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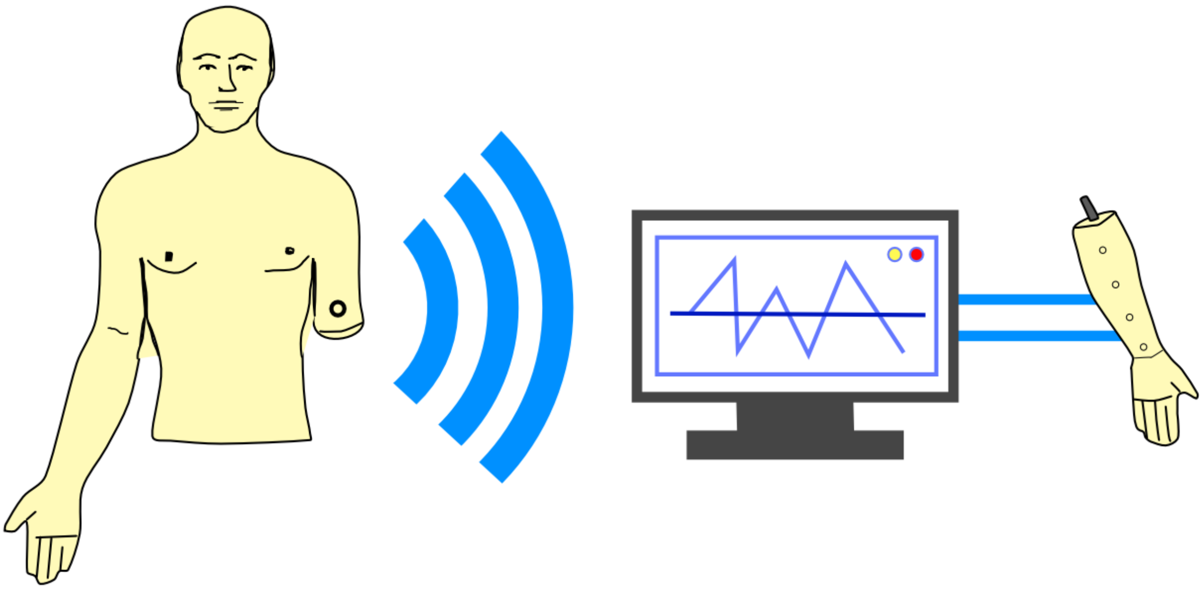

Development of a Wireless Interface for Fitting, Training, and Monitoring of Advanced Prosthetic Limbs

Master's thesis in Biomedical Engineering

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Gothenburg, Sweden 2015
Report No. EX029/2015

Abstract

An artificial limb control (ALC) system is a tool for helping patients to control their prosthetic limb. For fitting, training, and monitoring purposes, such system must be equipped with a wireless interface between the prosthesis and PC in order to bring the most safety and the most convenience to the patients. In this thesis, the possibilities to integrate a wireless interface into the ALC system were investigated. Commercially available wireless modules were compared. Bluetooth and WiFi technology were studied. Selected WiFi and Bluetooth modules were tested to evaluate performance and limitations. Hardware, software, and firmwere were design and built for the evaluation of the wireless modules. The wireless solution was integrated into the ALC system and tested with a full recording session in BioPatRec platform. WiFi allowed the raw electromygrophic (EMG) signals to be transmitted correctly up to 512 kbps following the system requirement. In contrast, Bluetooth is not suggested for transmitting raw EMG signals with data rate more than 256 kbps. It has been proved that in the case of data rate up to 128 kbps, Bluetooth works flawlessly and can be used as an alternative solution for transmitting the feature extracting from the raw signals instead.

Acknowledgements

This thesis was conducted at Chalmers University of Technology in cooperation with Integrum AB, Sweden. I would like to express my very great attitude to my supervisor Dr. Max Ortiz Catalan and my examiner Prof. Bo Håkansson for motivation and providing a chance to perform this thesis. Their guidance helped me through out the whole research and writing of this report. I am particularly appreciative for the assistance given by Enzo Mastinu, Alejandra Zepeda Echavarria and my colleagues at Integrum AB. In addition, a special thanks to my family and my relatives for continuous support and encouragement.

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Introduction

A century ago, wireless technology appeared only in science fictions. Who would have believed that a hundred years later, we would be living in a world where data are floating all around us everywhere. Wireless technology has already changed the way we live, the way we communicate, and even the way we play. From computer to smart phone, to headphone and television, we are moving slightly into the world without wires. This technology does not only made changes in the industry, but also affects health care services. According to a report from Markets and Markets company, a total wireless portable medical devices market was approximately $7.52 billion in 2013 and it is expected to reach $17.71 billion in 2020 [1]. However, the question is why wireless interface is so important to medical devices.

There are two major advantages that the wireless interface can provide: first, due to the perfect isolation of the patients and the system, the electrical safety is achieved, second, the patients will get the most convenience with freedom of movement [2]. Therefore, most of these medical device applications including temperature sensor, blood glucose sensor, blood oxygen sensor, ECG sensor, heart rate sensor, and pressure sensor are becoming more and more wireless. In addition to these devices, there are attempts to apply wireless technology to prosthetic devices which is a focus of this thesis.

An artificial limb is a prosthesis that replaces a missing limb of the body, such as arm and leg. Most of new amputations every year are caused by problems of the vascular system particularly from diabetes. Moreover cancer and trauma related amputation are also other causes leading to amputation [3]. In 2005, there were approximately 1.6 million people living with limb loss in the U.S. This number is expected to be double to 3.6 million people by the year of 2050 [4]. Patients who suffer from amputation require advanced prosthetic devices which can help them to do their daily activities and improve their daily live. This thesis examines how wireless technology can be used to improve prostheses. There are three ways that wireless can be applied to prosthesis according to the literatures [5]. First, the wireless interface can be used to transmit important information that is to be visualized in the graphical interface on the computer. Second, either patients or a physicians are able to monitor status of the prosthetic device remotely. Third, the prosthetic device can be controlled and adjusted by the patient or the physician. Although there are many advantages in using a wireless interface in prostheses, there are some essential issues such as safety, reliability, stability that have to be considered. These will be also discussed in this thesis.

In this thesis, wireless interface solutions were investigated. The purpose of this wireless interfaces is to substitute a wired communication for the fitting, monitoring, and training of advanced limb prostheses. The work covers the concept of wireless technology, standard, testbed for performance evaluation, hardware selection and also safety issue in communication.

1.1 Background

The idea of transmitting medical signals wirelessly was started since hundred years ago in the field of biomedical telemetry. The purpose of biomedical telemetry is to observe and to study the activities of animals and humans with minimal disturbance [6]. One of the earliest project in biomedical telemetry was developed in the U.S. Army Signal Corps in 1921 by Winters who succeeded in transmitting heart sounds over a marine radio link [7]. Then, the use of wireless technology was shifted to another direction as a new diagnostic tool using the signal from within the body. Originally, researchers focused on the transmission of signals from the human gastrointestinal tract for diagnosis. By the end of 1960, there were several renowned works in the development of a pill containing a wireless transmitter that small enough to be swallowed by patients [8–10]. Later, researches in this field expanded to all parts of the body, including body temperature, electrocardiogram (ECG), electroencephalogram (EEG), electromyography (EMG) and also pH in teeth [6]. However, due to a lacking of standards, it was difficult to shift this technology from the laboratories to the market, and the major problems were compatibility, reliability and also stability [11].

An important milestone in the world of wireless technology is the development of the Bluetooth standard in 1994 and 802.11 standard (WiFi) in 1997. These standards came with more reliable and stable connection. They changed the way of wireless technology implementation in all areas including the medical field. Since then, more and more medical devices were integrated with wireless interfaces. In chapter 2, these standards and technologies are discussed in details.

One of the first study of wireless interface in prosthesis appears in the late 1990's. A group of researchers in the UK developed a Blatchfords IP+ knee system that can be tuned wirelessly [12]. Another project about The wireless telemetry system for training upper limp prostheses user was presented in 2002 by a group of researcher from UK and Netherlands [5]. They transmitted muscle contraction, fingertip force, and also digit flexing angle wirelessly using radio module. Nonetheless, the wireless module are added to the prosthesis only for training session to save the power and avoid unintentional transmission when the hand is in normal use mode. This setting also provided an advantage in the protection of patient information. The full schematic of this system is shown in Figure 1.1

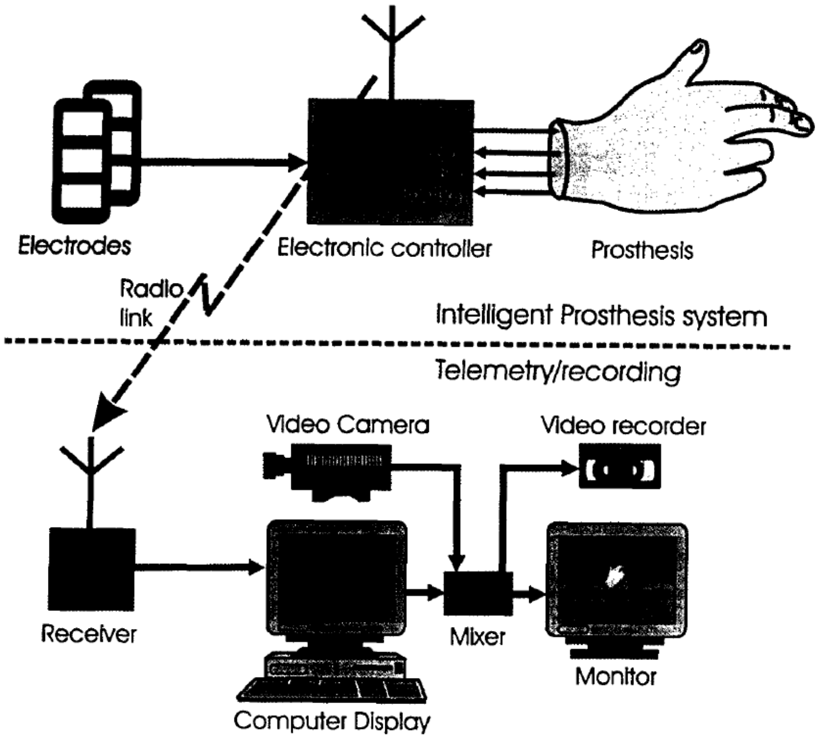


Figure 1.1: Schematic of the wireless training prosthesis system. (Source: P. J. Kyberd et al. A wireless telemetry system for training users of upper limb prostheses [5]).

In addition to the training and monitoring system, wireless interface used for controlling prosthesis was presented by many research groups. A project by D.J. Young et al. used a radio-frequencys (RF) coil to transmit EMG data to a receiver mounted on a prosthetic socket as shown in Figure 1.2 [13]. P.A. Lichter et al. and D. McDonnall et al. showed wireless systems which have the same concept in implanted EMG electrode with antenna coil. The differences of these two systems are the design of the circuit and the type of the module [14, 15].

1.2 Problem definition

At Integrum AB, Sweden, artificial prosthesis limb system has been developed for patients with missing limbs. The artificial limb control system used for fitting, training and monitoring patients as shown in Figure 1.3 consists of electrode grid, analog front end, micro-controller, digital signal processing board, and the main PC running BioPatRec

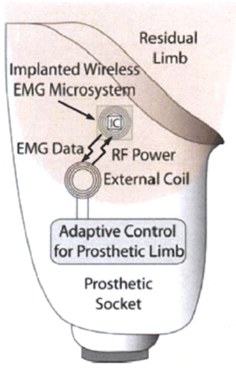


Figure 1.2: Wireless implantable EMG sensing system. (Source: D. J. Young et al. Wireless Implantable EMG Sensor for Powered Prosthesis Control [13]).

software which are discussed in detail in chapter 3. Previously, the prosthetic device communicated with BioPatRec on the main PC using serial communications interface. Although, serial interface worked properly, there were safety and patient's convenience problem that made essential to consider and to develop a new wireless solution. This wireless communication interface has to be a substitution of a serial interface and be compatible with the main data acquisition system.

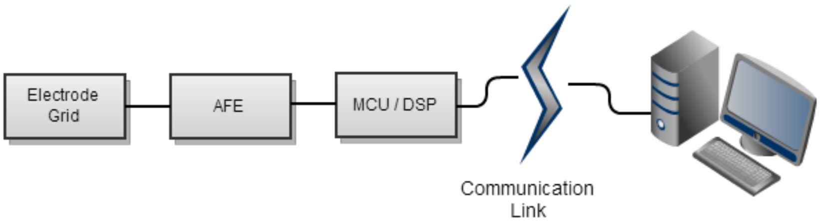


Figure 1.3: Configuration of Artificial Limp Control system. The system consists of three module for recording and processing EMG signal, communication interface and BioPatRec running on the main PC.

1.3 Aim of the thesis

The objective of this thesis is to identify more appropriate wireless module to be used as an interface between the patients, prosthetic device, and BioPatRec. At the end of this thesis, the prototype of wireless solution has to fulfill with the following requirements of the communication.

- Data rate: > 500 kbps
- Operational range: >= 3 meters

- Operational time: continuously run up to 5 mins
- Error rate: as low as possible
- Latency (Delay): as low as possible

The prototyping system should work properly following the requirements above and substitute the wired interface with reliability and stability. Besides, this thesis covers all aspects relevant to wireless communication, including related technology, testing protocol, standards, as well as the limitation of the wireless.

1.4 Limitation

In this work, the following constraints applied:

- **Using commercially available components and modules:** The first constraint of this thesis is utilizing off-the-shelf components and modules instead of developing a new one. The main reasons of this limitation are to reduce the development time and as well as increase time to the market. Before releasing the product to the market, every new RF component and module must pass certain testing procedure, which obviously need more resource in matter of cost and time. For this reason, the most suitable wireless module shall be selected as a conclusion.
- **Coexistence and interference issues:** In order to test coexistence and interference from the other devices, an experiment area has to be free from other sources of radio frequency to make the noise floor lower than the wireless receiver sensitivity [16]. Considering the complexity of having a RF free environment, such as an Anechoic chamber, this test was discarded from this work.
- **Security issues:** Security in patient information is another important factor in the context of medical device. However, developing a new protection system for the wireless communication requires advanced knowledge in computer network and encryption. Therefore, instead of developing a new system, the best security protection at this time already provided by the wireless technology will be utilized.

2

Wireless technology

After electromagnetic wave theory by Maxwell and Hertz was introduced, Tesla developed the first system that was able to transmit the information via these waves. Later, in 1895, Marconi developed the system that was able to transmit the information from a boat to the Isle of Wight in England, 18 miles away, and this is the first well-known wireless communication project that demonstrated the feasibility of using electromagnetic for transmitting information [17, 18]. Wireless communication is defined scientifically as a communication that transmits information from one place to another using electromagnetic waves. From this definition, all applications such as broadcast TV, radio, mobile communication are classified as the wireless communication system. Nonetheless, in this thesis, we focuses on two applications of wireless communication namely Wireless Local Area Networks (WLANs) and Personal Area Networks (PANs). In this chapter, basic knowledge of wireless communication, including 802.11 (Wireless Fidelity - WiFi), Bluetooth, and also other standards that are relevant to wireless medical devices were reviewed.

2.1 Frequency bands for wireless medical device

The first factor that is in concerned when selecting the wireless technology for medical device is frequency band. The frequency band is a limited resource and it is regulated differently from country to country. For medical purposes, only some specific frequencies can be used. These medical frequency bands are discussed in this section. It is worth to point out that the information in this section follows the US regulation.

2.1.1 Industrial, Scientific, and Medical (ISM) bands

Industrial, Scientific, and Medical (ISM) bands is a non-licensed frequency band that can be used without any licensed. However, manufacturers still need some approval for operating devices in these bands. Most popular wireless technology such as WiFi, Bluetooth, Near Field Communication (NFC), and also microwave, operate in this band. It means that the ISM band is crowded with a lot of data transmitting by the devices using these wireless technologies. The frequency located on this ISM band is displayed in the Figure 2.1.

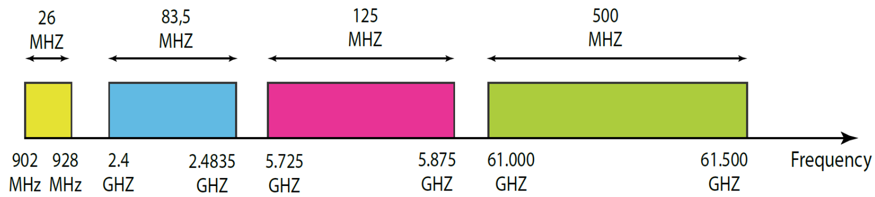


Figure 2.1: Illustration of ISM non-licensed frequency bands. Frequency bands that can be used without any licensed. (Source: CETECOM, Compliance & Regulatory Info Sheet/ July 2014 [19]).

2.1.2 Wireless Medical Telemetry Services (WMTS) bands

Wireless medical telemetry services are created for supporting the long-range medical data transmission used in a remote monitoring application. It is approved for any medical equipment with appropriate communication except voice and video. Allocated frequency are 608 - 614 MHz, 1395 - 1400 MHz and 1427 - 1429.5 MHz in United States [19].

2.1.3 Medical Implant Communications Service (MICS) bands

The Medical Implant Communication Service, originally, was used for licensed communication for implanted medical devices. It was allocated in 1999. Then, in 2009, the FCC added more frequency band to this service and created a new service called the Medical Device Radio Communication Service (MedRadio) used in implanted medical devices and also used by body-worn monitoring devices. These devices operated in the 401-406 MHz [19].

2.2 Wireless standards

A development of the standards is one of the main reasons for the success of wireless communication. These standards ensure that devices manufactured by different companies can communicate to each other. The most important standards that are very successful are cellular communication, wireless local area network (WLANs), and also personal area network (Bluetooth, Zigbee). Most of the wireless medical device also use these standards for communication and data transmission. A summary of wireless standard normally used in medical devices is presented in Table 2.1. This thesis focuses only on the wireless communication for data transmission with high data rate at a short range. Therefore, WiFi and Bluetooth are selected and used in this thesis. The summary of these two standards will be discussed in this section. It is worth to mention that most information in this section was summarized from books by A. S. Tanenbaum and A. F. Molisch [18, 20].

Table 2.1: Summary of wireless standard. (Source: CETECOM, Compliance & Regulatory Info Sheet/ July 2014 [19]).

Standard	Frequency	Data Rate	Range
Inductive Coupling	< 1Mhz	1-30 Kbps	< 1 m
Wireless Medical Telemetry System	608-614, 1395-1400, 1427-1429.5 MHz	> 250 Kbps	30-60 m
Medical Device Radio-Communication(MICS)	401-406 MHz	250 Kbps	2-10 m
Medical Micropower Networks (MMNs)	413-419, 426-432, 438-444, 451-457 MHz	-	< 1 m
Medical Body Area Networks (MBANs)	2360-2400 MHz	10 Kbps-1 Mbps	< 1 m
802.11a Wi-Fi	5 GHz	54 Mbps	120 m
802.11b Wi-Fi	2.4 GHz	11 Mbps	140 m
802.11g Wi-Fi	2.4 GHz	54 Mbps	140 m
802.11n Wi-Fi	2.4, 5 GHz	600 Mbps	250 m
Bluetooth Class I	2.4 GHz	3 Mbps	100 m
Bluetooth Class II	2.4 GHz	3 Mbps	10 m
802.15.4 (Zigbee)	868, 915 MHz, 2.4 GHz	40 Kbps, 250 Kbps	75 m
WiMax	2.4 GHz	70 Mbps (fixed), 40 Mbps (mobile)	Several km

2.2.1 Wireless Local Area Networks - 802.11(WiFi)

Wireless Local Area Networks (WLANs) is a system that connects two devices together using wireless operating within and nearby a single building. The main usage of WLANs is to connect personal computers and consumers electronic devices to the Internet or connect those devices together to share resources. WLANs can be found in home, office, cafeteria, airport and everywhere that needs internet connection. These WLANs over the world use the same standard called IEEE 802.11 or popularly name is WiFi and operate in the unlicensed ISM band at 2.4 and 5 GHz.

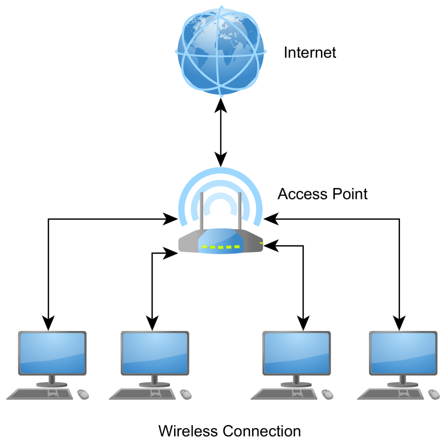


Figure 2.2: WiFi network infrastructure. All devices in infrastructure mode connects to the wired network through access point.

WiFi network consists of two important components, *clients*, such as laptops and mobile phones, and *infrastructure* or Access Points (APs). Access point connects to the wired network and mostly connect to the internet. Each client can communicate with each other or connect to the internet through an access point. This concept is shown in Figure 2.2. Nevertheless, two or more clients can talk to each other directly without access point and this network called Ad-hoc network illustrated in Figure 2.3.

Actually, several amendments were added to the original standard. The original 802.11 standard was announced first time in 1997. The data rates was 1 and 2 Mbps. It operated in the 2.4 GHz ISM band and using 2 techniques called frequency hopping and direct-sequence spread spectrum for transmitting the information. Obviously, the speed of the original 802.11 was not enough and there was a requirement of the higher speed. Then in 1999 the first two amendments of 802.11 were released, 802.11a and 802.11b. 802.11a used Orthogonal Frequency Division Multiplexing (OFDM) technique to transmit the information in 5 GHz ISM band. In contrast, 802.11b continued using spread spectrum technique and the maximum data rate was 11 Mbps. 802.11b hit the market and became popular first. Then 802.11a was announced and provided the data rate up to 54 Mbps. The 802.11g adopt the OFDM technique and operate in 2.4 GHz ISM band was announced in 2003. Currently the last amendment 802.11n, released in

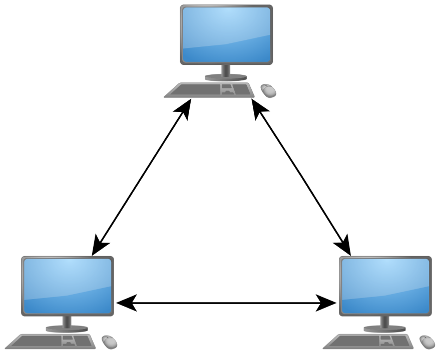


Figure 2.3: Ad-hoc mode. Ad-hoc network allows all devices in the same network talk to each other.

2009, used Multiple Input Multiple Output system(MIMO) and OFDM to transmit the data. This technique provides data rate up to 600 Mbps and can operate both in 2.4 and 5 GHz ISM band.

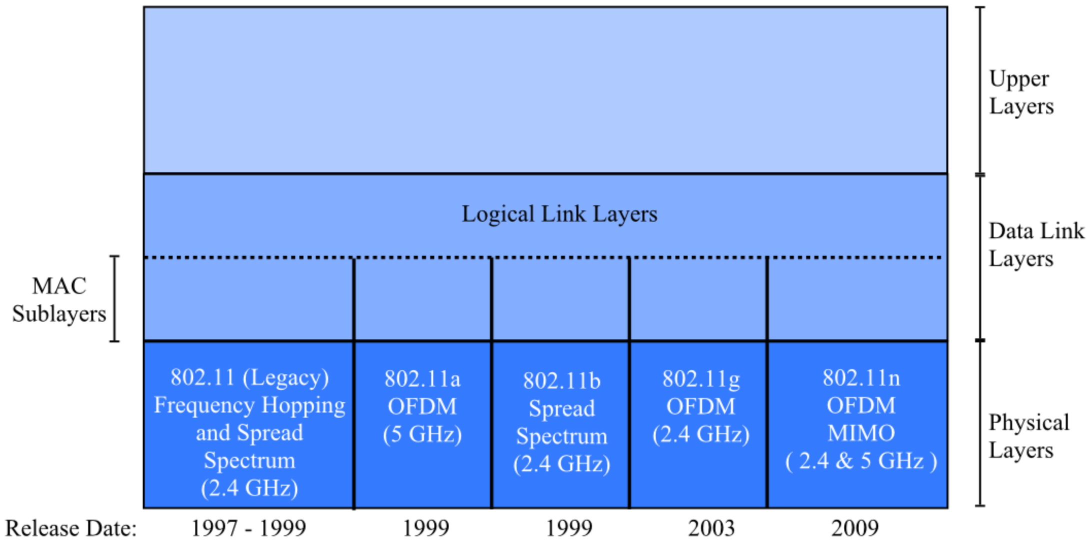


Figure 2.4: 802.11 WiFi protocol stack consists of three layers: Upper layers, Data Link Layers, and Physical Layer. 802.11 a/b/g/n are versions of 802.11. Different versions of 802.11 uses different transmission technique and operates on the different frequency band. The first version of 802.11 was released since 1997.

The overview protocol stack of 802.11 is depicted in Figure 2.4. The protocol can be roughly divided into 3 layers. The lowest layer is physical layer concerning with how to transmit raw bit over a communication channel. These layers were developed over years since the first version. The second layer is a data link layer which is divided into two sublayers. The MAC (Medium Access Control) manages the channel allocation, e.g. which data and which data use the channel next. The MAC layer also manages the collisions by using CSMA/CA technique. Second sublayer, the LLC (Logical link Control) provides service to the layer above it and to hide the layer below which make the the upper layer works in the same way for every 802.11 version. Besides, LLC also used to identify IP of the received packets. Error detection and handling also happen in this Data link layer. The top layer, upper layer, includes the application layer, the internet layer, TCP/IP layer which will be discussed later very soon.

Although it has been mentioned earlier that WiFi operates at 2.4 and 5 GHz ISM bands, actually, WiFi divides this frequency band into sub-band called *channel*. Wifi system has to select a channel to operate. 2.4 GHz band is divided into 14 channels and each channel has bandwidth 22 MHz and has space 5 MHz apart except the space between channel 13 and channel 14 which is 12 MHz. Channel 1 start at 2.41 GHz and has a center frequency of 2.412 GHz. There are some differences in regulation between each region. In the US, only 11 channels are available for the WiFi. In Europe, 13 channels can be used and in Japan all 14 channels are available for the WiFi. The illustration of the channel in 2.4 GHz band is shown in Figure 2.5. It can be seen that these 14 channels are overlapping each other. This overlapping can cause conflict and inference problems when two WiFi systems operating in two overlapping channels. The solution is selecting non-overlapping channel or moving to 5 GHz ISM band which has more free bandwidth [19, 21].

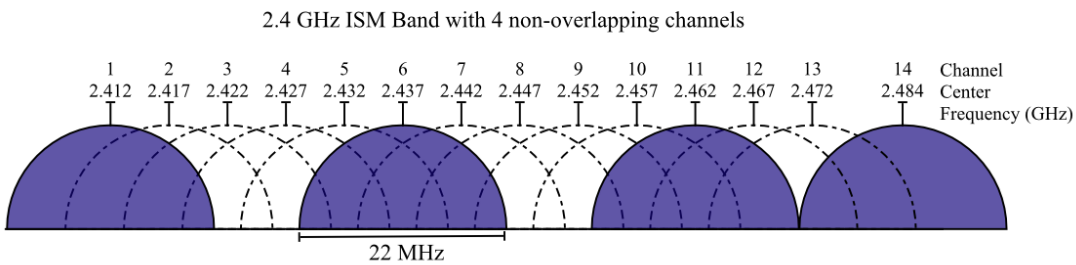


Figure 2.5: 2.4 GHz band Channels of 802.11. WiFi divides ISM band into channel. Each channel has overlapping regions. In the U.S. only 11 channels are available for the WiFi. In Europe and Japan, 13 and 14 channels are available for WiFi respectively. Channel 1, 6, 11, 14 are 4 channels that are non-overlapping each other.

For 5 GHz band, there are more differences in regulation from countries to countries. In U.S. 802.11a operate in frequency band called *Unlicensed National Information Infrastructure (U-NII) bands*. These bands are divided into 3 levels; 5.15–5.25 GHz for low power system, 5.25–5.35 GHz for medium power system and 5.725–5.825 GHz for high power systems. Each channel has a bandwidth of 20 MHz. The summary of frequency band, allowed power, channel number and channel center frequency are shown in Table 2.2. The limitation of 5 GHz band is the higher the frequency, the shorter the operational range. However, in Japan and Europe, the number of available channels is lower.

Table 2.2: Summary of 5 GHz ISM band for 802.11a in the U.S. (Source: A. F. Molisch. Wireless Communications. Page 735, Wiley-IEEE Press, 2nd edition, 2011. [18]).

Bands (GHz)	Allowed power	Channel numbers (nCh)	Channel center frequency (MHz)
U-NII lower band	40mW	36	5,180
(5.15–5.25)	(2.5 mW/MHz)	40	5,200
		44	5,220
		48	5,240
U-NII middle band	200mW	52	5,260
(5.25–5.35)	(12.5mW/MHz)	56	5,280
		60	5,300
		64	5,320
U-NII upper band	800mW	149	5,745
(5.725–5.825)	(50mW/MHz)	153	5,765
		157	5,785
		161	5,805

Protocol suit of the Internet

Protocol suit is the communication protocol for internet service. This protocol integrated with 802.11 allows all computers and devices to communicate with each others. The well-known and basic protocol is called *Transmission Control Protocol/Internet Protocol (TCP/IP)* TCP/IP is divided into 4 layers as shown in Figure 2.6. Actually, in each layer, there are large quantities of protocols that were developed since the beginning of the internet. Some were selected to show in this diagram. Nonetheless, we will discuss only some protocol that will be applied in this thesis.

Internet Protocol (IP): The role of IP is to transport packets from source to destination using IP address as a packet header. The major version of IP that has been used worldwide is IPv4, which uses 32-bit addresses. On the internet, every device or PC has to have its own address so we can know who is who. IPv4 used dot-decimal notation, for instance 192.168.1.1. There is a need of more IP address in the near future. Thus, the next version of IP is IPv6 and it uses a 128-bit addresses. Using IPv6 we can have up to 2^{256} addresses.

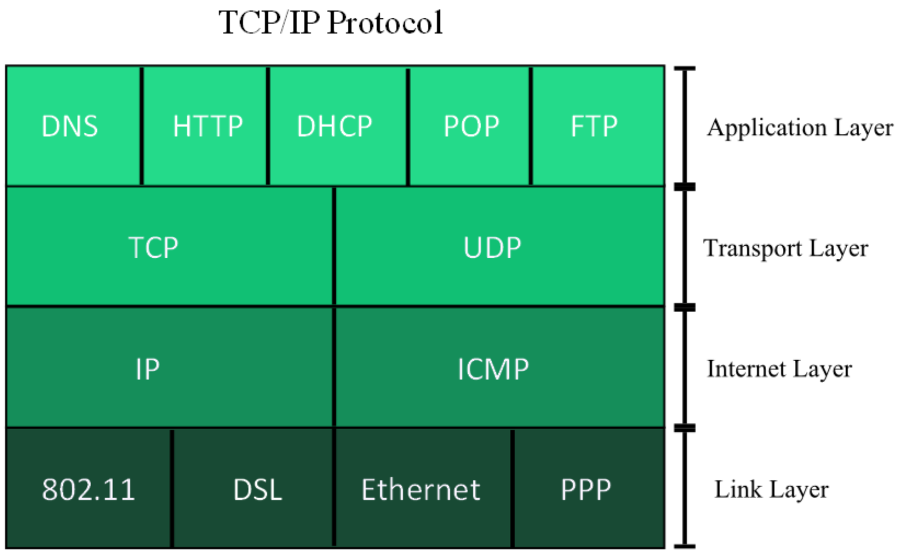


Figure 2.6: TCP/IP internet protocol suit with interesting protocols. In this protocol, 802.11 is located in the bottom level. TCP/IP are 2 main protocols used for creating the internet. The other protocol can be used to add more features to the internet.

Transmission Control Protocol (TCP): TCP is the upper layer from IP. The role of the TCP is to break data into a packet and pass this data packet to IP. The main function of TCP is managing the flow control, providing reliable connection and also checking the error. TCP ensures that the communication is reliable and pass the data to the upper layer.

Dynamic Host Configuration Protocol (DHCP) is an application used to control IP address. This protocol very important to the the large network. It assigns IP address to the client automatically.

2.2.2 Personal Area Networks - Bluetooth

Personal Area Networks is a system that has a purpose to replace a cable of devices operated within a range of a person. An example of PANs is a network of a computer and its peripherals, or a connection between smart phone and hands-free headset. The IEEE 802.15 group was formed in order to develop standards for PANs. As a consequence, many standards were developed under this group such as Bluetooth, Wireless Body Area Networks (WBANs), 802.15.4 (Zigbee). In this thesis, the most important standard, Bluetooth, was used and will be reviewed in this section.

In 1994, Ericsson began interesting in a new technology that can connect devices without any cables. Together with other company, they formed a Special Interest Group (SIG) for investigating and developing this technology named *Bluetooth*. Then, Bluetooth 1.0 was released in 1999 and that became the starting point of the cordless world. Most of the consumer electronic now uses Bluetooth.

Bluetooth operates in the range of 2.4 GHz and 2.483 GHz ISM band and use a method called *frequency-hopping spread spectrum* for transmitting signals. These methods divide the whole data set into a small set called packets. The transmitter and receiver exchange a packet at one available channel. The ISM band is divided into 79 channels and each channel has a bandwidth of 1 MHz in Bluetooth 1.0 to 3.0 and 40 channels with bandwidth 2 MHz in Bluetooth 4.0. Then, they hop to another available channel to exchange data. This process are repeated until the whole data are sent. Bluetooth, normally, performs the hopping process 1600 times per second. The concept of this technique is depicted in Figure 2.7.

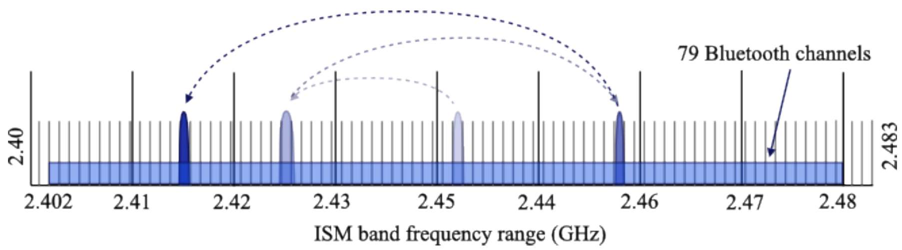


Figure 2.7: Illustration of Frequency hopping spread spectrum(FHSS). Bluetooth divides ISM band into 79 channels start from 2.402 GHZ to 2.48 GHz. FHSS technique select an available channel for transmitting data. Then it jumps to the next available channel for transmitting the next set of data. This process continues until all data set have been transmitted.

A group of Bluetooth device sharing the same network is called *piconets*. A piconet consists of a *master* node and *slave* nodes. One master node can have an active slave node up to seven nodes. Two devices can communicate in the form of master-slave mode only. However, a piconet can communicate to other piconet by forming a *scatternet* structure and communicate via bridge slave. Besides an active slave node, a device can switch to a parked mode, which is a low power state. The device in the parked mode cannot do anything except response to an activate command from its master. A piconet can have up to 255 parked nodes. The summary of these Bluetooth topology concepts is depicted in Figure 2.8.

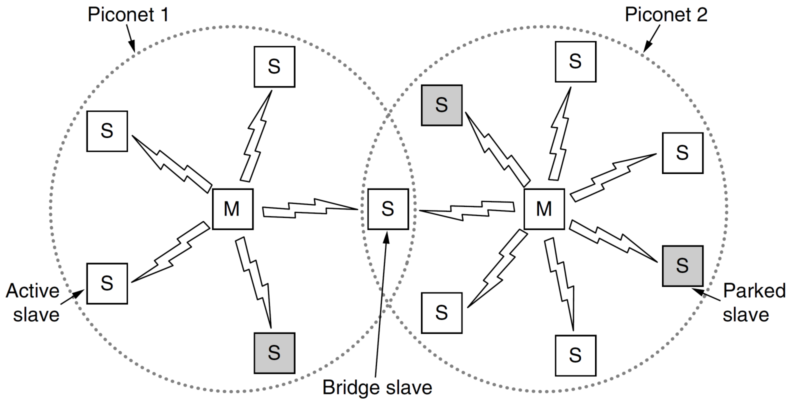


Figure 2.8: Schematic of Piconet system of Bluetooth. Bluetooth employs master-slve concept to form a network. Slave node can be set to operate in active mode, parked mode, or bridge mode. (Source: A. S. Tanenbaum et al. Computer Networks [20]).

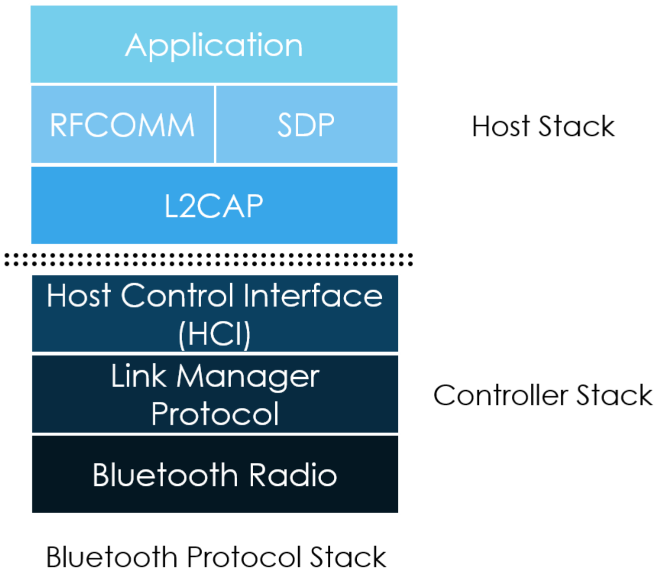


Figure 2.9: Bluetooth protocol stack can be divided into 2 main layers: Host stack and Controller stack. Host control interface stack control the communication between host and controller stack. Bluetooth devices need to have both stack for functioning.

To communicate, Bluetooth uses its own protocol stack called a Bluetooth protocol stack which can be divided into two parts, *Host stack* and *Controller stack*. These two stacks connect by Host - controller interface as shown in Figure 2.9. For simplicity, the diagram below shows only the main important stack. Normally, the controller stack can be implemented on a Bluetooth chip and the host stack is implemented on a device or computer that host the chip as a part of the operating system. The controller stack deals with the RF communication, including power management, pairing and also encryption. The host stack is a software part that controls data flow and data management. The top layer is an application protocol. Bluetooth has different applications which are called *profiles* for different type of devices. For instance, Serial Port Profile (SPP) is used in the device that emulate a serial port cable or Health Device Profile (HDP) is used in device for medical purposed.

Currently, Bluetooth SIG have released 4 Bluetooth versions. In Bluetooth version 2.0 and 2.1, Bluetooth SIG introduced a new mode called Enhance Data Rate (EDR). This mode can increase the data rate of Bluetooth devices up to 3 Mbps by using different modulation technique. The last version of Bluetooth is Bluetooth 4.0 or Bluetooth Low Energy (BLE). BLE came with a new design that provided energy consumption 20 times lower than the previous version. Due to the low energy consumption, The maximum data rate for BLE is 100 kbps, which is lower than the Bluetooth classic with EDR mode. In addition to the version, Bluetooth devices are divided into 3 power classes. Each class specifies a maximum power and range. A comparison of each class of Bluetooth is shown in Table 2.3.

Table 2.3: Comparison of Bluetooth class.

Class	Max. Output Power (mW)	Max. Output Power (dBm)	Range (m)
Class 1	100	20	100
Class 2	2.5	4	10
Class 3	1	0	1

3

Artificial Limb Control System

Artificial limb control (ALC) system developed at Integrum AB is intended to provide to amputees the control of their own prosthesis. For fitting, training, and monitoring patients, the ALC system combining with BioPatRec system are used. The system has been developed to be mechanically and electrically compatible with an Osseointegrated Human-Machine Gateway (OHMG) by M. Ortiz Catalan and R. Brånemark [22]. The ALC system shown in Figure 3.1 consists of 2 main parts; data acquisition system and BioPatRec software. In this section, we will take a look closer to each component of this system. It is noted that information in this chapter was summarized from doctoral thesis by M. Ortiz Catalan [23].

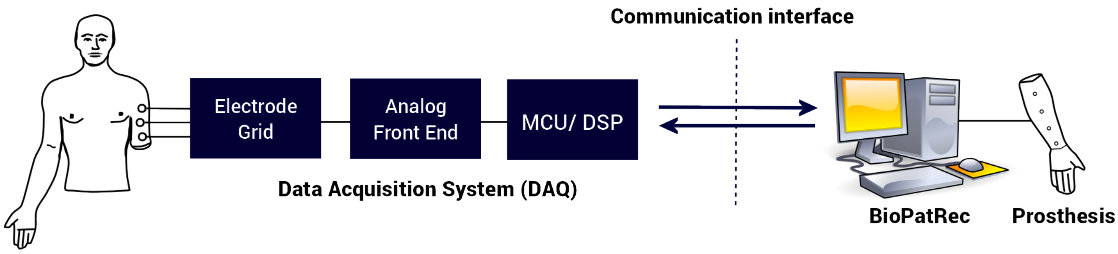


Figure 3.1: Artificial Limp Control system with BioPatRec used for fitting, training, and monitoring the patients consists of 2 main parts: Data Acquisition System (DAQ) and BioPatRec. DAQ acquires and processes EMG signals from the patients and transmitting to BioPatRec using communication interface. BioPatRec performs pattern recognition and selects interesting features for controlling the prosthesis.

3.1 Data Acquisition System

A Data acquisition system was developed for recording the electromyographic (EMG) signal from patients. EMG signal provides electrical signal information generated from muscle contraction. It can be used to detect muscle activities and to study neuromuscular system. The recording system is divided into 3 parts; electrode, analog front end and the micro-controller unit (MCU). In order to record the EMG signal using surface electrode, a suitable bandwidth for acquiring significant information is between 10 - 500 Hz. High pass filter with cutoff frequency at 10 Hz is commonly used to remove or reduce motion artifact. The minimal sampling frequency to store the signal information in an MCU should be at least twice the highest cutoff frequency of the filter as specified by the Nyquist theorem [24, 25].

In this thesis, Arm-based microcontroller from Texas Instruments was used as the main controller unit for acquiring and processing EMG signals before sending this information to a PC. The sampling frequency was set to be 2000 Hz. The analog to digital conversion was achieved using the oversampling technique to reduce quantization error and reshape noise by shifting it on higher frequencies. The acquisition system can record the signal up to 8 bipolar channels simultaneously with a resolution of 24 bits per channel. After acquisition, MCU converted the 24 bits information into a voltage value expressed in a single precision format. Thus the data rate for transfering EMG raw data can be up to 512 kbps. The processed information was then transmitted via communication interface to BioPatRec running on the PC.

3.2 BioPatRec

BioPatRec is an open source research platform written in MATLAB environment. It includes several tools for acquiring and plotting signals and apply features extraction and pattern recognition algorithms. The real time predicted movements can be used to drive a prosthetic arm. It is also possible to simulate the control with a virtual reality arm. The purpose of this software is to provide a common platform for research and evaluation of control algorithm and pattern recognition for prosthesis devices [26]. This software is provided as an online project using Google project platform (http://code.google.com/p/biopatrec). The summary of the software is presented in the flow diagram on Figure 3.2. The software is divided into 5 following sections:

1. Signal Recording
2. Signal Treatment
3. Signal Features
4. Pattern Recognition
5. Control

The input to the software is EMG signal recorded beforehand or real-time. The signal is then processed in the software and the output is the control signal for virtual reality hand or prosthetic devices. This work was focused mainly on the first module, the signal recording.

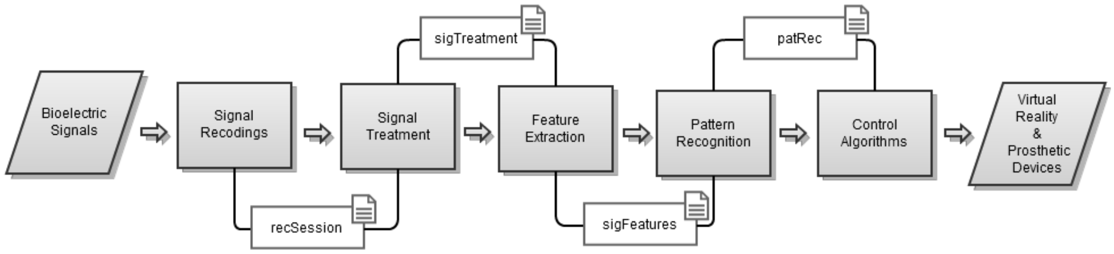


Figure 3.2: BioPatRec flow diagram. The software is divided into 5 modules for recording signal, selecting feature, applying Pattern recognition and controlling the prosthesis [26].

BioPatRec provides 3 different ways for recording the signal: One-shot recording, Recording session, and Recordings for real-time control.

- **One-shot recording session** is used to test the hardware and communication. The signal is recorded and is presented real time on the screen. Therefore the signal quality can be observed using this session.
- **Recording session** is the main recording session to get the signal for processing. Patients have to perform a set of movements selected using the setting GUI shown in Figure 3.3 in the initial part of the recording. Then, the patients are asked to follow a real time guide that shows on the screen which are performing movement or staying in rest position. A sample of recorded signal from one channel shown in Figure 3.4.
- **Recordings for real-time control** used for recording the signal for real-time control of prosthesis or virtual reality hand. The algorithm used for controlling is generated from the recording session.

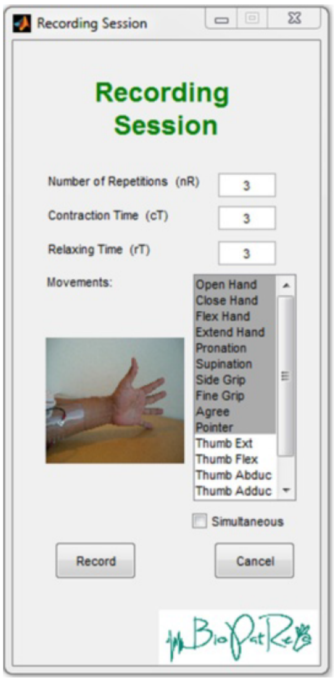


Figure 3.3: User Interface of a Recording Session on BioPatRec. User can select interesting movements from the list [26].

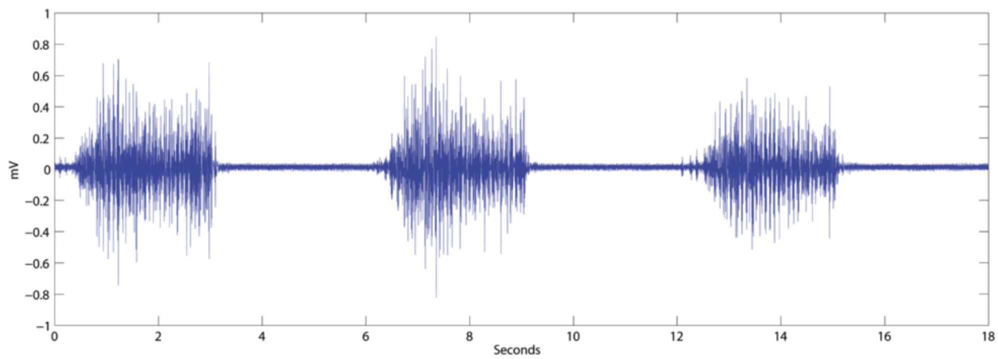


Figure 3.4: Recorded signal from one channel with 3 seconds of contraction alternated with 3 seconds of relaxation, repeated for three times [26].

In this thesis, we tested the wireless interface with two recording way; One-shot recording session and Recording session only. More information about testing protocol and methodology will be provided in the next chapter.

4

Methodology

The main objective of this thesis is to find the suitable wireless module solution to use in the artificial limbs control system. To achieve this goal, this work was divided into 3 following parts:

1. **Wireless module selection**: The first part of the project was to select the suitable commercial module and wireless technology for this system. Important factors for selection are discussed in this part.

2. **Performance Testing**: In order to test the performance and investigate the limitation of wireless module, testing protocol was required. The selected modules were tested using designed testing protocol to evaluate the performance.

3. **Integration of wireless module to the ALC system** The last part of the thesis was integrating the module to the ALC system. Printed circuit board (PCB) for module was designed. Then the complete integrated system was tested with BioPatRec.

4.1 Wireless module selection scheme

Medical devices, normally, have stricter requirements than a normal wireless device. These requirements are necessary to ensure that the devices are safe for patients and work properly. In 2013, U.S Food and Drug Administration (FDA) announced guideline for radio frequency wireless technology in medical devices [27]. These following considerations are recommended by the FDA when designing and developing the wireless medical devices:

1. Selection of wireless technology

2. Wireless quality of service

3. Wireless coexistence
4. Security of wireless signals and data
5. Electromagnetic compatibility
6. Proper setup and operation
7. Maintenance

Following the guideline of the FDA, the first thing needed to be considered was the selection of the suitable wireless technology. This thesis already had some requirements since the beginning. The most two important requirements were the data rate and range. Considering these requirements with the knowledge of the wireless standard in chapter 2, Bluetooth and Wifi were two wireless technologies that had possibility to fulfill these requirements. Therefore, this thesis focused on the selection of the WiFi module and Bluetooth module to be used for ALC system. Moreover, an advantage of WiFi and Bluetooth was both technologies operate in the ISM band and no license was required. Another advantage was there were a large number of commercial modules available in the market already. Using the available module in the market also reduced development time and speed up time-to-market.

There were numerous wireless modules in the market using different standard and providing different function. So the problem was how to select the module for a specific application. According to Wireless Communication textbook by Molisch [18], the following requirement should be considered when designing the general wireless system.

1. Data rate
2. Range and number of user
3. Mobility
4. Energy consumption
5. Use of spectrum
6. Direction of transmission
7. Service quality

From these factors, data rate, range, energy consumption was applied to the selection process. Price was another variable that was used to compare the wireless module. Feature and ease of use were the last factors that we had taken into an account.

4.2 Wireless performance testing protocol

Although, specifications of each wireless module were provided in the module's data sheet, the testing was still necessary to ensure that the module was compatible with the system and the limitation of the module was acceptable. The relevant standards had been studied in order to design the testing protocol. These standards will be discussed in this section first. After that, testing protocols for testing the performance of wireless modules will be described.

To design the testing protocol, first, we analyzed the WiFi and Bluetooth standard. WiFi and Bluetooth standards provided some specific requirement that a device using WiFi and Bluetooth needs to follow. However, for some requirements such as transmitting power, output power, power density, frequency bandwidth, particular testing tools were required. In the following, we are going to focus only on data rate, delay, the signal stability performance. Therefore, some tests that are relevant to this factor had been selected

For WiFi, we measured the receive packet error rate (PER). Packet error rate for this test was calculated from the following equation:

$$PER = \frac{N_{PErr}}{N_{PTr}}$$

N_{PErr} is the number of incorrectly received packets and N_{PTr} is the number of all transmitted packet. To perform the test, the packet generator sent predefined packets. PER can be calculated from the number of correct packets [28].

For Bluetooth testing we used another technique call Bit Error Rate (BER) to measure the performance of the receiver. BER is defined by this following equation:

$$BER = \frac{N_{BErr}}{N_{BTr}}$$

N_{BErr} is the number of the error bit and N_{BTr} is the number of all transmitted bit. One important test using BER is sensitivity testing. The sensitivity is input level that provides the required maximum value of the BER. The test are done by continuously sending 1,600,000 bits to the device under testing, then the device transmits received data back. After measuring bit error, BER can be calculated [29].

Besides these tests, we tried to find the way to test the system in application level for the medical device. In order to get an idea of how the wireless system is tested, we consulted another document for testing ISA 100.11a, the WiFi standard for industrial environment [30]. The performance tests were done to investigate the factor that affects the quality of the wireless:

1. Attenuation of signal strength in proportional to the distance
2. Interference due to the multipath problem
3. Interference from the other wireless devices

The most interested parameter was the first one. The test was performed by measuring PER for each position from 20 m to 60 m in order to get an idea of how the distance affect the signal attenuation.

In this thesis, we designed our test method by applying all knowledge from the literature. These three following parameters were utilized for evaluating the performance of selected wireless modules:

- Bit Error Ratio (BER): BER is defined as the number of incorrect bit divided by total number of the transmitted bit
- Packet error rate (PER): PER is defined as the number of missing packet divided by total number of the transmitted packet
- Latency: Latency is defined as the different between actual time and the expected time of the transmission.

4.2.1 Testing Protocol

The following testing protocol was designed to test the wireless modules. The test was performed by varying the interested variable and measuring BER, PER, and Latency. The aim of the first testing protocol was to find the effect of the data rate of the transmission. The second testing protocol was employed to find the relationship between distances and the transmission. The measurement was done in the application layer not in the physical layer.

1. Data rate (kbps):

Fixing parameters:

- The distance between transmitter and receiver: 3 meters
- Transmitting time: 3 Minutes

Varying parameters: Data rate

- From 32 kbps
- To 512 kbps
- Step size: multiply by 2

2. Distance (meters):

Fixing parameters:

- Data rate: 512 kbps
- Transmitting time: 3 Minutes

Varying parameters: Distance

- From 1 meter
- To 7 meters
- Step size: 1 meter

3. Energy consumption:

We measured the current draw in order to test the energy consumption of the device. The test was performed by connecting the battery to the system under test through current meter. During the full time operation, the current was measured and the total power consumption was calculated.

4.2.2 Testing data

The tests used a set of dummy data as shown in Figure 4.1. The data was a continuous ramp from 1 to 255 used for evaluating the error in long-time transmission. An advantage of using this kind of data was that the error can be detected easily when it occur.

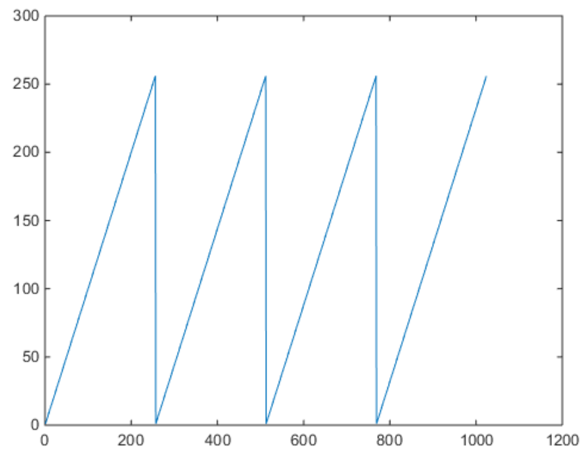


Figure 4.1: Dummy data set for evaluation wireless module. The data was a number looping between 0 and 255.

4.2.3 Testing scenarios

To avoid problems of interference, the test was performed in the empty classroom at Chalmers University of Technology. Nevertheless, we could not control the electromagnetic environment outside the classroom. Therefore, there were chances of interference during the test. These interference signals were microwave oven, cordless phone, other

WiFi access points and also other WiFi and Bluetooth devices. The illustration of the testing scenario is shown in Figure 4.2. The receiver module was placed at the fixed position and the transmitter module was placed at the 3 meter away for the first module and was moved to 7 different positions for the second experiment.

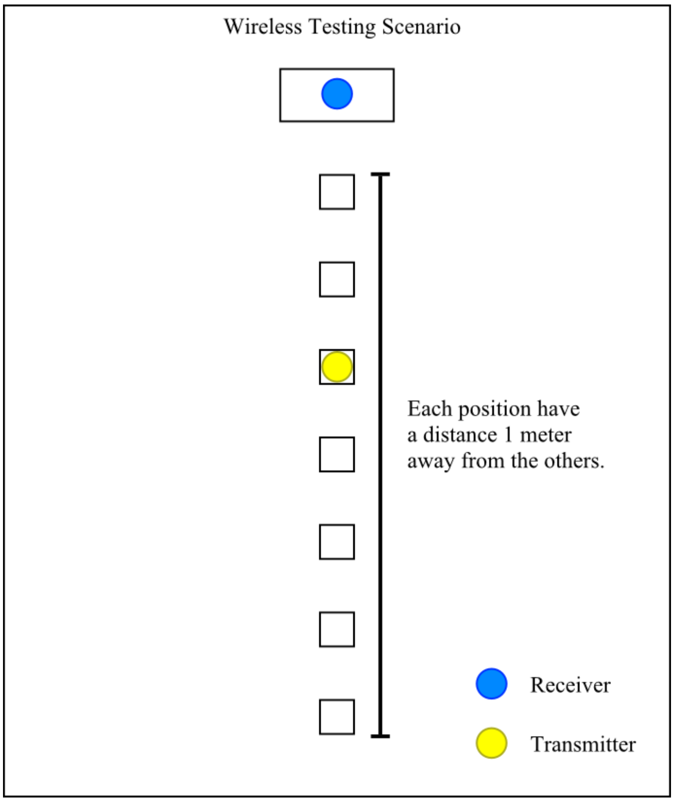


Figure 4.2: Illustration of the testing scenario. The test was performed in the empty room. The receiver was place at the fix position and the transmitter was placed at the different position following the tests.

4.2.4 System configuration

The system configuration of WiFi for testing is shown in Figure 4.3 It could be divided into two sides; transmitter and receiver. The transmitter side consisted of Tiva launchpad micro-controller and WiFi module connected with UART interface. PC and access point (AP) were in the receiver side connected together by LAN wire. All devices was set to be operated on channel 1. Users was able to control the system by using MATLAB GUI running on the main PC as shown in Figure 4.4. Parameters including test number, running time and bit rate for transmission could be set. Data were able to be sent from transmitter side to access point (AP) and PC and vice versa. GUI running on the main PC received data from the AP and showed the result on the screen.

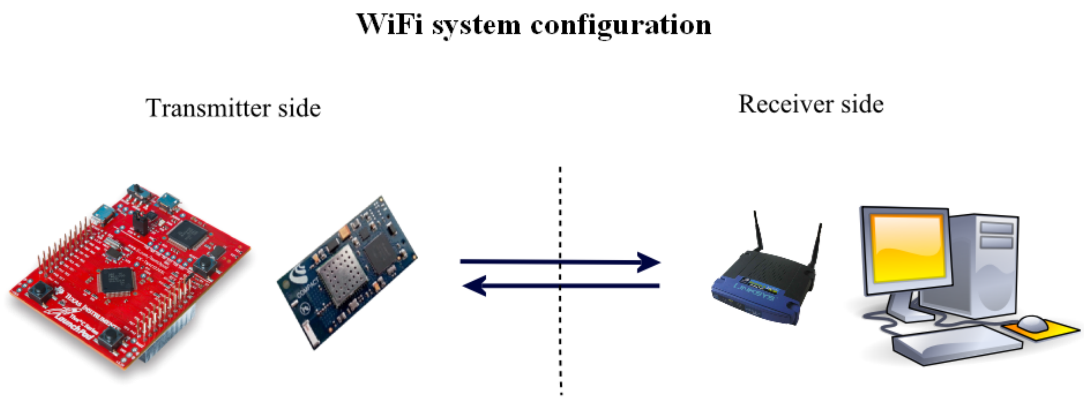


Figure 4.3: WiFi system configuration for testing. The system consisted of transmitter side and receiver side. Access point was connected to the main PC for receiving data from WiFi module.

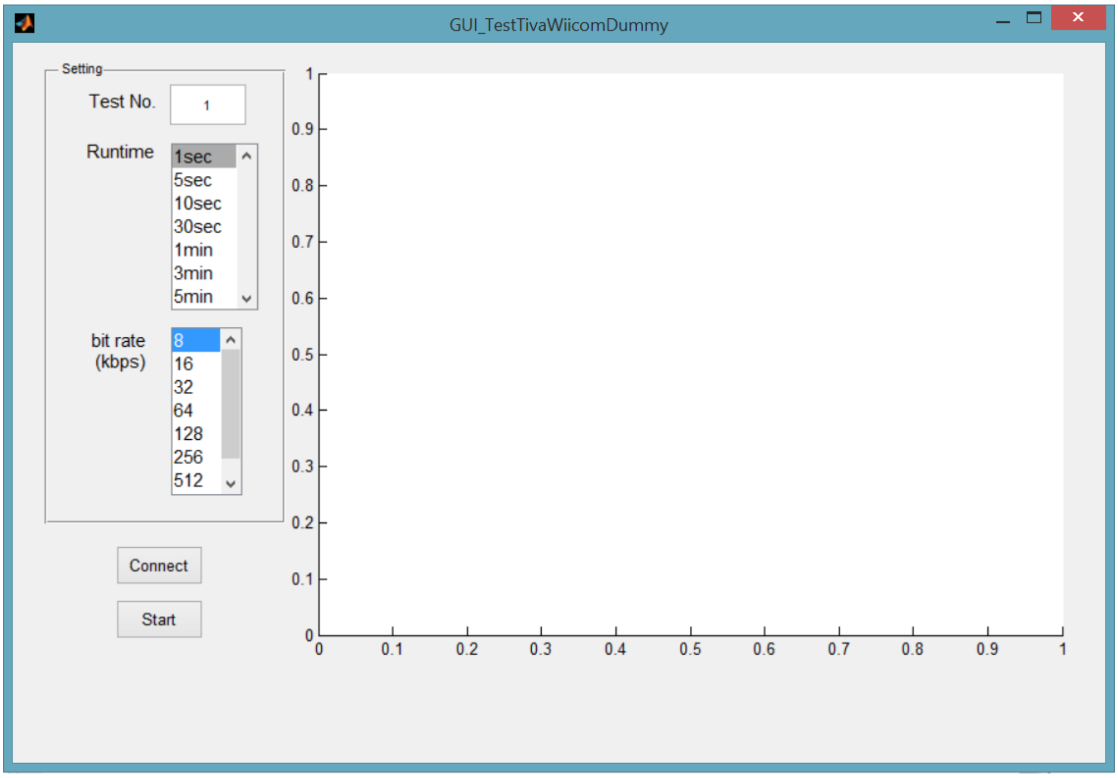


Figure 4.4: GUI for WiFi testing. User can set test number, running time and bit rate from the menu.

For the Bluetooth system testing, the configuration shown in Figure 4.5 was employed. The system worked in the same fashion as WiFi system except that there was no access point. The Bluetooth module was attached to Tiva launchpad and communicating via UART. The data were able to be transmitted from transmitter side to receiver side using Bluetooth technology. On the receiver side, another Bluetooth module was connected to the main PC through UART-to-USB interface. Users could control the communication by MATLAB GUI running on the main PC as shown in Figure 4.6. Test number, Port for UART, Runtime, and bit rate could be set by the users.

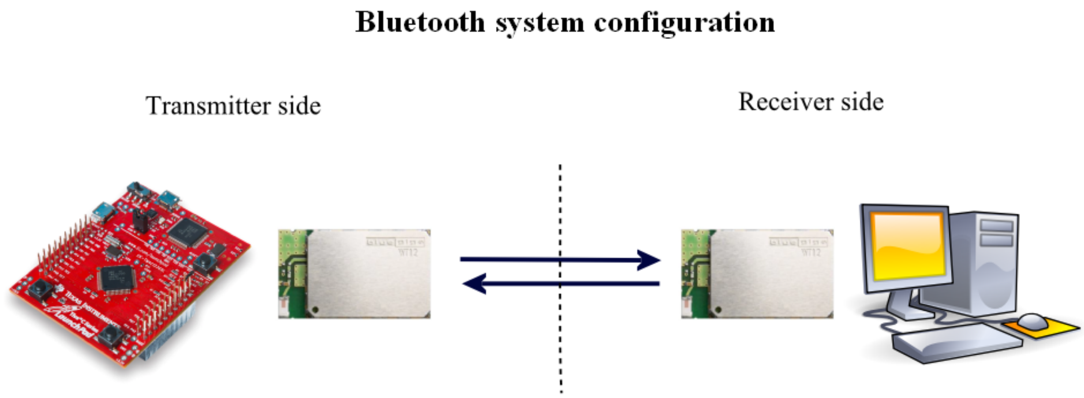


Figure 4.5: Bluetooth system configuration for testing. The system was divided into transmitter side and receiver side. Two Bluetooth module was used in both sides

4.3 Integrated with ALC system testing

In order to ensure that the wireless modules properly integrate with the ALC system, the recording session using BioPatRec was performed. For WiFi, ten-movements recording sessions with 8 channels provided the data rate at 512 kbps was employed to test the stability of the connection. In contrast, due to the data rate limitation of Bluetooth connection the test were performed with 1-movement recording session with 4 channels with the data rate at 256 kbps. This aspect will be discussed in the next session. It is worth noting that There was only one channel that record EMG signal from tested object as shown in Figure 4.7 and the other channels were not connected to electrodes.

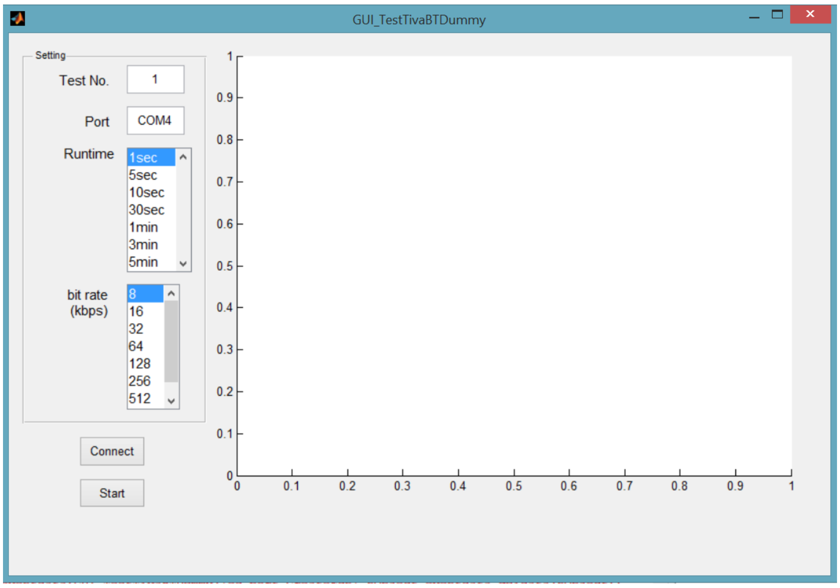


Figure 4.6: GUI for Bluetooth testing. User can set test number, port, running time and bit rate from the menu.

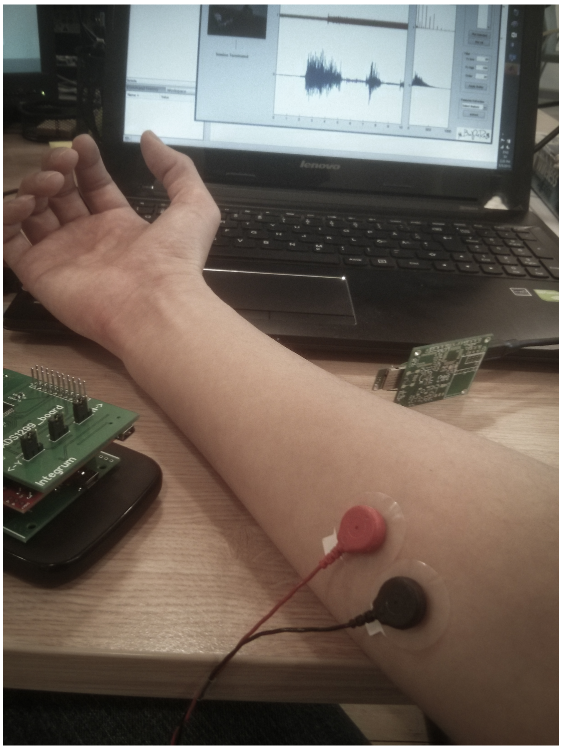


Figure 4.7: Testing scenario for ALC system testing. One bipolar electrode was used for recording the EMG signals.

5

Results and Discussion

This chapter is divided into 3 parts. The first part includes the results of the wireless survey and important specification of the selected modules. The result from the performance testing are presented in the second part, while the last section shows and discusses the result of the integrated system.

5.1 A survey and modules comparison

As described in the previous chapter, some considerations were used to compare the modules and, consequently, two modules were selected. For WiFi, Compact-CS module from Wiicom was chosen, while WT12 from Bluegiga technology were employed as a Bluetooth module. Results from the comparison and the specification will be presented and discussed in this section.

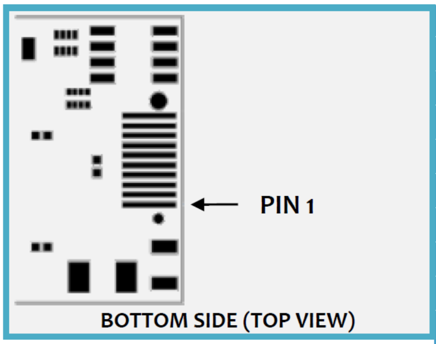
5.1.1 WiFi module selection

After a research, three modules had been found that they were suitable for the ALC application. Table 5.1 shows the comparison of these three modules; ES-WiFi, xPico, and Compact-CS. All three modules came with 802.11 b/g/n and UART port as an interface. The UART was the main interface for communication in our ALC system. The differences were configuration method, UART maximum baud rate, and Wireless mode. All aspects had been considered and Compact-CS module was selected. The good things about Compact-CS module was its usability — it could be configured easily by using its configuration software called *CompactReadyGo*. In addition, with data speed 2.5 Mbps, and Ad-hoc and client mode, it was the best choice for testing the system. In contrast, ES-WiFi and xPico came with a special WiFi mode called *SoftAP*. SoftAP is able to control the module to operate as a virtual access point and allow the other devices to connect to the modules. This function may be useful, but it needs more investigation [31–33].

Table 5.1: Comparison of WiFi module [31–33].

	Inventek: ES-WIFI	Lantronix: xPico	Wiicom: Compact-CS
WiFi Version	802.11 b/g/n	802.11 b/g/n	802.11 b/g/n
Host Interface	UART, SPI, USB	UART, SPI, USB	UART
Configuration	AT command	web Manager, XML, Commandline	specific software
UART Max. Baud rate	2 Mbps	921 Kbps	2.5 Mbps
Wireless Mode	SoftAP, Client	SoftAP, Client	Ad-hoc, Client

Compact-CS module had 10 pins with rugged connector as depicted in Figure 5.1 [31]. Supply voltage was between 4 to 10 V and current consumption during receiving and transmitting data was 56mA and 13mA respectively. UART TX and RX pin were used for transmitting and receiving data to and from the MCU.



1	Vsupply
2	Nc
3	Nc
4	Nc
5	UART TX
6	UART RX
7	Reserved
8	I/O PIN 0
9	I/O PIN 1
10	GND

Figure 5.1: Compact-CS pins specification. Vsupply was voltage source. UART TX/RX was used for communication. CND was ground. (Source: Compact Hardware Guide, Wiicom, 2013 [31].

As mention earlier, Compact-CS module could operate in two modes; Ad-hoc and Client mode. In Ad-hoc mode, the module creates its own WiFi network, and allows the other WiFi-enabled devices join the network. Ad-hoc mode had been tested first, it was found that sometimes the connection was not stable and the transmission fails. Consequently, the mode was changed to client mode and an access point was introduced to the system allowing each devices talk to each other in the WiFi network.

5.1.2 Bluetooth module selection

For Bluetooth, three modules from the market was chosen as well. These three modules, WT12 from Bluegiga, RN42 from Microchip, and BTM443 from Laird, have Bluetooth 2.1 with Enhanced Data Rate (EDR). Bluetooth 2.1 + EDR was selected because it had the fastest data rate among all Bluetooth versions. Bluetooth class 2 was enough for the communication within 10 meters. From the list, WT12 from Bluegiga was selected since its function and its maximum speed. WT12 could provide data rate up to 500 kbps. Moreover, WT12 came with its own software called *iWrap* which provides the usability to control all functions. WT12 also provides 13 Bluetooth profiles including iAP for connecting to Apple's product. Serial Port Profile (SPP) was employed in this thesis as a virtual serial ports for communication [34–36].

Table 5.2: Comparison of Bluetooth module [34–36].

	Bluegiga: WT12	Microchip: RN42	Laird: BTM443
Bluetooth Version	BT 2.1+EDR	BT 2.1+EDR	BT 2.1+EDR
Class	2	2	2
UART Max. Baud rate	500 kbps	300 Kbps	300
Range	30 m	10 m	50 m
Interface	UART, USB	UART	UART
Current Consumption	70 mA	30 mA	40 mA
Profile	13 Profiles including iAP	SPP, HID	SPP,HID,HDP

WT12 operated with 3.3 V voltage supply and had 4 pin for the UART communication with MCU as shown in Figure 5.2. UART_TX and UART_RX used for transmitting and receiving data to and from MCU. Request-To-Send (RTS) and Clear-To-Send (CTS) provide the flow control of the signal in order to obtain more stable communication. The module could be set to operate as a master or a slave module. As described in chapter two, Bluetooth was designed for low power consumption. Thus, slave was able be controlled by master module to enable or disable its function. Current consumption of master and slave module in each operational state was different as shown in Table 5.3

The most useful feature of WT12 module was iWrap firmware. The iWrap was a

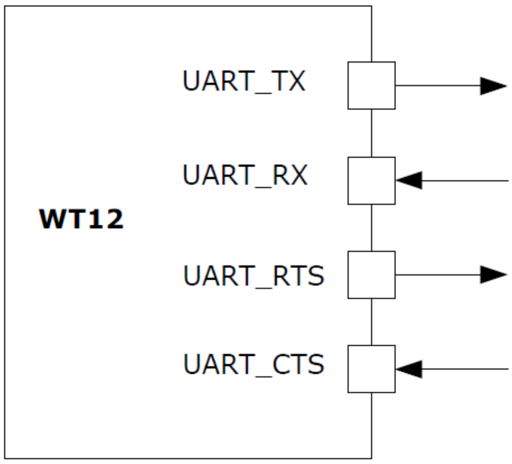


Figure 5.2: WT12 UART interface. UART TX/RX was used for transmitting data. UART RTS/CTS was used for controlling the communication. (Source: WT12 Data sheet, Bluegiga Technologies, 2014 [36]).

Table 5.3: WT12 current consumption [36].

Operation mode	AVG current supply (mA)
Master connected	6.2
Slave connected	22.4
Master transmitted	31.5
Slave transmitted	29.2

host stack running above the controller stack. It hided all low level layers and provides users capabilities to control all Bluetooth functions using command line. The set up for integrating the module to the ALC system will be discussed more in the last section of this chapter.

5.2 Performance evaluation

In this part, the result from all performance testing are presented. Notwithstanding, before discussing the result, it is worth to mention that there were hardware limitation problems that had been found during the experiment. These problems caused the failure to follow the test. As a consequence, only the result form succeeded test will be shown and all problems will be discussed along with this result.

5.2.1 WiFi module evaluation

Data rate was the first parameter that had been measured. It has been found that there were no bit error and packet error for all data rates. The only parameter that was able to be measured is a delay and the result presents in Figure 5.3. The result shows that when data rate increased, the delay increased as well.

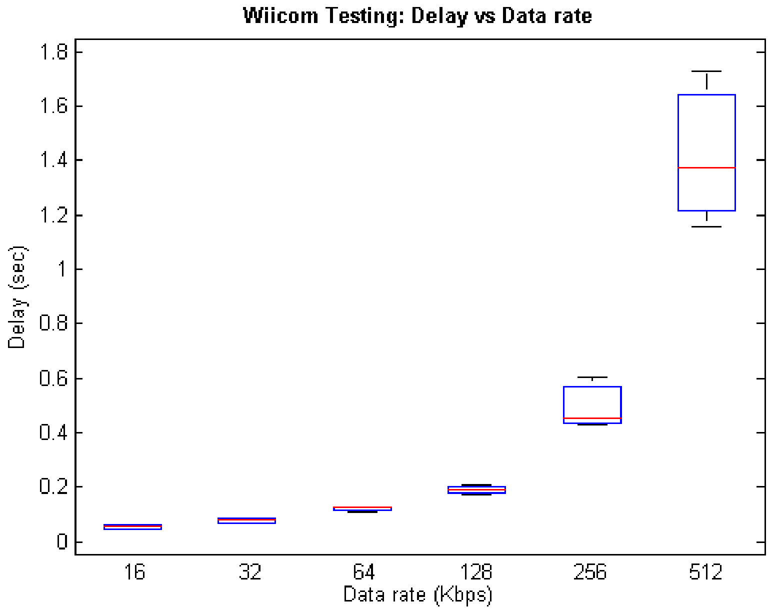


Figure 5.3: WiFi evaluation: A box graph plotting delay versus data rate.

For the distance testing, on the contrary, there were some packet errors when the data was transmitted with the rate at 512 kbps. The result of the delay and PER is presented in Figure 5.4 and 5.5. However, the delay was calculated from the test that had no packet error only due to the problem of the delay measurement. At each distance, the test was performed five times and the number of test that had packet errors are shown in Table 5.4

Table 5.4: Number of the error when testing at 512 kbps at the different distance.

Distance (m)	No. of test with PER (out of 5)
1	2
2	1
3	2
4	4
5	2
6	1
7	2

One observation was when the packet reaches the receiver, there was no bit error due to the error correction process in the lower layer of the WiFi. From this observation, it can be concluded that BER cannot be used to measure the performance of the WiFi in application level. The results show that at the distance below 10 m, there were no significant differences in term of both delay and PER.

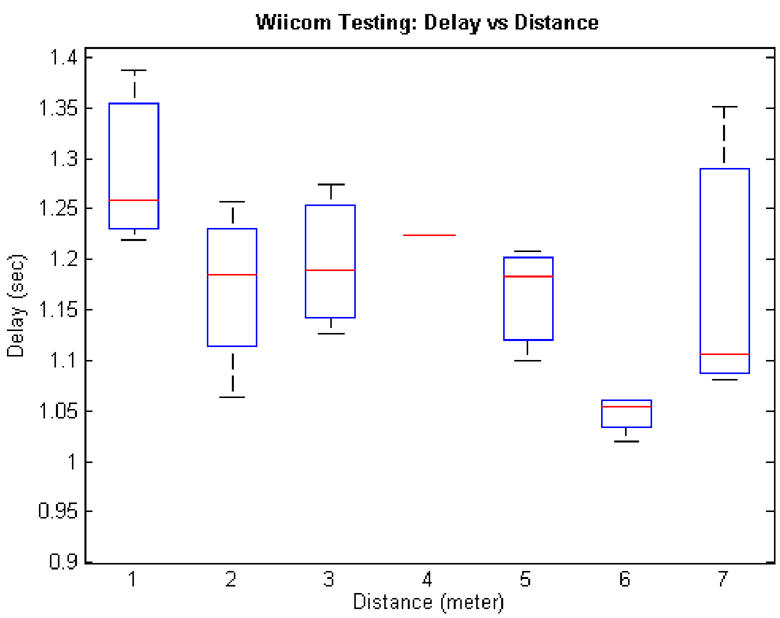


Figure 5.4: WiFi evaluation: A box graph plotting delay versus distance.

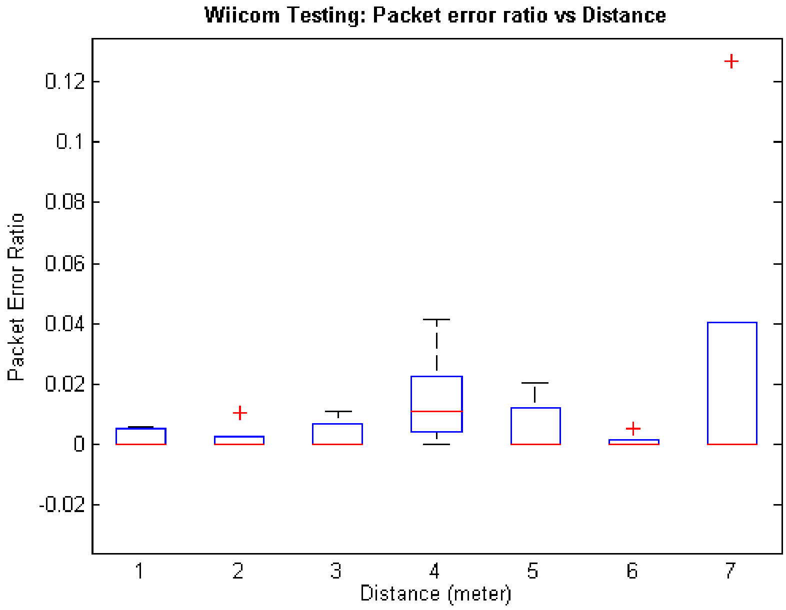


Figure 5.5: WiFi evaluation: A box graph plotting PER versus distance.

Nevertheless, a number of packet error at 4 meters were greater than packet error at other positions. In order to investigate more about this error, two network observation software was employed. The first software called *inSSIDer* provided the information of operating channel of the access points around the observation point. Figure 5.6 illustrates the channel of all access points around Integrum's office. Wiicom_ap was the main access point in our system operating on channel 1. It can be seen that there are several other access point operate on the channel. This co-channel and adjacent access point can cause interference to the main access point. This interference known as co-channel and adjacent channel interference could cause the error to the system [37].

The second software named NetSurveyor was employed for investigating received signal strength of the WiFi signal in time domain and the result is shown in Figure 5.7. Red color in the graph indicates the highest signal strength and the purple color indicates the lowest signal strength. It has been found that there was a chance that the signal drop occasionally during the transmission shown as a small gap in the graph. Interference was still the main reason for the signal dropping and all devices emitting electromagnetic field can generate the interference [37].

From these observations, we have found that the interference occurred randomly from time to time. Besides, the source of the interference is not under control. Therefore, the method to deal with this kind of problems is needed. We will present proposed methods in the last section of this chapter.

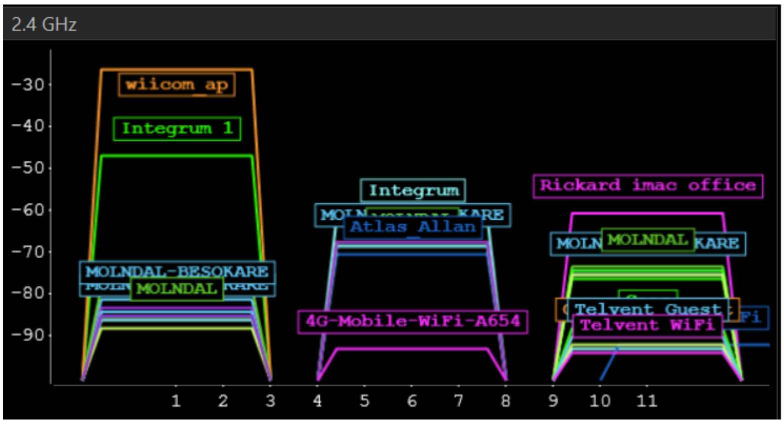


Figure 5.6: Operating channel of access points around Integrum's office. The main access point used in this project was Wiicom_AP operating on channel 1.

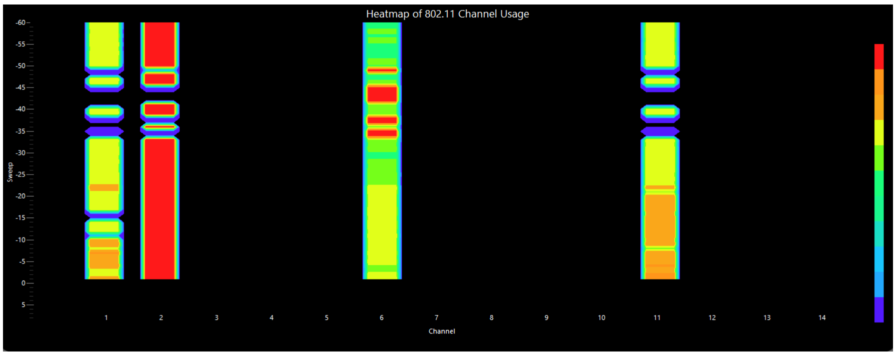


Figure 5.7: Received signal strength of WiFi signal showing in time domain recording at Integrum's office. Red color indicates the highest signal strength and purple color indicates the lowest signal strength.

5.2.2 Bluetooth module evaluation

It was more difficult to collect the data of the Bluetooth module. When testing the transmission with data rate above 400 kbps, the system randomly crashed. As a consequent, unfortunately, we could not measure anything. After the investigation, it was found that the WT12 had a hardware problem with high speed data rate and required a new firmware. Thus the maximum data rate for testing was changed to 256 kbps and the result shown in Figure 5.8. It is worth noting that the system was implemented with enabled UART flow control.

From the graph, it can be seen that the delay at data rate 256 kbps was around 15 seconds. In contrast, the system worked properly with a little delay at the other data rate. This brings to the conclusion that the Bluetooth module operates properly with the data rate up to 128 without significant delay and up to 256 kbps with some delays.

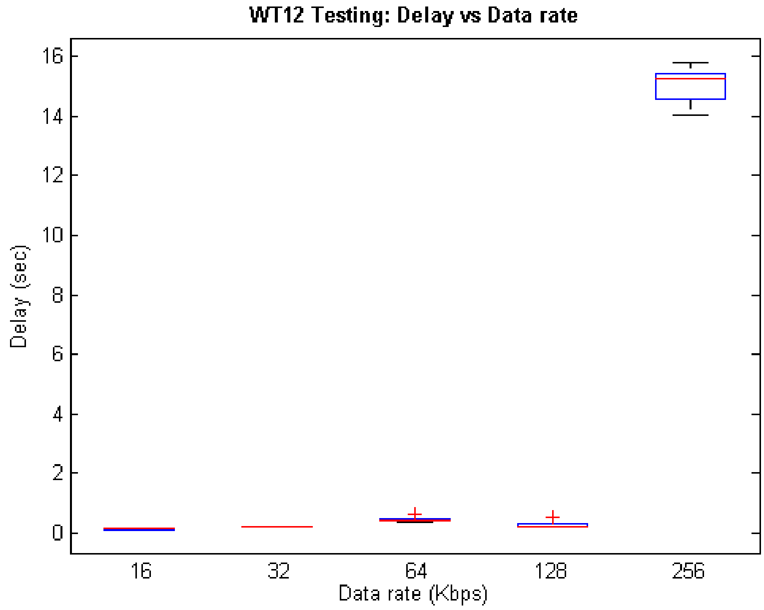


Figure 5.8: Bluetooth evaluation: A box graph plotting delay versus data rate.

5.2.3 Current consumption comparison

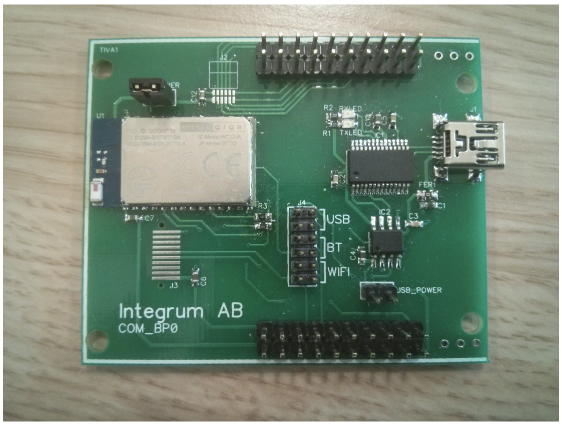
The result from the current consumption of WiFi module, Bluetooth module, and USB presented in Table 5.5. The tests were done using 12 V battery with rate 0.8 mAh and Voltage regulator board to regulate 5 V. The result show that WiFi module consumes large energy comparing to the USB and Bluetooth.

Table 5.5: Current consumption of each module and estimated battery life.

	Current consumption		Estimated Battery Life
	Standby state	Acquisition state	
USB	61 mA	65 mA	12 hr
WiFi	195 mA	205 mA	4 hr
Bluetooth	71 mA	81 mA	10 hr

5.3 ALC system integration

Two printed circuit board were designed to integrate the module into the system. One PCB designed by the outsource company was used for adding all communications to Tiva launchpad. It consisted of USB, WiFi and Bluetooth interface as a boost pack for Tiva Launchpad. The second PCB designed by us was utilized for adding only Bluetooth to the main PC. WiFi did not require the new PCB on the PC since all devices in the network communicate via an access point. The board was a USB stick that was able to plug into the USB port and enable Bluetooth in the PC. These two boards are shown in Figure 5.9.



(a)

(b)

Figure 5.9: PCB for implementing wireless interface in ALC system (a) PCB for communication board it consists of Bluetooth WiFi and USB interface (b) USB stick for adding Bluetooth to PC.

5.3.1 WiFi configuration and testing result

In order to connect WiFi to the access point, an IP of the WiFi module and the access point had been set to specific value shown below. In addition, IP must be in this format 192.168.100.xxx (xxx are any number from 1 to 255)

- Compact-CS IP: 192.168.100.10
- Access Point: 192.168.100.100

When connecting a new device to the network, new specific IP of that device must be set. However, the new IP could not be 10 and 100. For testing, the IP of the main PC had been set to 192.168.100.5.

To increase the usability of the system, we have created the specific window-based software for connecting the PC to the access point automatically. This software used window command for setting up the IP and running in a command-line fashion. An example of the software set up are displayed in Figure 5.10.

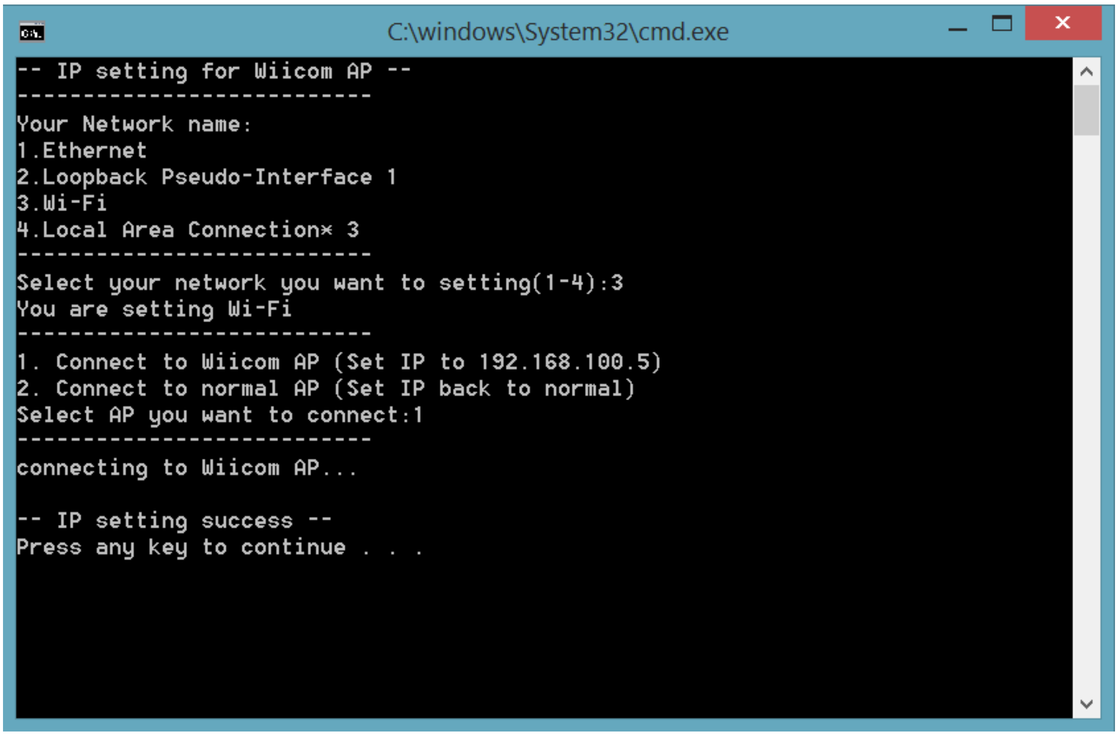


Figure 5.10: Window-based software for setting up the IP automatically. The software showed available network and users can set the IP for the selected network.

For instability problem due to the interference, we came up with 3 following solutions to improve the connection and to avoid the system crash.

- **Changing the access point's channel to a lesser crowded channel:** To ensure that the system get the most stability, channel of Wiicom access point had been change to channel 13.
- **Moving the access point to closer to the device:** This helped the system to increase the received signal strength of WiFi signal.
- **Implement the error catcher algorithm in the software:** Try-catch statement was recommended to be implemented in the system. This could help users to understand what is going on when an error occurs and users can choose what to do next. We had implemented try-catch statement in BioPatRec for testing the system.

The integrated system was tested with BioPatRec and it works properly. An example result of the recording session with 8 channels (512kbps) for open hand movement shown in Figure 5.11.

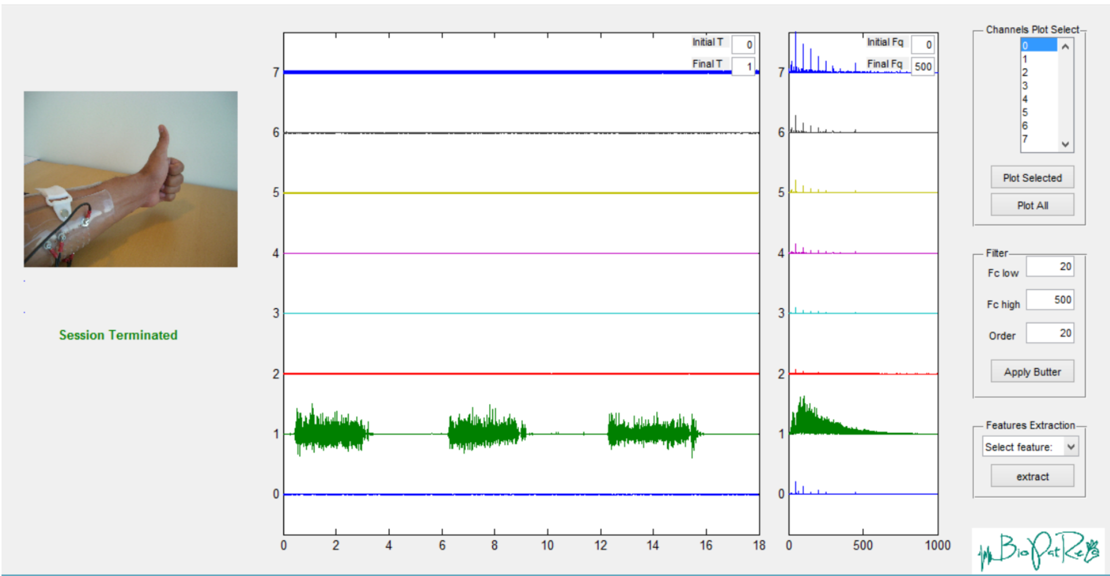


Figure 5.11: The result of open hand movement from recording session of BioPatRec and ALC system with Compact-CS WiFi module. One bipolar electrode was used and 8 channels was recorded .

5.3.2 Bluetooth configuration and testing

WT12 modules running with iWrap firmware had been set to operate in SPP mode. Two Bluetooth modules were set to connect automatically when both module were powered. The problem with high data rate still appeared in the testing as well. Therefore, the system was tested with 4 channels (256 kbps) only and a result from the recording session with open hand movement is displayed in Figure 5.12. However, the problem of the delay sometimes leads to crashing in the system. Thus, for Bluetooth, recording with 2 channels only (128 kbps) or reducing the sampling frequency is recommended.

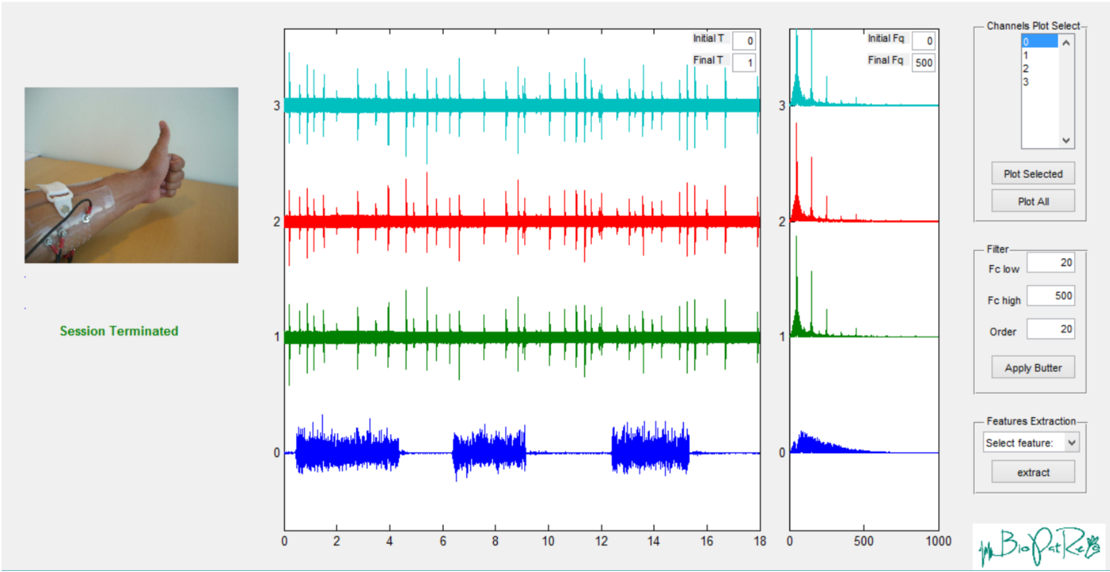


Figure 5.12: The result of open hand movement from recording session of BioPatRec and ALC system with with WT12 Bluetooth module. One bipolar electrode was used and 4 channels was recorded.

6

Conclusion and Future work

Medical devices integrated with wireless module are becoming more and more popular these days. As a consequent, improvements of a wireless technology in medical applications are needed. Patients gain more safety and more convenience when devices gone wireless. However, selecting the suitable wireless technology for specific medical devices as well as making the communication stable are essential.

In this thesis, the possibilities to integrate wireless technology into artificial limb control (ALC) system used for fitting, training, and monitoring patients were investigated. The aim of this thesis is to find the most suitable wireless solution to be used as an interface between patient and BioPatRec. Requirement for the system was setup. Bluetooth and WiFi technology were studied. Compact-CS WiFi module taken from Wiicom and WT12 Bluetooth module taken from Bluegiga Technologies were evaluated and integrated into ALC system. The modules were selected and tested based on relevant standards for wireless medical device. The limitation and the performance of the modules were measured. Printed circuit boards for integrating the modules to the ALC system were designed and built. ALC system therefore can transmit signal wirelessly to BioPatRec platform running on the main PC. Real-time recording session was conducted in order to investigate the problem of communication.

The result shows that communication interface worked appropriately. The WiFi system worked properly within the requirements set in the beginning of this master thesis. WiFi enables the transmission of raw EMG data with the rate up to 512 kbps flawlessly. Nonetheless, the failure in WiFi data transmission occurs randomly during the recording session due to interference. Channel selection scheme and error catcher algorithm therefore were suggested to add to the system in order to improve system performance as well as avoid the system failure that may occur. On the other hand, the Bluetooth module can transmit data with the rate up to 128 kbps without any delay and 256 kbps with some delays. In addition to this result, the ease of use of the system is in consideration and a software aiding users to use the system was implemented.

Future work

It is obvious that Bluetooth module is not suitable for transmitting raw EMG data at rate 512 kbps following the requirements set. However, Bluetooth module works properly at data rate up to 128 kbps. One suggestion is that Bluetooth should be used to transfer processed features instead of the raw signals since data rate below 100 kbps is enough to transfer interesting features from microcontroller to the computer. Another suggestion for transmitting feature is to employ Bluetooth Low Energy (BLE). BLE consumes less energy than the regular Bluetooth. Nevertheless, it provides lower data rate. Additional research is required in order to validate the possibility of using BLE in the system.

Finally, the next stage to develop WiFi is to investigate the possibilities of using module that comes with Software Access Point (SoftAP). SoftAP is a function allowing module create its own network without using real access point. It would provide a more convenient solution to users and reduce system cost.

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