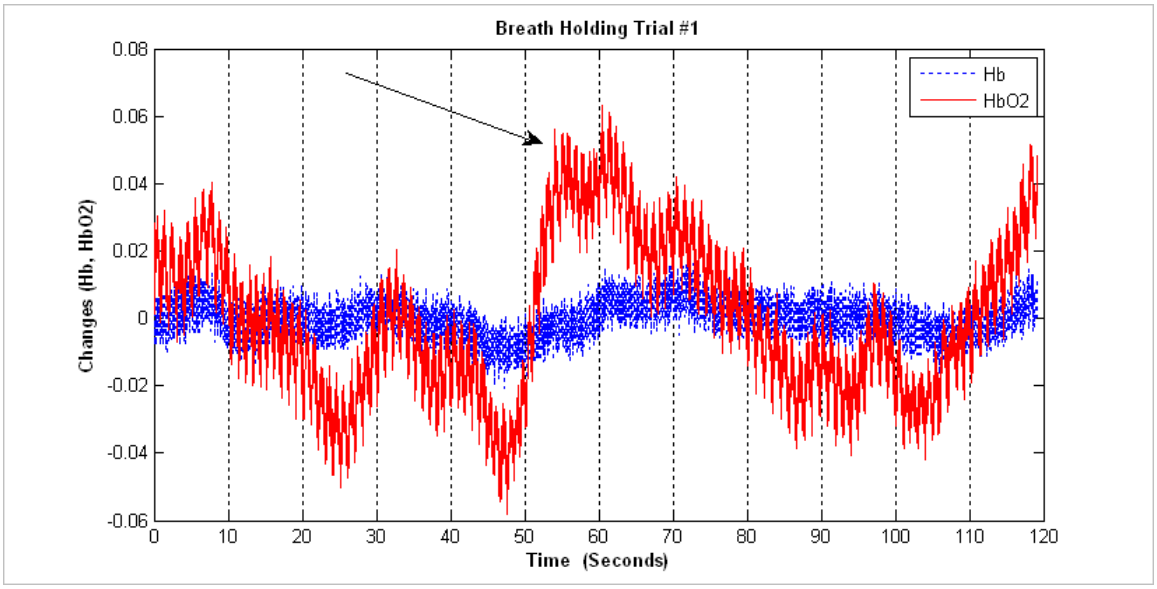

Figure 0.2: Breath-Holding Trial # 1

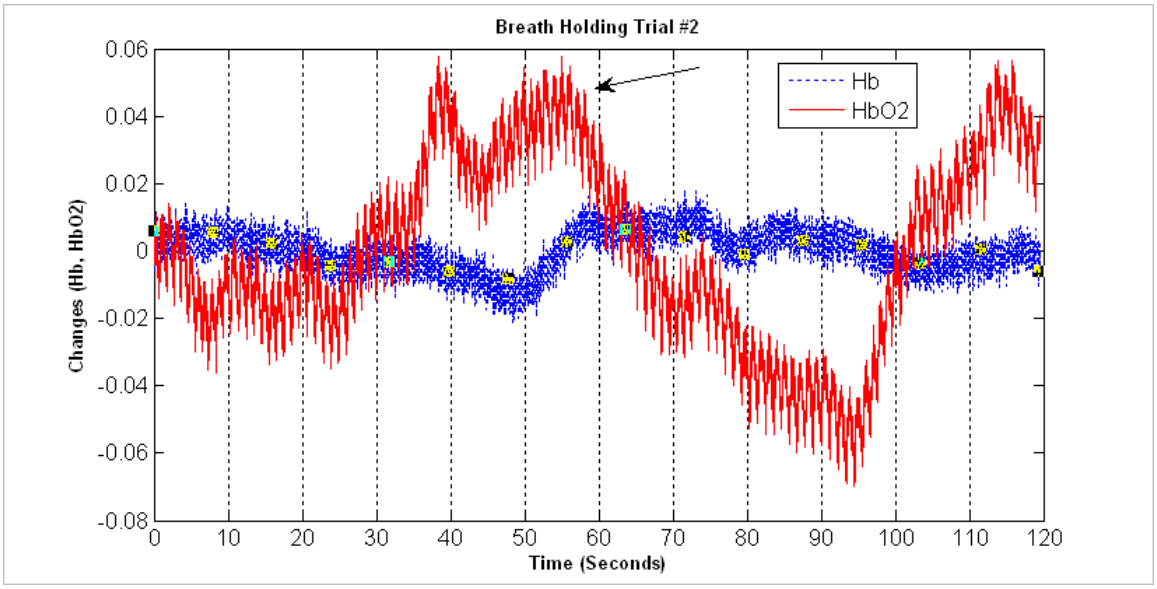

Figure 0.3: Breath-Holding Trial # 2

5.2.3 Smoking Experiment Results

There is an agreement among scientists that cigarette smoking causes lung cancer, heart diseases, and other serious illnesses [99, 100]. Almost five million Canadians smoke

15 times or more per day [101, 102]. The chemical substances, including nicotine, found in cigarettes [103, 104, 105, 106] entering the human body during smoking can cause several physiological changes. Few studies have applied fMRI to detect the oxygen level changes in the human brain under the effect of direct nicotine administration. The results have proven that nicotine can impact the level of oxygen in the hemoglobin in the brain [100, 107]. It is important to emphasize, however, that all these studies have tested the impact of the nicotine on the oxygen level in the brain using direct nicotine administration rather than actual smoking.

To understand the real effect cigarettes (nicotine and other chemicals) have on the brain, as opposed to direct administration of nicotine, smoke testing must be performed in a natural way rather than in a controlled environment. One contribution of the system [103] used in this research is to address this need. In fact, there are pragmatic health and safety reasons why our method is superior to in-lab testing. Because test subjects can be tested independently of the environment, no collateral damage from smoking need be accidentally inflicted on auxiliary participants in the test. Thus our method is safer, does not require special lab modifications, and is as effective as other methods.

In total, six smoking trials were conducted. The experiment's purpose was to examine the relationship between smoking and HbO_2 and Hb changes in the brain. Five healthy, human males and one healthy, human female participated in the experiment. The test subjects' ages ranged from 30 to 40 years old. All the test subjects were active smokers for a period of more than 2 years. During the trials, the test subjects were asked to wear the sensor on their foreheads and sit on a chair in the open where they were asked

not to move more than they had to in order to smoke and not to speak. The sensor was fixed with a bandage on each test subject's head to improve the sensor's stability on the head and minimize the effect of the test subject's movement during the smoking process. Instructions as to when to smoke were communicated to the subjects by the person running the trials. Each trial lasted for 15 minutes, which included a 5-minute baseline, 5 minutes of smoking, and a 5-minute recovery after smoking. Figure 5.4 shows the test subject wearing the sensor during the smoking experiment.

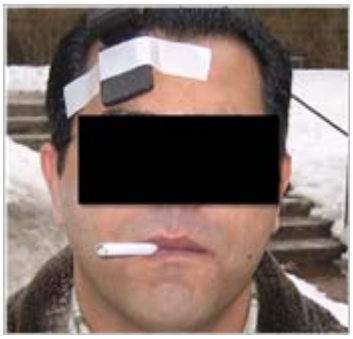

Figure 0.4: Test Subject Wearing the Sensor During the Smoking Experiments

Baseline data was recorded for 5 minutes before the test subject started smoking. The test subject was asked to smoke for 5 minutes, during which time the test subject inhaled every 20 seconds. After the 5-minute smoking period, the test subject was asked to keep wearing the sensor for another 5 minutes. The data collection continued during the 5-minute waiting period after the smoking was completed. The recovery period allowed us to capture any delayed after-effect changes that occurred due to smoking.

When we analyzed the data, we observed HbO_2 and Hb changes during the baseline, the smoking, and the recovery periods. Figures 5.5 and 5.6 illustrate the results

from the smoking experiment. The graphs show that during the baseline, changes in HbO_2 and Hb reflected normal physiological states. Sharper changes in HbO_2 and Hb appeared during smoking. These changes were similar to changes that occur during functional brain activities. Usually, such changes occurred due to the increase in the blood flow [108].

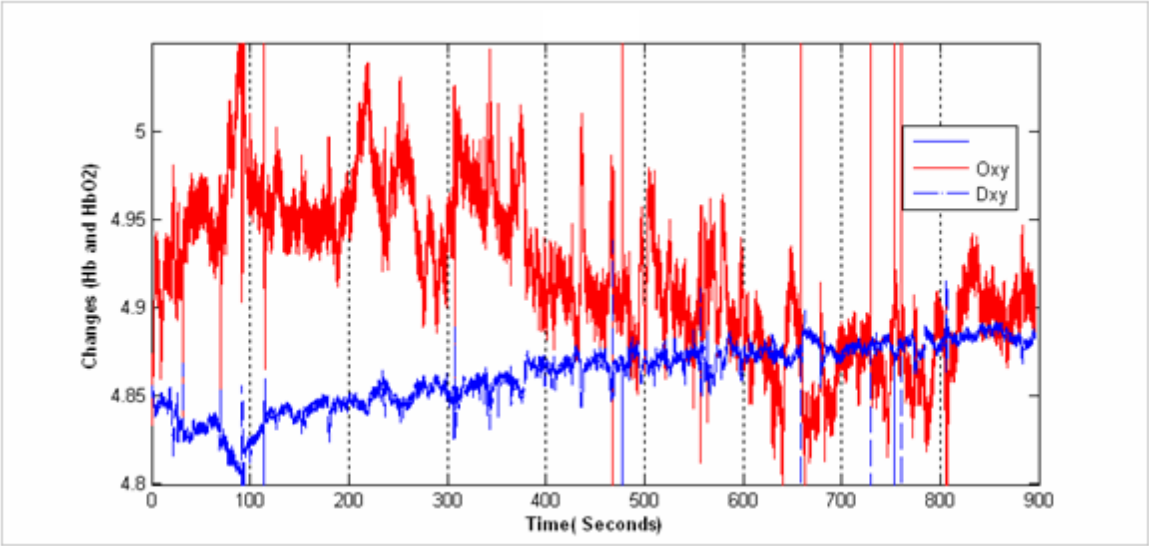

Figure 0.5: Smoking

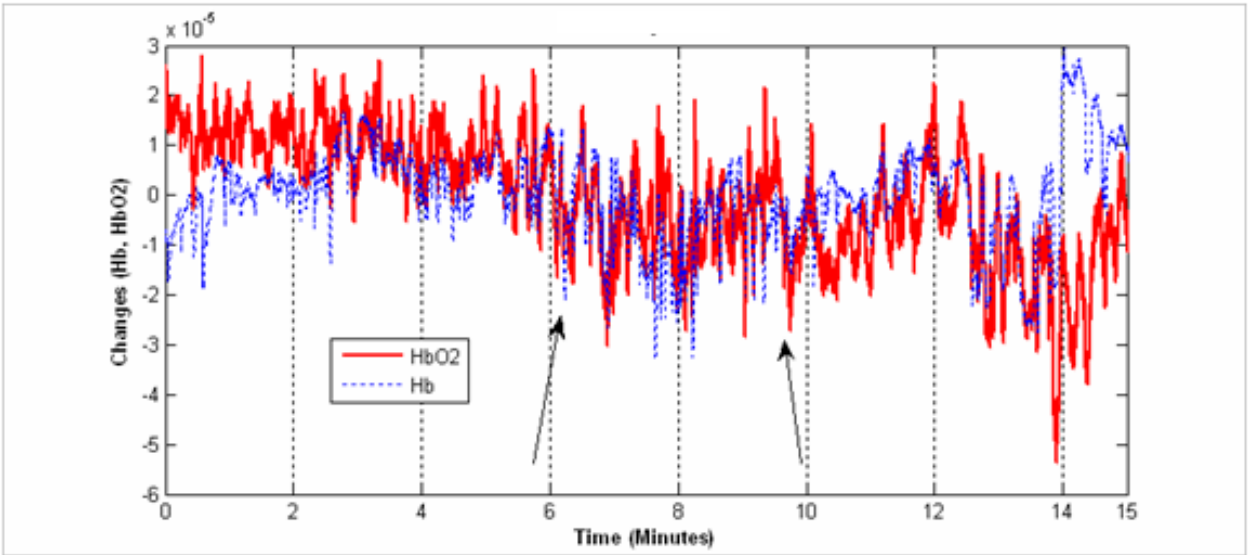

Figure 0.6: Sample Smoking Trial

5.2.4 Canine Experiment Result

The purpose of canine experiments is to determine the possibility of measuring changes in the blood oxygenation in the canine brain *in vivo*. The experiment was conducted employing trained Urban Search and Rescue (USAR) canine teams in two phases. The first phase was to determine an appropriate place to position the sensor (intended for humans) on the canine head. We received the assistance of USAR canine teams from three Canadian national USAR Task Forces. We determined a feasible location to collect data through trial and error resulting in a general understanding of where the sensor should be held. No attempt was made to hold the sensor in place except through the assistance of the canine handler who held either the sensor in place or their dogs during the tests.

We found that we were able to measure a signal from a canine head however the signal was rather noisy if the dog was very active as the handlers had difficulty in keeping the sensors in place.

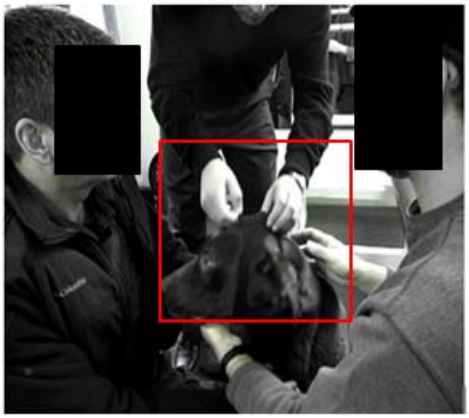

Figure 0.7: Picture While Performing the Experiment

In the second phase we used what we learned from the first phase to run a controlled test similar in nature to those employed by Pavlov [109]. The sensor was placed and held on the dog's head and the handler was asked to keep the dog as motionless as possible for 120 seconds. While no dog remained motionless throughout this entire period, the time allowed the dogs to calm themselves and, by the time the period had elapsed, the dogs were still. After the 120-second period, an assistant was asked to show the dog its favourite chew toy. The data collection process continued for another 60 seconds after the dog saw the toy. The sensor was then removed and the dog was given its toy to play with.

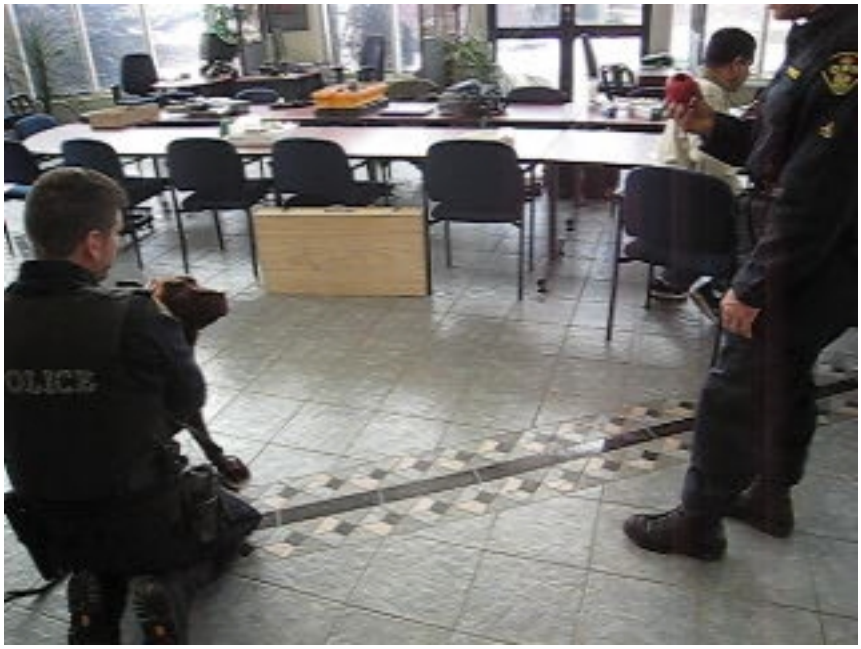

Figure 0.8: Canine Experiment

Figure 5.9 shows the collected data in the second phase of our experiment, indicating that it was possible to obtain data from dogs with our sensor. However, the system did not detect any HbO_2 and Hb changes from some dogs. Some factors that might have caused the failure to detect HbO_2 and Hb changes in all the canines' brains were the canines' movements, their head anatomy, and/or the fur on their heads.

Figure 5.9 shows the obtained results from the canine experiment while showing the canine its favourite toy. The arrows indicate the time when the canines saw the toy. The time when the canine was shows the toy starts at second 560. HbO_2 and Hb levels start increasing at that moment. The changes indicated between the arrows may indicate the brain's activity response to the toy.

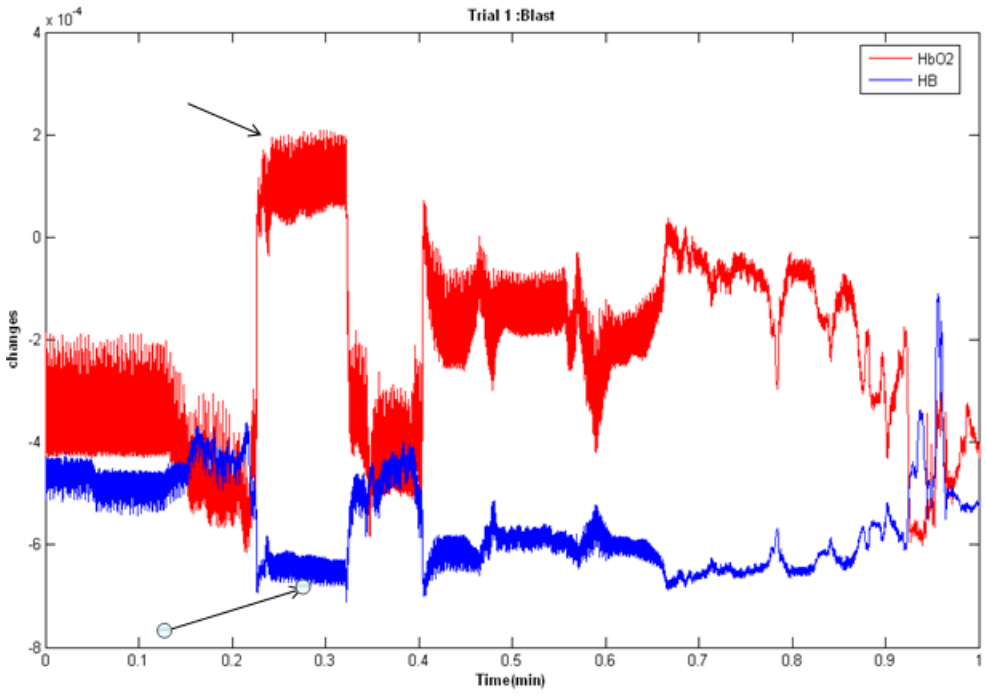

Figure 0.9: Canine Trial # 1

5.3 Data Transmission Discussion

The results show that the system can detect HbO_2 and Hb changes in the brains of humans and animals in their everyday environments. This is a major indicator that the contributed protocol achieved their goals. The protocol increased the accuracy of the system to transmit accurate data in near real-time over heterogenic networks.

The collected data during smoking trials was different in its quality. Some trials were able to provide good results while other trials showed no effect for smoking. We noticed that test subjects' movements and positions could impact the acquired data. In Figure 5.6, we conducted the experiment on the test subject while he was standing. We

noticed a big difference in HbO_2 and Hb changes resulting from the test subject while sitting. The changes are different between subjects; therefore, further research will be required to understand the differences.

Finally, the collected data from the dogs showed some changes. It was a challenge to keep the dogs motionless for a period of time long enough to complete the data acquisition. However, even with the sharp movements of the canines, the system was able to detect HbO_2 and Hb changes in their brains.

The result gives us the confidence that the protocol is functional as expected and ready to be used to monitor hemodynamic changes in tissues during other behaviours. In short, the protocol achieved the specified goals and, as such, supports our claims.

CHAPTER 6- SUMMARY, CONCLUSION, AND FUTURE WORK

6.1 Conclusion and Contributions of this Work

This research introduced a medical data transfer protocol to monitor human brain functions in real-life, not in the lab.

The research contributes to the body of knowledge in the biomedical engineering field a protocol that supports monitoring human tissues in near real-time. The research also contributes to the body of knowledge in computer science a protocol to support medical data transfer over heterogenic networks through integrating wired networks, wireless networks, and sensor networks to detect tissues' oxygenation in near real-time. Further, a new architecture model has been created to address the challenges and the issues that arise from integrating heterogenic networks. The protocol ensures the acquired data's integrity and accuracy during near real-time online transmission. The MDTP protocol performed better than HTTP protocol to stream binary data from the near-infrared sensor used in this research. We have demonstrated that without employing our MDTP protocol it would not be possible to stream data in near real-time over the heterogenic networks using the HTTP protocol and achieve desired results (event-to-action time).

The results have shown that it is possible to utilize mobile networks and near-infrared technologies to create a system to monitor HbO_2 and Hb in the human brain and

tissues in near real-time. The protocol provided the necessary support to make the data useful. Further work will be required to ensure that the system tests larger sets of tissues that have different timing requirements.

The major difficulties we faced were network related, challenges arising from network speed and congestions. We found that networks get congested in busy areas that have high wireless traffic which cause the connection to drop. Moreover network coverage inside the city is not always comprehensive. In addition network speed varies from one network provider to another. Some network providers have better networks than others which provide better event-to-action timing. The protocol need to be tested further with different network providers to give a comparison between the network operators. This becomes important if the protocol will be implemented in all available networks in a specific country.

6.2 Future Work

In order to address the challenges we faced during the research, further work will be required. There are several improvements that can be completed to make the protocol more universal.

Network congestion is an interesting challenge that can be examined further. One can try to enhance the protocol to ensure it is not affected by congestion. Moreover the protocol can be tested further over different wireless network types and network providers to determine if the protocol can still be useful over all available wireless networks.

The protocol can also be tested further over different short-range networks, such as Wi-Fi, to see if the system still can achieve its timely functionality. Finally, it would be interesting to try different types of sensors that have higher frequency (more than 100 Hz) than the sensor we used to ascertain if the protocol will perform in the same manner.

Canines are useful animals in search and rescue and other domains where their sense of smell can be employed. Understanding what goes on inside their brains when they are far away from their handlers can provide important information to the handlers, allowing them to better understand the canine's signals and, in turn, what they found during the search operation. Modifying the sensor to better fit canines' anatomy would be another area where our initial work can be fruitfully employed. It may be possible to make improvements to diverse areas such as law enforcement (drug and bomb detection), public safety (fire accelerant detection), and search and rescue work (disaster victim cadaver search). Finally, designing a heterogenic network that is a combination of wired and wireless networks that can be deployed on demand to support communication in disaster areas where wireless networks only is not an option could be another outcome of this research. Canines can be used to deploy these heterogenic networks on demand.

Appendix

Detailed Packet Structure

	Packet					
	Head					Body
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	Packet Types Table	Data Types Table	Sequence Number Table	0xFF	Any value between [0x0000000000000000-0XFFFFFFFFFFFFFFFF]

Table 0.1: Packet Description

Packet Types: Bit 8 in the packet		
Packet Type (ID)	**Value**	**Description**
OPEN	0x00	The packet is an Open packet
DATA	0x01	The packet is a Data packet
CLOSE	0xFF	The packet is a Close packet

Table 0.2: Packet Type Table

Data Type: Bit 16 in the packet			
Operation Code (ID)	**Value**	**Description**	**Direction**
COMMAND	0x00	Command packet (no measurement data)	Any Source node→ Any Target nodes
HUMAN_BRAIN	0x01	Packet contains human brain measurement data	Data Source →target
CANINE_BRAIN	0x02	Packet contains canine brain measurement data	Data Source→ target
GENERAL_TISSUES	0x03	Packet contains general tissues measurement data	Data Source → target
ERROR	0xFF	Packet contains information about the status of a device	Any Source node→ Any Target nodes

Table 0.3: Data Type Table

Sequence Number: Bit 24 in the packet		
Description		
Start Sequence Number	0	Sequence number always starts at zero
Next Sequence Number	Previous +1	[0x PSEQ+1] The sequence number is always incremented by one after each packet.

Table 0.4: Sequence Number Table

Error Codes		
Error Code (ID)	***Value***	***Description***
GENERAL_ERROR	0xE0	General error
DATA_ERROR	0xE1	Data related error
CONNECTION_ERROR	0xE2	Connection related error
UNKNOWN_ERROR	0xEE	Unknown error

Table 0.5: Error Codes Table

Detailed Packet Type Description

Open Packet

OPEN	**Packet**					
	Head					**Body**
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	0x00	0x00	0x00	0xFF	0x0000000000000000

Table 0.6: Open Packet

Close Packet

CLOSE	Packet					
	Head					Body
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	0xFF	0x00	0xPSEQ+1	0xFF	0x0000000000000000

Table 0.7: Close Packet

Data Packet – Human Brain

DATA	Packet					
	Head					Body
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	0x01	0x01	0xPSEQ+1	0xFF	Values

Table 0.8: Data Packet – Human Brain Measurement Data

Data Packet – Canine Brain

DATA	Packet					
	Head					Body
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	0x01	0x02	0xPSEQ+1	0xFF	Values

Table 0.9: Data Packet – Canine Brain Measurement Data

Data Packet – General Tissues

DATA	Packet					
	Head					Body
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	0x01	0x03	0xPSEQ+1	0xFF	Values

Table 0.10: Data Packet – General Tissues Brain Measurement Data

Data Packet – Error

DATA	Packet					
	Head					Body
Packet Fields Bits Location	0	8	16	24	56	64
Packet Fields Name & Sequences	Fixed Filler	Packet Types	Data Types	Sequence Number	Fixed Filler	Binary Data
Packet Fields Value	0xFF	0x01	0xFF	0xPSEQ+1	0xFF	Values

Table 0.11: Data Packet – Data Error Packet

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PUBLICATIONS

This thesis work has generated the following publications.

Books

- **Salah Sharieh**, *Functional Brain Spectroscopy Using Wireless Networks*, LAP Lambert Academic Publishing, 2011) (ISBN: 978-3-8433-9431-4).

Book Chapters

- **Salah Sharieh**, Franya Franek and Alexander Ferworn, "Mobile Functional Optical Brain Spectroscopy over Wireless Mobile Networks Using Near-infrared Light Sensors," in *Data Acquisition Applications.* InTech, 2012) (ISBN 979-953-307-817-4).

- **Salah Sharieh**, "Ad-hoc Networks as an Enabler of Brain Spectroscopy" in *Book, Theory and Applications of Ad Hoc Networks.* InTech, 2010) (ISBN: 978-953-307-416-0).

Papers

- **Salah Sharieh**, Franya Franek, Alexander Ferwon. "Using Cloud Computing for Medical Applications" SpringSim '12, 15th Communications and Networking Symposium, 2012

- **Salah Sharieh**, Franya Franek, Alexander Ferwon. "Mobile Medical Application Model for Heterogeneous Networks" SpringSim '11, 14th Communications and Networking Symposium, 2011

- **Salah Sharieh**, Kamran Sartipi, Alexander Ferworn. "Light-weight Protocol Simulation for Binary Data Exchange over Heterogeneous

Networks" in Proceedings of the 13th Communications and Networking Simulation Symposium (CNS 2010) Orlando, FL

- **Salah Sharieh**, Alexander Ferworn. "A GSM Mobile System to Monitor Brain Function Using a Near-Infrared Light Sensor" in Proceedings of the 21st Canadian Conference on Electrical and Computer Engineering, Computer Applications, Niagara Falls, Ont., 2008

- **Salah Sharieh**, Alexander Ferworn, Vladislav Toronov, Abdolreza Abhari. "An Ad-hoc Network Based Framework for Monitoring Brain Function" in Proceedings of the 11th Communications and Networking Simulation Symposium, Ottawa, Ont., April 14-17 2008.

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