TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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ARCHITECTURE AND SYSTEM LEVEL CONCEPT FOR WIRELESS BRAIN MACHINE INTERFACE

Master of Science thesis

Examiner: Prof. Leena Ukkonen (Ph.D) and Prof. Lauri Sydänheimo (Ph.D)
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ABSTRACT

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The recent progresses in the field of medicine and biotechnology have made it possible to implant micro-electronic devices in the human body. In the field of semiconductor technology, the immense progress provides a way for devices at a millimeter scale or less such as micro-implants, but still there are some challenges in the miniaturization of the power source. This is the major hurdle in the development of a BMI device with micro electrodes for clinical use that are less or fully invasive. In upcoming BMI models, it is possible to implant data extraction electrodes and controls the device as a natural part of its representation of the body. As a short term solution for all these vast bulk of implantable electronic devices consists of harvesting components or energy storage. The revolutions and innovations in last era, to develop the interface of neuroscience and engineering lead to the advent of the field of Brain Machine Interfaces (BMIs).

In a BMI system, it is difficult to analyze the brain waves because it carries a large amount of information. Data acquisition unit can receive the particular information through wired or wireless system. The neural recordings will also need to go through a process of pre-signaling for feature extraction and translation algorithm. Brain signal pre-processing can be done by using three methods. These methods are Basic Filtering, Adaptive Filtering and Blind Source Separation. The data from acquisition unit can be sent through a wireless ZigBee/UWB/WiFi module, depending upon the number of electrode arrays used in BMI system.

In this thesis, we have proposed an end-to-end wireless BMI system based on available literature that provides a feasible way for paralyzed patients to communicate and control their muscles and robotic body parts by using their neurological signals. According to this idea, the above mentioned systems can enable a high power efficient and wireless BMI development. From a medical point of view an implantable wireless system is necessary for the applications of invasive BMI to reduce the risk of infection.

PREFACE

The Master Thesis, "Architecture and System Level Concept of Wireless Brain Machine Interface (BMI)", was done in partial fulfillment of the requirements for the Master degree in Electrical Engineering with Specialization in Wireless Communication Circuits and Systems, in Tampere University of technology (TTY). All the research and development was carried out in the Wireless Identification and Sensing Systems Research Group (WISE) of Rauma Research unit, Department of Electronics in Tampere University of technology.

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Tahir Muhammad Naeem

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LIST OF SYMBOLS AND ABBREVIATIONS

BMI	Brain Machine Interface
SNR	Signal-to-Noise Ratio
EEG	Electroencephalography
RF	Radio Frequency
BER	Bit Error Ratio
ECoG	Electrocorticography
Hz	Hertz
UWB	Ultra Wide Band
WiFi	Wireless Fidelity
DC	Direct Current
ALS	Amyotrophic Lateral Sclerosis
DNA	Deoxyribonucleic Acid
LFP	Local Field Potentials
EMG	Electromyography
MEG	Magnetoencephalography
NIRS	Near Infrared Spectroscopy
FMRI	Functional Magnetic Resonance Imaging
PET	Positron Emission Tomography
SUA-MUA	Single - Multiunit Action Potentials
IC	Integrated Circuit
µECoG	Micro Electrocorticography
MHz	Mega Hertz
GHz	Giga Hertz
LSI	Large Scale Integrated Circuits
RMS	Root Mean Square
KG	Kilogram
BOLD	Blood Oxygen Level Dependent
FDG	Fludeoxyglucose
FCC	Federal Communications Commission
ICNIRP	International Commission on Non-Ionizing Radiation Protection
TDM	Time Division Multiplexing
AC	Alternating Current
SVM	Support Vector Machine
WBAN	Wireless Body Area Network
EM	Electromagnetic

1. INTRODUCTION

Brain Machine Interface (BMI) systems offer a new way of communication to humans by translating their thoughts into actions. BMI is a connection between brain and an external device that provides a medium of communication in between them by extracting neural signals from the brain to transfer them for some external activity, like control of a prosthetic limb or robotic arm. The BMI system provides a direct route for communication of neural signals between the brain and the external object that need to be controlled. The theory of neural interface communication between brain and the external body parts, for example, to connect a brain to a computer or any other machine, is not new and many researchers have been trying to trigger this field by new scientific approaches. Moreover, researchers have started to consider unspoken forms of responses and intentions of human mind as an input that is not explicitly performed to direct a computer to do something [1]. Researchers are attempting to infer information about human state of mind and intentions by observing and analyzing their behavior, physiology and the situations in which they performed functions. With the help of this neurological and physiological information, systems can dynamically adapt themselves in order to support the user in the task at hand.

The recent advancements in the field of medicine and biotechnology have made it possible to implant micro-electronic devices in the human body. In the field of semiconductor technology, the immense progress provides a way for devices at a millimeter scale or less such as micro-implants, but still there are some challenges in the miniaturization of the power source remains there. This is the major hurdles in the development of a BMI device with micro electrodes for clinical use that are less or fully invasive without any hazard. In upcoming BMI models, it is possible to implant data extraction electrodes and controls the device as a natural part of its representation of the body. As a short term solution for all these vast bulk of implantable electronic devices consists of harvesting components or energy storage. The revolutions and innovations in last era, to develop the interface of neuroscience and engineering lead to the advent of the field of Brain Machine Interfaces (BMIs).

BMI systems are characteristically divided into three main classes, depending upon the way of neurological signal collection, invasive, noninvasive and minimally invasive. Invasive systems are the most accurate form of all these classes, depending on implanted electrode arrays, these electrode arrays are suitable for inferring brain wave activities in the cerebral cortex, such kind of systems offer very high Signal to Noise Ratio (SNR) measurements. The current concern now-a-days is that with invasive systems, the electrodes need to be implanted in human brain. These devices were traditionally wired and now-a-days researchers are trying to make it wireless, and they are doing tests to make it more secure for clinical usage. Noninvasive BMI systems are well suited for the conditions where the surgical implantation of electrodes is not possible and consequently, we have a much broader field of application. The most common noninvasive measurement technique is Electroencephalography (EEG) that is used to analyze the brain wave activity through the scalp. It's really good that it can record the signals through the scalp but the main challenge with noninvasive EEG is that it has a low SNR. Finally, the third class of BMI signal extraction is minimally or partially invasive BMI technique, in which the electrode arrays are implanted inside the skull but resides outside the brain rather than within the grey matter. They have a better resolution signals with high Bit Error Ratio (BER) than non-invasive BMIs [2].

A BMI system usually consists of four main parts i.e. input power unit, data acquisition unit, signal processing unit and main processing unit. Subject to the type of connection between these four BMI units, we can distribute these systems into two types, wired and wireless BMI systems. Wired BMI systems generally come with heavy and bulky neurological data acquisition and processing units. The connection of wiring is typically complex because of too many cable connections between the electrodes, acquisition and processing units.

Currently many researchers are focusing on a miniaturized wireless BMI system, with wireless power transmission, fast data acquisition and portability. In a wireless system the brain waves are acquired and processed, and then these digitized physiological signals are wirelessly transmitted to the translation unit and main processing unit respectively. Wireless systems are different from their traditional wired systems and are designed to provide ease in observing the neural activities of human brain. In contrast to conventional wired BMI systems, the wireless BMI system eliminate the wire connections in between different units of a BMI system from input power till the end user which offers an improved wear-ability and portability [1].

1.1 Thesis Scope and Outline

In my thesis, I have proposed a wireless BMI system with all possible and best available results. In the proposed wireless BMI system, there is a wireless power transmission system; the transmitted energy can be scavenged by a rectenna system which consists of two main modules, an antenna and a rectifier. This suggested power supply rectenna array has a maximum transformation efficiency of 75.6%, and the systems overall efficiency is 33%. Keeping in mind the end goal to comprehend the vision of completely independent Brain Machine Interface (BMI) frameworks, neural implantable devices should be successful in their capacity, as well as meet clinical limitations, for example, simplicity of implantable electrodes, their life span, portable, and miniaturized size.

Electrocorticography (ECOG) is an invasive or minimally invasive intracortical neural recording method through implanted microelectrode arrays and in EEG, electrodes located outside the skull, on the surface of the cortex.

Analyzing the brain waves in BMI is very complex because it carries a large amount of information received through electrodes. Data acquisition can be wired or wireless, EEG has a sampling frequency of 250 Hz to 1000 Hz and the ECOG data is collected with a sampling frequency of 1000 to 2000 Hz. A higher digitization rate 1000 Hz would provide a good temporal resolution to study the brain activity from DC to 200 Hz. The neural recordings will also need to go through a process of pre-signaling for feature extraction and translation algorithm. Brain signal pre-processing can be done by using three methods. These methods are Basic Filtering, Adaptive Filtering and Blind Source Separation. The commands from data acquisition unit can be transmitted through wireless medium like ZigBee/UWB/WiFi module by depending upon the number of used electrode arrays in BMI system. The rest of the thesis is organized as follows: in chapter 2, there is a brief overview of a BMI system, in chapter 3, different types of BMI and wired vs wireless systems are discussed, in chapter 4, a complete wireless BMI system is proposed, with wireless input power supply till end user command, the hardware working, processing and characterization of the BMI system is explained with the help of ZigBee/UWB/WiFi with all advantages, challenges, and technologies involved in it and finally, in chapter 5, there will be a conclusion in which future aspects of proposed system are discussed.

2. OVERVIEW OF BMI

This chapter contains a brief literature review of a BMI system that is intended to provide the framework for the next chapters. It will make a base for later discussion by providing some information about historical background of BMI, its need, applications areas and important elements.

2.1 History of BMI

History tells us that the people belonging to Stone Age used to communicate by drawing different signs or diagrams. The revolution in the communication department greatly depends on the technology progression. Today, technology is crucial in almost every aspect of life, by resolving many issues and providing ease in miscellaneous areas; such as training, learning, clinical usage, daily life works and entertainment. The significance of workstations in our lives creates human and computer interaction, which is one of the most critical elements in the field of systems design. However, there are some limitations in human and computer communication. In 1875 the electrical currents in brain was revealed by a Liverpool surgeon named Richard Caton (1842-1926) [3]. By using rabbits and monkeys, he researched on action potentials. Caton's work was followed by a German neuropsychiatric Hans Berger (1873-1941), who studied and analyzed the cerebral localization and intracranial blood circulation. The first EEG measurement of human brain's electrical activity from the scalp was done in 1924 by Hans Berger with his radio devices. He was the first one to make it possible to record the neural weak electrical signals without any surgery or implantation, and illustrated them graphically on a sheet of paper for further analysis. In early 1970's the BMI research was premature, and in 1980s researchers and scientists used a monkey to discover the mathematical formula related to electric signals transmitted by physical movement and the motor cortex [3]. In 1990s, the foremost intra-cortical BMI was made by implanting electrodes in to the monkey's skull. That experiment led the path for further and frequent BMI research and it proceeded to the experiments carried out on human beings. In the last era, research on BMI has been growing very dramatically and rising exponentially. The research communities like surgeons and specialists from different fields of engineering like electrical and biomedical have already been doing research by considering the characteristics and features of human's capability to converse with other adherents of the species. However, human interaction with machinery and computers remains very essential. Current research now targets the interface between humans and machines.

2.2 Need of BMI

Presently, the most fascinating and significant application of the BMI technology is in medical sciences. BMI offers only the medium for communication to control the effected body parts of human beings; for example, a spinal-cord injury, and mitochondrial disease, cerebral palsy, brainstem stroke, a traumatic brain injury or an Amyotrophic Lateral Sclerosis (ALS). These injuries and diseases affect the person's ability to control the muscles and with the passage of time it leads to paralysis. These muscles are, however, cognitively intact and alert and only need to communicate with the brain. The purpose of a brain machine interface is to analyze those neural signals directly from the brain and translate them into a form that can be understandable by a computer or any other device showing the particular intents of human. These translated signals enable the patients to control the robotic arm or leg, wheelchair, or an artificial limb that was not possible previously because of disease.

The current advancement in neurological research is to extend its scope to implement it for the real world and practical environments. During the last era, great developments in the field of BMI applications have inspired a majority of researchers. The progress is partially due to the significant developments in computer equipment's and devices, as well as due to an enhanced understanding of the different functions of the brain. Despite all this, it is important to remember that the human brain is a really complex organ, and the interpretation of extraction information from brain is really hard. To design a reliable communication link between the computer device and human brain remains a tough challenge. Figure 2.1 shows some application areas.

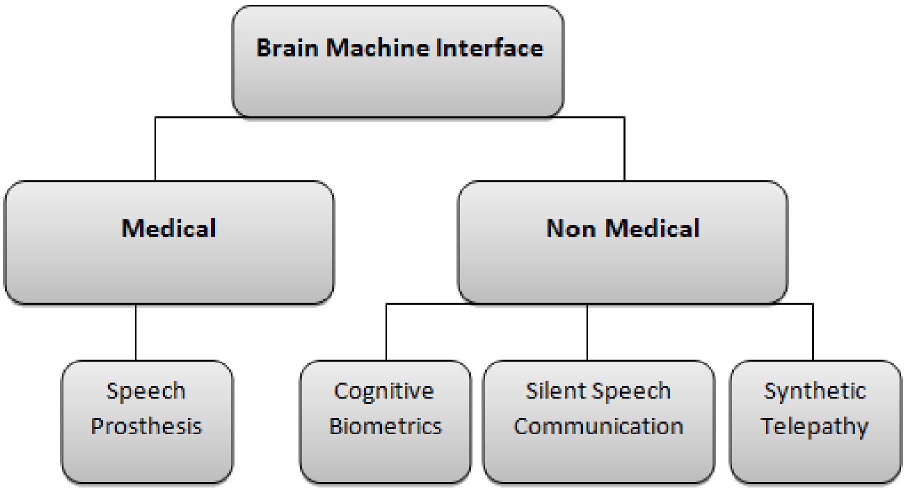


Figure 2.1 *Application areas of BMI*

2.3 The Neuron

The flow of ion based electrical current within the human body is the reason behind any biometric potential detected on the skin. Normally a human brain by birth consists of nearly 100 billion (1011) neurons with an average density of 104 neurons per cubic mm. The neural quantity decays with the increase of age [4]. All neurons almost have the same physical characteristics as well as have the same parts as other cells. The electrical signals can be transmitted with the help of electrochemical feature and it also conveys the messages to each other over long distances. Neurons have three basic parts as seen in Figure 2.2.

2.3.1 Cell body

It is the main part in the neural structure and has all of the essential constituents of the cell, for example, the nucleus Deoxyribo-Nucleic Acid (DNA), endoplasmic reticulum and ribosomes (proteins) and mitochondria (energy). If the cell body expires, the neurons also die [4].

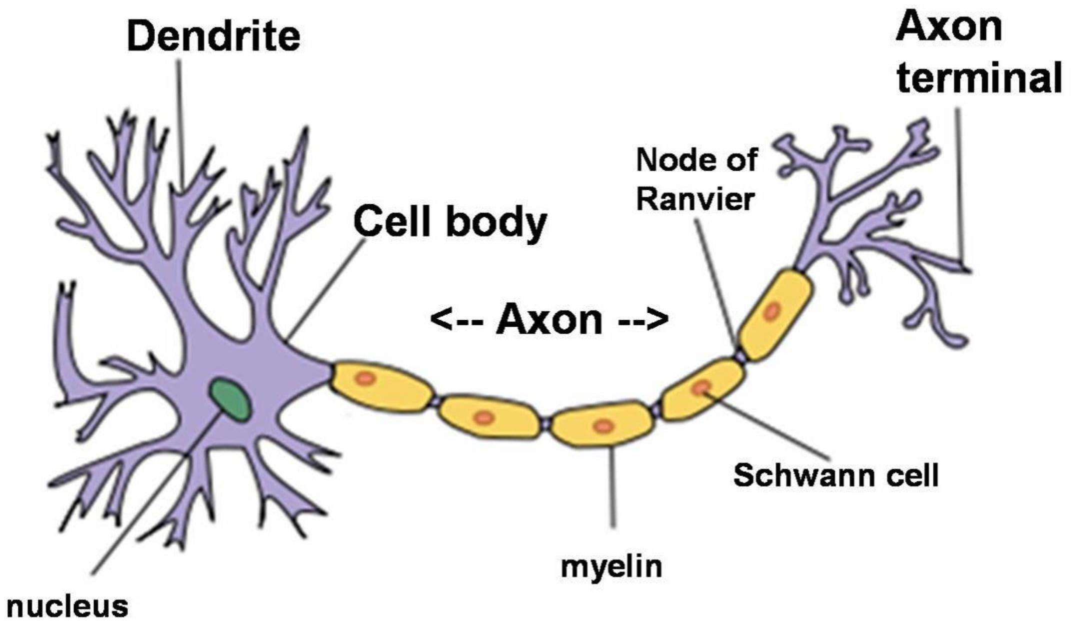


Figure 2.2 *Neuron Structure [4]*

2.3.2 Axon

It is like a long cable projection of the cell that carries the electrochemical message action potential alongside the cell.

2.3.3 Dendrites

Dendrites are the small branch like projection of the cells that make links to other cells for a network communication with different neurons. Dendrites can be found on one or on both ends of the cell [4].

2.4 Function of Lobes in Cerebral Cortex

This section discusses the human brain physiologically and aromatically. Figure 2.3 shows the areas responsible for dedicated parts of perception.

2.4.1 Frontal lobes

The frontal lobes are situated at the front side of the human brain, just before the adjacent parietal lobe and directly above the temporal lobe. The frontal lobe shown in Figure 2.3, that is mainly responsible for the tasks related to decision making, planning and problem solving.

2.4.2 Temporal lobes

The temporal lobes are located under the frontal and parietal lobes at individual side of the brain. The important functions of temporal lobes are mainly to sense the sound and smell, and more complex features such as semantic processing of visual scenes or to recognize face or language.

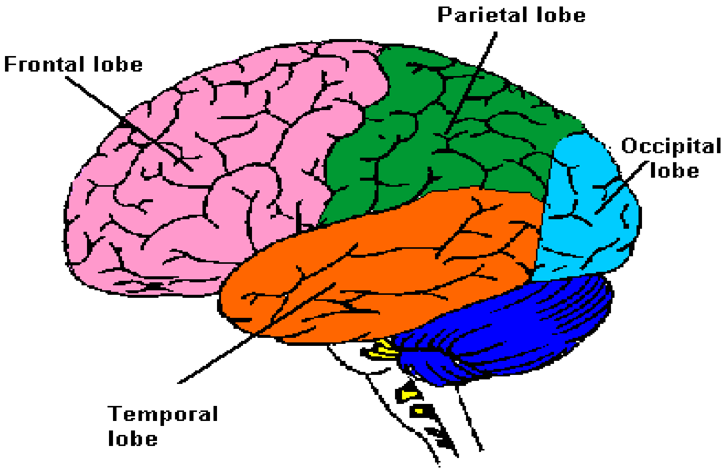


Figure 2.3 *Areas showing modularity in the Brain [5]*

2.4.3 Parietal lobes

Following the frontal lobe, there is also a parietal lobe that can be seen in the Figure 2.3. The main functionality of this lobe is processing and integration of sensory information from the body.

2.4.4 Occipital lobes

The occipital lobes are located next to the parietal lobe at the back of the head. It is the least functional area of the cortex and consists mainly of the visual system. The functions of these occipital lobes are absolutely limited to responsibilities related to the vision.

2.5 BMI Elements

As shown in the Figure 2.4, BMI has four main functional elements from a practical point of view, regardless of its recording techniques and applications.

1. Signal acquisition Unit.
2. Feature extraction Unit.
3. Feature translations Unit.
4. Device output Unit.

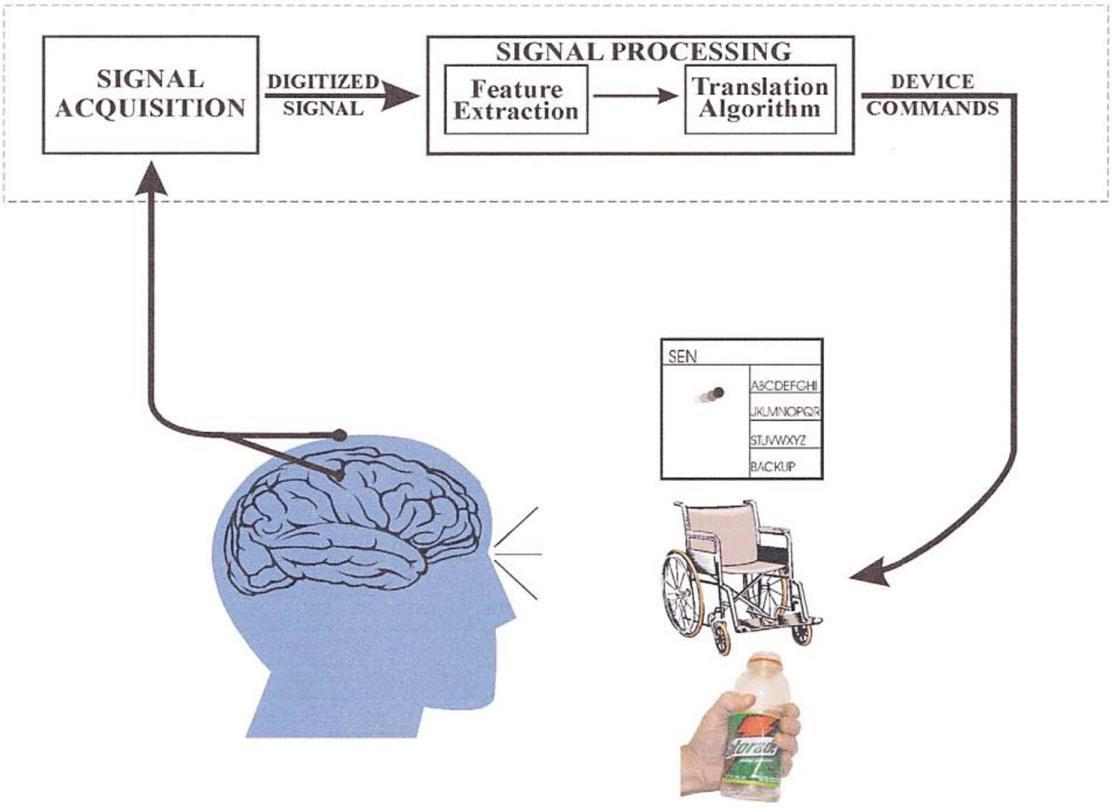


Figure 2.4 *Basic design and operation of BMI Elements [12]*

2.5.1 Signal Acquisition

In signal acquisition unit, the neurological data is extracted from the brain by invasive, noninvasive or partially invasive methods. In BMI operation, the recording interface tracks the neural information reflecting a person's intent embedded in the ongoing brain activity. In the signal acquisition part of BMI operation; the elected input information is acquired by the recording electrodes, amplified, and then digitized. The most common neurological signals employed for BMI systems include: EEG signals extracted by electrodes on the scalp, ECoG recording by the electrodes positioned beneath the skull and over the cortical surface and Local Field Potentials (LFPs) and action potentials are the nerve impulses or spikes; recorded by micro-electrodes from the brain tissue [6]. After extraction of electrical signals from the brain, they are amplified and then digitized for further processing.

2.5.2 Feature Extractions

For an effective BMI process, the extracted neurological signals should have robust and strong correlations with the intentions of the human being. The signal processing unit of a BMI system has two basic steps. The first step is feature extraction or classification of data, i.e. it extracts the features from the encoded data that shows the intentions of a human. The extracted signal features can be frequency domain or time-domain. Now a days the most common signal features used in a BMI system include delays or amplitudes of event evoked potentials for e.g. P300 [6], firing rates of single cortical neurons, and frequency power spectra like sensorimotor rhythms. To ensure accurate measurements for the classification of data, an algorithm is used to filter out the artefacts like Electromyography (EMG) activity or 60 Hz noise [6], which are removed from the brain signal features. That algorithm is also used to transmit the featured digitized data that will be used to control the BMI.

2.5.3 Feature Translations

Feature extraction is also a part of signal processing unit and in this step of signal processing; the extracted features are further processed by the translation algorithm. It converts the extracted signal features into device commands for end user. Cerebrum electrophysiological mechanisms or parameters are interpreted into charges that will create the output command, for e.g. alphabetic letter determination, controlling a cursor or control of a robotic arm or leg [6]. A translation algorithm must be dynamically sound to accommodate and regulate the continuous changes in the signal features and to assure that the scope of the particular signal features is conceivable from the user end, i.e. showing the accurate intent to control a particular device.

2.5.4 Output Device

The brain wave information, classification and translation provide the output command to activate an external device. Currently, the computer screens are commonly used as an output device for BMI communication. The output device is the targeted device or equipment that needs to be operated and output command can be used to move a cursor on a screen or to control and drive a wheelchair and other assistive devices for e.g. operate and control the movement of a paralyzed arm replaced by a robotic arm.

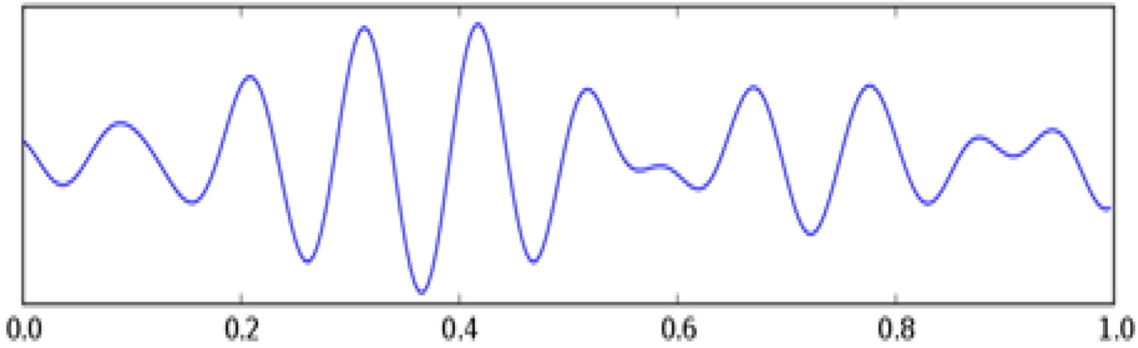
2.6 Brain Waves and Frequency Bands

Brain waves are initiated in the cerebral cortex and it also reflects the actions in diverse parts of the brain that influence the cortex, such as reticular formation (interconnected nuclei). The significant variation in the neurological activity results in change in the amplitude and frequency of brain waves between sleep, wakefulness and consciousness.

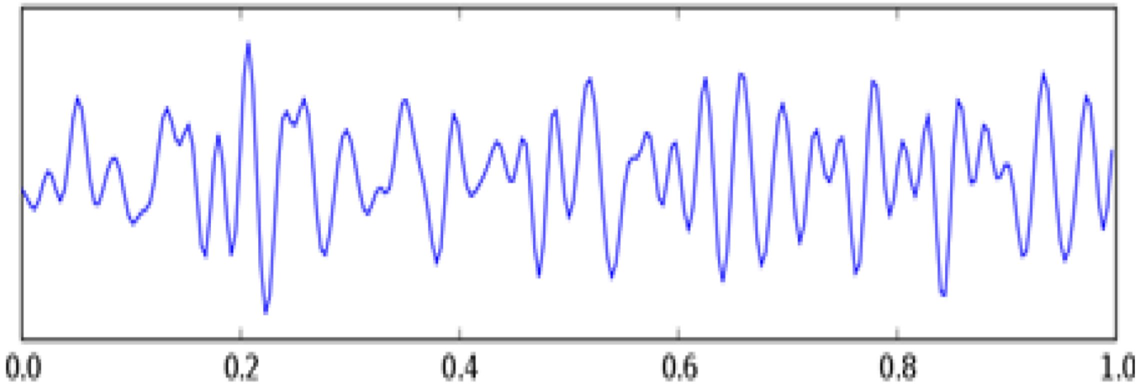
Basically, brain waves are the recordings of electrical variations in the brain during different neural states. To measure and analyze these recordings; electrodes are positioned in different ways, such as in EEG on the outer surface of the head or on the scalp, and in ECoG on the surface of an exposed cortex. The variations in the extracellular fluid of the brain are measured by the electrodes, which give the information of electrical reaction to the variations in potential amongst the large group of neurons. The following extracted signals from the brain, with the help of electrodes, are then amplified and recorded.

Brainwaves can be divided into the following five different types; as shown in the Figure 2.5 below and the description in the Table 2.1 also showing the brain wave characteristics.

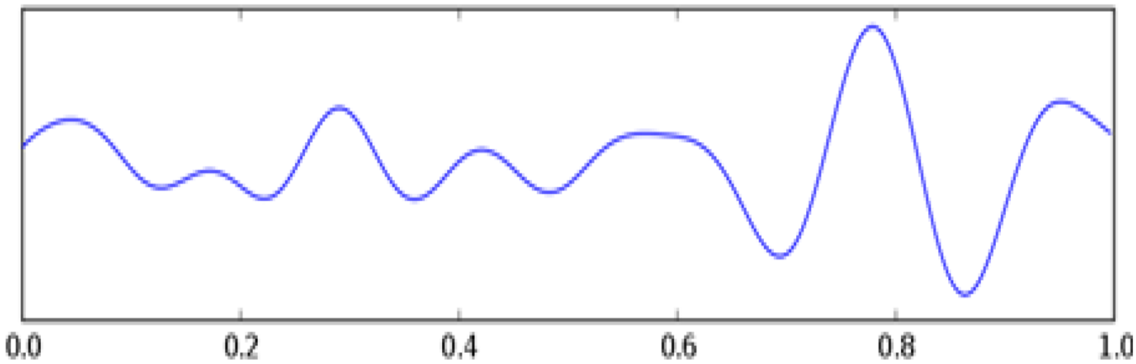
1. Alpha.
2. Beta.
3. Theta.
4. Gamma.
5. Delta.



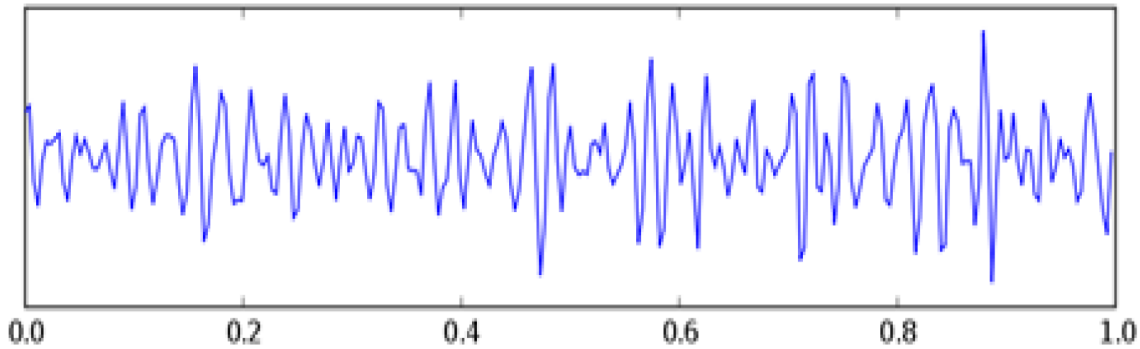
(a) Alpha (8 - 12 Hz)



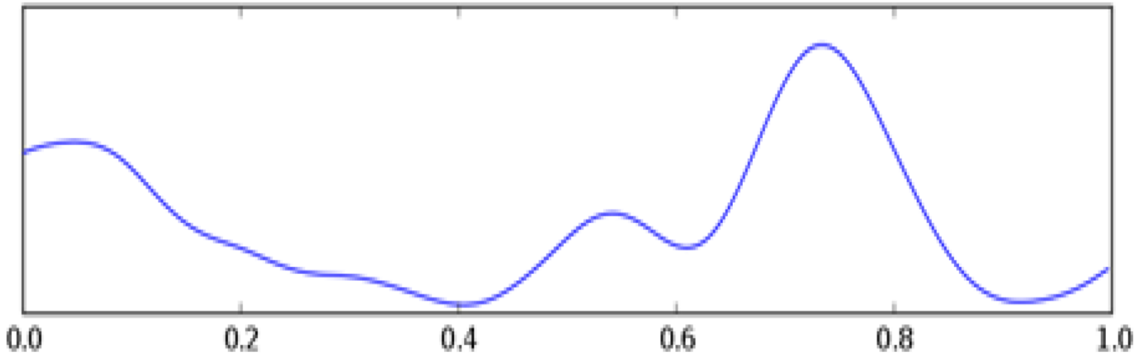
(b) Beta (12 - 30 Hz)



(c) Theta (4-7 Hz)



(d) Gamma (30-100 Hz)



(e) Delta (0-4 Hz)

Figure 2.5 *Brain wave activities [5]*

Table 2.1 *shows the frequency based human body neural communication database. [7]*

Types of Brain Waves	Frequency Ranges	Neurological States
Delta	0.1 Hz to 3 Hz	Dreamless sleep, fatigue, unconscious
Theta	4 Hz to 7 Hz	Dream, meditation, recall, fantasy, imaginary
Alpha	8 Hz to 12 Hz	Conscious, relax, tranquil
Low Beta	12 Hz to 15 Hz	Calm, relax, focus
Midrange Beta	16 Hz to 20 Hz	Attentive, focus, conscious of self and surroundings
High Beta	21 Hz to 30 Hz	Awareness, anxiety

2.7 Neural Imaging Techniques

In this section, some of the most common brain imaging techniques have been discussed that measure the different characteristics of neural activity as shown in the Figure 2.7. Some methods exploit the electrical signals of the brain and measure voltages such as EEG or magnetic field changes in Magnetoencephalography (MEG). Some of the other methods like, functional imaging methods in Near Infrared Spectroscopy (NIRS) and Functional Magnetic Resonance Imaging (FMRI) or Positron Emission Tomography (PET) measure the metabolic processes of the brain. Some of these brain imaging techniques are more complex than others due to their invasiveness for instance; in ECoG technique, electrodes are implanted on top of the cortex's gray matter.

2.7.1 Microelectrodes

Microelectrodes can be a cluster of wired electrodes, either fabricated by utilizing carbon fiber Nano-electrodes or by carbon fiber with a glass of capillary and they are arranged in the form of a dense grid. The sizes of these microelectrodes are type and material dependent. Generally its width ranges from 5 µm to 100 µm (approx.) [8]. These implanted electrode arrays can be used to study and analyze the biological changes in single cells and brain [8]. However, it involves a huge risk of tissue damage and infections. In BMI research, microelectrodes played a vital role in the development and understanding of the brain. Fortunately, these microelectrodes are restricted to animals like rats or monkeys, in which features like neural firing rates can be translated into control signals.

2.7.2 Electroencephalography (EEG)

The EEG measures the fluctuations in the cortical field potential induced by the summation of postsynaptic potentials. When the power of these field potentials exceeds a certain level, it can be recorded from the skull surface with the help of electrodes. EEG measurements can be obtained by placing electrodes on the scalp of the subject. The interference due to high impedances between electrodes can be reduced by improving the conductivity between skin and electrodes by using conductive gels, ethanol and light abrasive pastes. Basically EEG measures the voltage differences; hence for comparison, it is necessary to define a pair of electrode. Each pair of electrode is connected to a differential EEG amplifier which amplifies the voltage difference up to 100.000 times, and which is equivalent to 100 dB voltage gain. In EEG measurement from the scalp, the maximum amplitude of a non-pathologic EEG usually doesn't go beyond 100 µV [8].

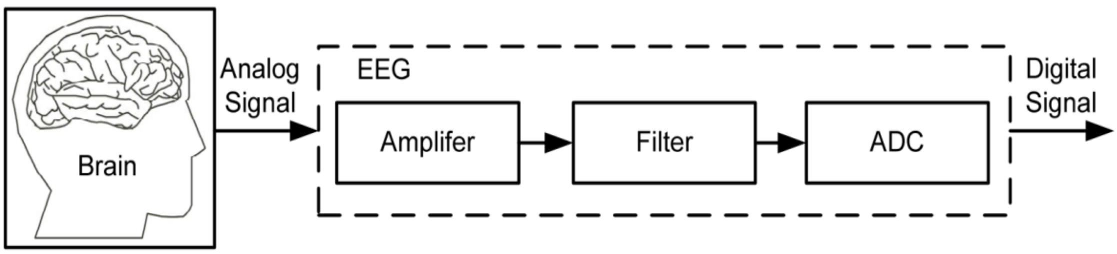


***Figure 2.6** Block Diagram Showing EEG Measurement*

2.7.3 Positron Emission Tomography (PET)

In neurology research, PET is a type of measurement that can be executed to determine the high neuronal activity regions. This technique uses a radioactive marked substance, to take an image in the metabolic processes within the human brain; called tracers. The tracer is a substance that is metabolized by the brain during activity. Typically an analogue of glucose, called Fludeoxyglucose (FDG) is used as a tracer. Neural activity in brain tissues increased the glucose uptake which can be measured by detecting pairs of gamma rays emitted by the tracer. In this type of scan, the anatomic structures of the tissue resulting in a 3 dimensional image of the brain augmented with metabolic activity can be visualized with the help of computer tomographic x-ray scans [8].

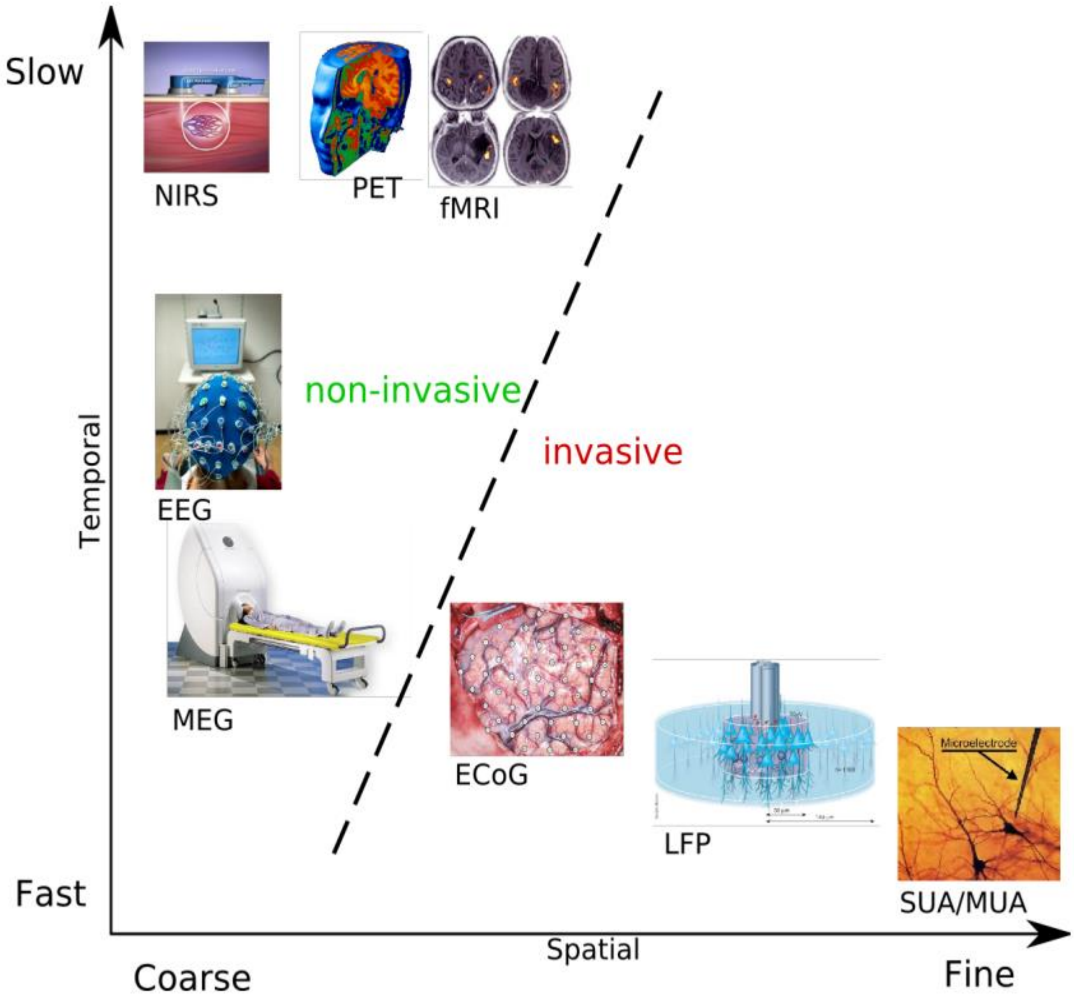


***Figure 2.7** Recording techniques ordered by their temporal and spatial resolution. Invasive techniques generally expose better spatiotemporal properties than non-invasive techniques but are more complex to apply and pose higher risks of injuries.* *[8]*

2.7.4 Functional Magnetic Resonance Imaging (FMRI)

Functional Magnetic Resonance Imaging (FMRI) is a neuroimaging technique that uses Magnetic resonance imaging (MRI) technology to record the neurological activity by measuring the reaction of the atoms in the body after applying a strong magnetic resonance pulse. The variation and fluctuation in the blood flow and in blood oxygenation in the brain are correlated to the neural activity. When a particular region of the brain is in active state, the blood flow to that region is also increased. Function Magnetic Resonance Imaging (FMRI) is able to measure metabolic changes in living brain tissues. The oxygen carrier protein in the blood, called oxygenated hemoglobin, has different magnetic properties than deoxygenated hemoglobin making it possible to make a comparison between them by using Blood Oxygenation Level Dependent (BOLD) change. The temporal resolution is really low because of hemodynamic time lag and the spatial resolution of this method is quite good. Like PET, this brain imaging technique also requires quite long scan times and picks up signal frequencies in the range of 4 to 5 Hz [5, 8].

2.7.5 Near Infrared Spectroscopy (NIRS)

Analogous to the FMRI, Near Infrared Spectroscopy (NIRS) has an operational working principle based on physical dissimilarities between oxygenated and deoxygenated hemoglobin. The differences and changes between them can be measured in a modified light absorption in the near infrared light frequency band. NIRS emits near infrared light of a specific wavelength. This light penetrates the skull and the cortex to a depth of 1-2 cm. Subject to the absorption and position of the light, blood oxygenation can be deduced from that data. NIRS has a low temporal resolution similar to FMRI [5].

2.7.6 Magnetoencephalography (MEG)

This technique is used to measure the induced magnetic fields produced by the electrical currents of neuropsychological signals. It is good for high population neural activities and it is very prone to the movements of artifacts which affect the signal. The advantage of this imaging technique is that it offers a very good and high temporal resolution; consequently, to acquire the signals from the brain, it also requires very costly and huge setup of hardware equipment [5].

2.7.7 Electrocorticogram (ECoG)

Electrocorticogram (ECoG) technique is usually used to record neural signals from the sensors, in which electrode grids are directly located subdurally. Subsequently, the signals do not have to pass the skull and skin anymore and as a result the signal quality is really enhanced as compared to the non-invasive techniques. The good spatial and temporal resolutions are achieved at the expense of its invasiveness [5]. In ECoG, opening the skull is unavoidable because the gray matter of the cortex must be accessible for the implantation of electrodes.

2.7.8 Local Field Potentials (LFP)

The Local Field Potential (LFP) is used to measure the summed electrical activity within a small cluster of neural tissues. In LFP the single neurons should have enough distance from the clustered neural tissues so that the implanted microelectrodes would be able to record the summed neural signals without any interference of single neural activity. The LFP recordings have a better spatial resolution [5].

2.7.9 Single - Multiunit Action Potentials (SUA-MUA)

In Single/Multiunit Action Potentials (SUA-MUA), microelectrodes are implanted directly into the single neuronal cells and cortex. It is used to precisely record the firing rates of single or multiple cell action potentials [5]. Currently this technique is used in animals only, because of its high health risk. The extracted signals are most perfect in terms of spatial and temporal resolution.

3. TYPES OF BMI AND WIRED VS WIRELESS BMI

In this chapter, I have discussed the different types of BMI and their invasiveness as well as the difference between the wired and wireless BMI technology. This chapter will give a brief idea of several trends in wired and wireless BMI technology, by summarizing the several research topics like portability, user friendliness and novel wireless BMI approaches.

3.1 Introduction

BMIs can be defined as any system that can monitor neural activities and translate a person's intents into a command. In Brain Machine Interface (BMI) frameworks, the neural recording devices should be successful in their capacity, as well as, to meet the clinical safety restrictions [9]. There are three basic types of BMIs invasive, non-invasive and minimally invasive. Invasive BMI is a surgical way to extract the neural information and measures the brain signals from intracranial electrodes, as we can see in Figure 3.1, the sharp needle electrodes are implanted, whereas in non-invasive BMIs, the brain signals can be extracted non-invasively by using scalp electrodes outside the body and in minimally invasive method, the spatial location for electrodes (implantation in between skin and dura brain) can be determined before surgery by using non-invasive neural imaging. In Figure 3.1, it shows an orthodox wired neural implant. It is implanted in the brain tissue, typically reaching depths of 1-2 mm [10]. It can be seen that a data acquisition IC or a buffer amplifier is placed very near to the implanted device. Finally, a wire carries the brain wave activities to a computer for storage and processing. A low SNR and high impedance signals from the electrodes are susceptible to electrostatic pickup and 60 Hz interference [10], as a result which leads to motion artifacts. A buffer amplifier or acquisition IC helps to encounter these effects. In Figure 3.1 we can see that there is an implanted μECoG electrode that acquires the data from brain in the form of brain waves. In a BMI system, it is difficult to examine the brain waves because they carry a huge amount of information. The Data can be acquired through wired or wireless systems as mentioned above and we can also see in the diagrams. The neural recordings will also need to go through a process of pre-signaling for feature extraction and translation algorithm. The data from acquisition unit can be sent through wires or wireless (ZigBee/UWB/WiFi) module, depending upon the data extraction technique that we used in a BMI system.

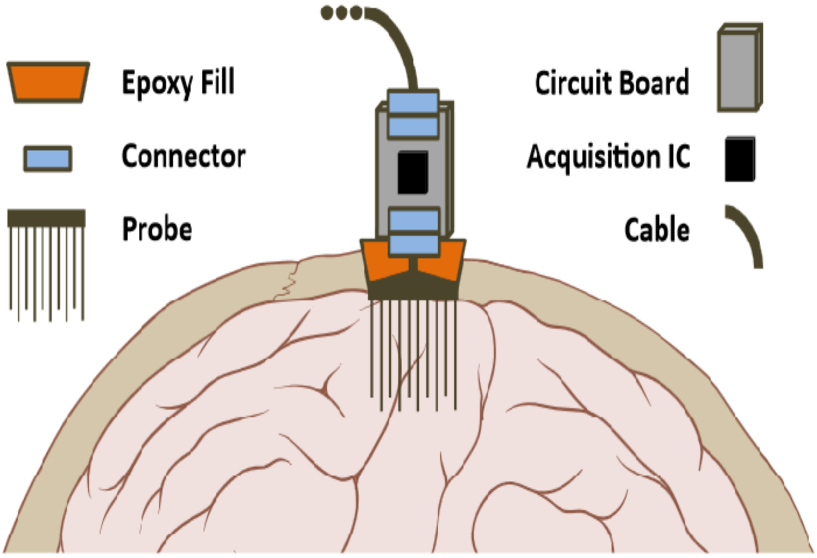


Figure 3.1 *A conventional wired neural interface [10]*

3.2 Types of BMI

3.2.1 Invasive BMI

In biomedical engineering, the technology that is related to eternal elements on the sub epidermal tissue (any tissue excluding hair and skin) is known as invasive way of data acquisition [11]. An example of invasive BMI is shown in the Figure 3.2, in which microelectrodes are implanted in to the grey matter of brain during surgery. There are microchips implanted with sharp needles, penetrating the cerebral cortex that have hundreds of pins, with less than the width of a human hair. These neural firings in the brain are than sent to signal processing unit for translation by using special algorithms to decode the raw neural language into digitized machine readable form. Invasive devices reside in the grey matter, so that we could be able to get the highest quality of signals from the BMI devices but they are prone to scar tissue build up, by damaging the signal strength weaker as the body reacts to an external object in the brain [12]. The significant features that invasive BMI could provide to users are,

1. Neural signal acquisition with high spatiotemporal resolution.
2. Extraction of appropriate neurophysiological features.
3. Data transfer with high speed and fast processing.
4. Appropriate neural signal translation.
5. Robust and well enough control of external devices such as robotic arms and electric wheelchairs to perform a certain task.
6. Implantation and integration of electronic devices by using wired or wireless technology.
7. For target surveys and to analyze the needs of patients.

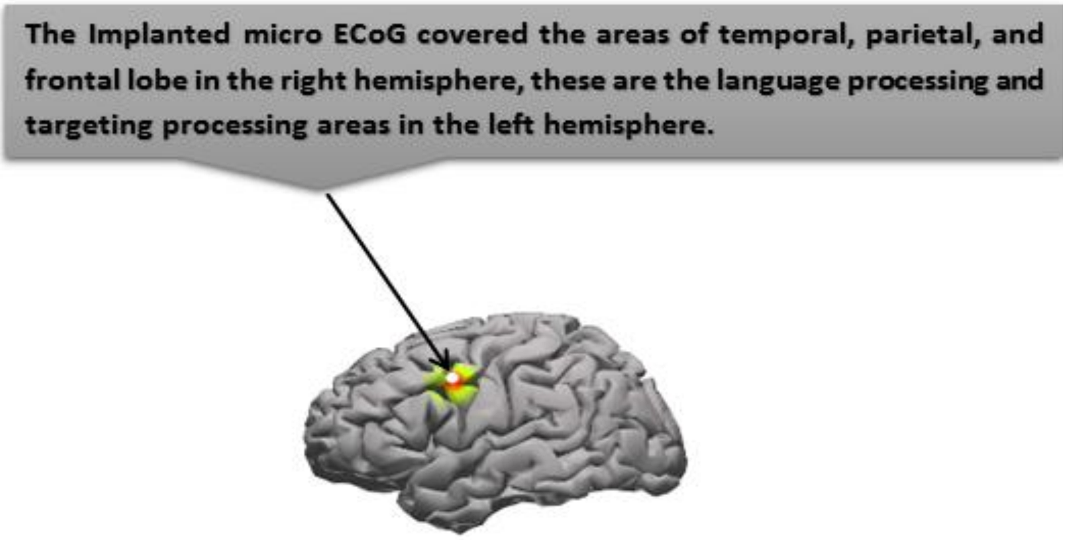


Figure 3.2 . *Example of an invasive BMI method*

3.2.2 Minimally Invasive BMI

Minimally invasive or partially invasive BMI devices are implanted in the skull but rest outside the cerebral cortex instead of implantation of electrode arrays within the grey matter. As a result they can produce improved signal resolution with high Bit Error Ratio (BER) than non-invasive BMIs where the bone tissue of the cranium refracts and distort the signals that have a minor risk of forming scar tissue in the brain as compared to fully invasive BMI.

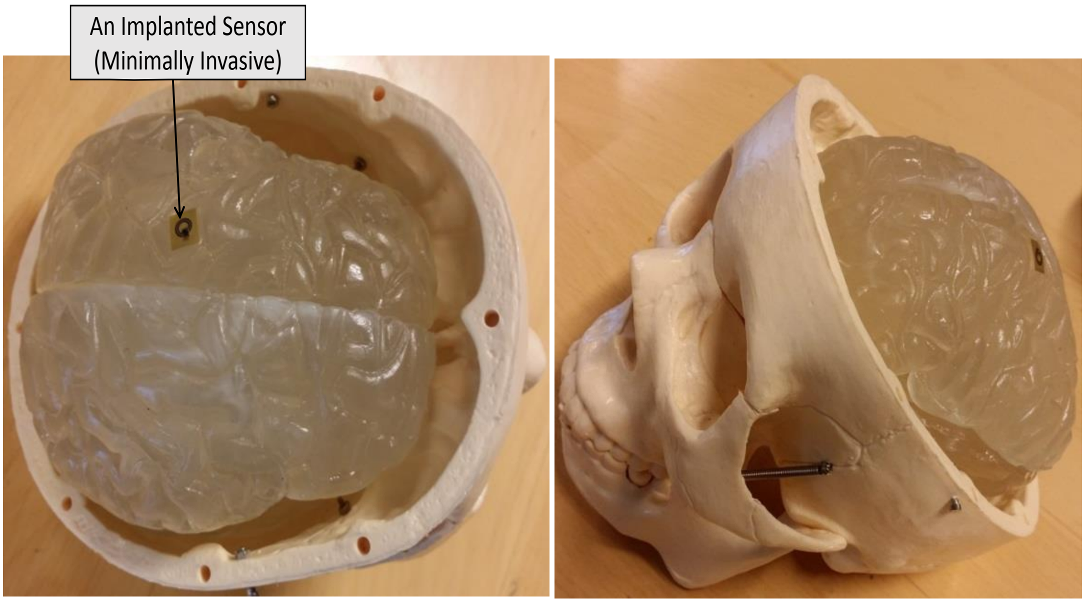


Figure 3.3 *Example of a minimally invasive BMI*

In Figure 3.3, there is an example of minimally invasive BMI in which an implanted Electrocorticography (ECoG) measures the neural activity of the brain waves taken from underneath the skull in a quite similar fashion to noninvasive electroencephalography, but the electrodes are inserted in a thin plastic pad that is placed above the cortex, under the dura. Partially invasive ECoG is a very likely intermediate BMI technique to get the brain signals because it has quite good SNR, better spatial resolution, wide frequency range, and requires less training in contrast to scalp recorded EEG. At the same time, minimal invasiveness also has some other advantages like, less technical complications as compared to EEG, low clinical risk, and perhaps, in contrast to intra-cortical single neuron recording, it has long term stability [12].

3.2.3 Non Invasive BMI

The easiest and most comfortable neural data extraction method is a noninvasive method, as seen in Figure 3.4, the brain waves can be extracted from the head mountable devices attached to the scalp. The EEG is a noninvasive neural signal extraction technique in which, the recordings of electrical neural activity along the scalp by measuring the fired neurons produced within the brain. These electrodes array measures the voltage difference between neurons to distinguish between different brain wave signals. These raw signals are then amplified and filtered [12]. The EEG electrodes have a spatial resolution with a range of 3 cm, with a frequency range of 0 to 50 Hz. Early work in this field [13], observed modality for extracting neurological information to control a communication device, such as to control a cursor on a computer screen to select different letters for communication.

Although some brain wave signals are blocked by skull and these neural information carrying signals are more vulnerable to the electrical noise and artifact. In non-invasive BMI the distorted and weak brain signals are more accepted than the other types of BMIs because of their respective disadvantages.

To design and develop a new BMI system, there are some EEG signal properties that use to distinguish between the different neural functions and that can be used to control and communication mechanisms. EEG basically needs to have a significant level of knowledge to perfectly characterize and classify the neurological signals.

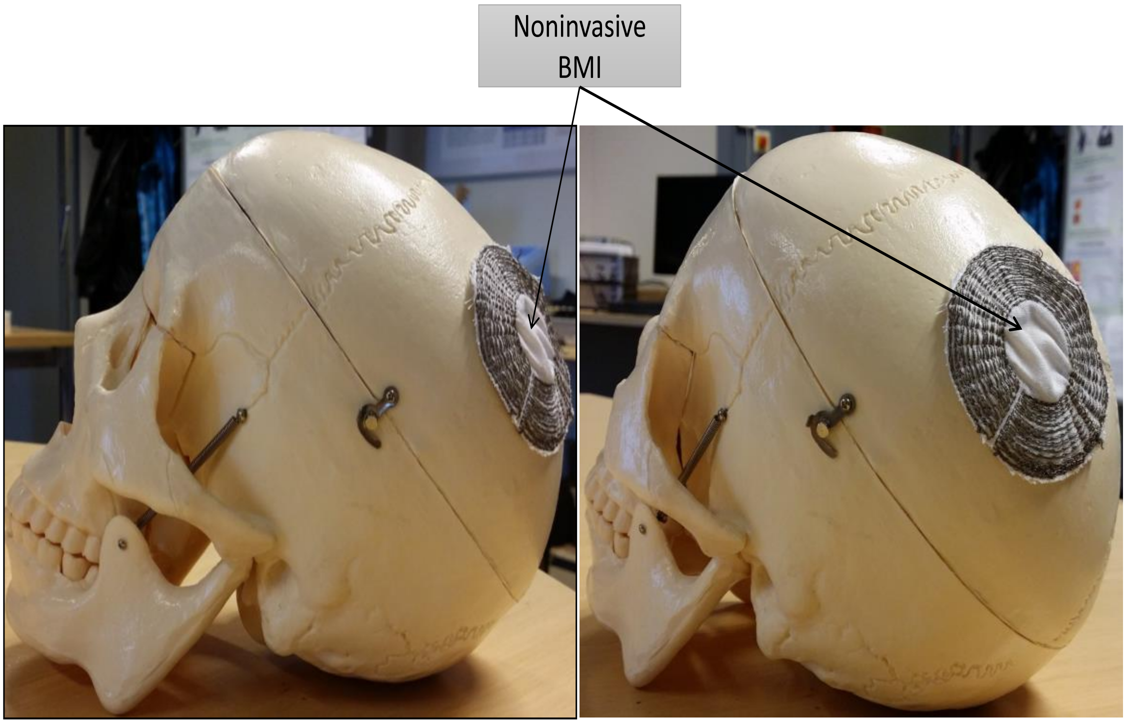


Figure 3.4 *Example of noninvasive neural signals extraction*

3.2.4 Difference between Invasive, Non-invasive and Minimal Invasive BMI’s

Although the signals in EEG, ECoG and µECoG stem for the same activity in the brain, there are many differences between them, some are shown in the below Figure 3.5 and Table 3. 1 are as follows

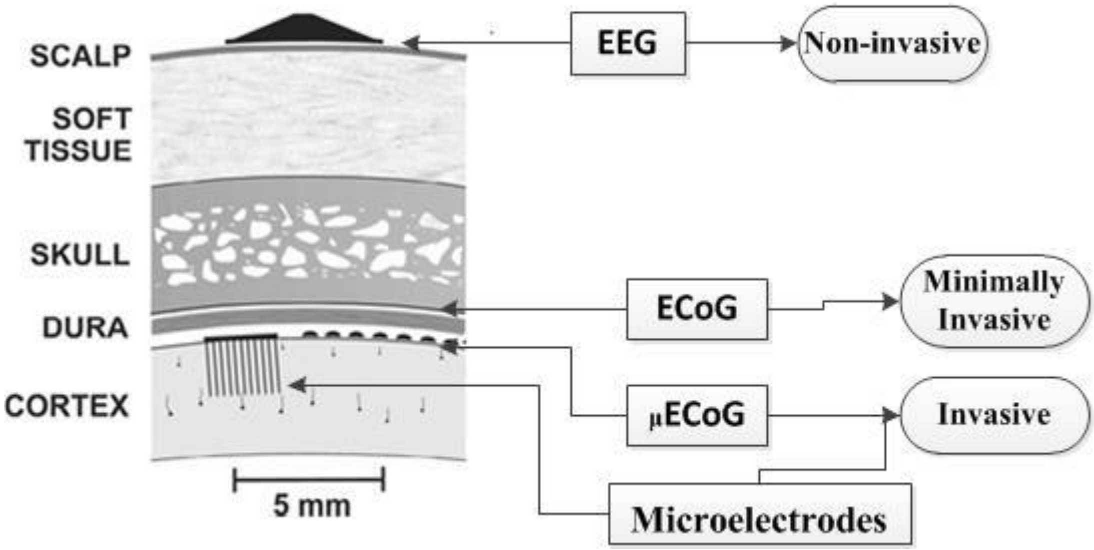


Figure 3.5 *BMI electrophysiological view according to signal extraction technique*

***Table 3. 1** Difference between Invasive, Noninvasive and Minimally Invasive BMI [13, 14, 15, 16, 17, 18]*

Features	**Invasive**	**Non-invasive**	**Minimally Invasive**
Techniques for neural Signal extraction	ECoG, μECoG and Multiunit Electrode Array, Local Field Potentials (LFP), Single/Multi-Unit Action Potentials (SUA-MUA)	EEG, Magneto encephalograms (MEG), Blood-oxygen-level-dependent (BOLD) signals, and (de) ox hemoglobin concentrations, NIRS (which deposit near infrared light on the tissue), FMRI (which applies magnetic fields) and PET	ECoG
Location of Electrodes	Subdural, Epidural, or Intracortical Electrocorticogram, ECoG	Outside the brain. on the scalp	Implant into the skull but outside the brain instead of within the grey matter
Tissue Damage	More Damage	No Damage	Minor damage
Signal Quality	High Spatial resolution Signal	Very Low Spatial and spatial Resolution Signal	Low Spatial and temporal Resolution Signal
BMI Applications	Repairing damaged sight and providing facility to Paralyzed people	For Clinical applications of BMI to decrease the risk of infection.	Can help the people with motor disabilities.
SNR	High SNR	Very Low SNR	Low SNR
Spatial Resolution	ECoG (2-3mm), NIRS (2cm), FMRI (3-5mm)	EEG (3-4cm), MEG (5-10 mm)	ECoG (2-3mm)
Temporal Resolution	ECoG (0.1ms), NIRS (4-5s), FMRI (4-5s)	EEG (1ms), MEG (0.1ms)	ECoG (0.1ms)
Time delay	ECoG (0), NIRS (4-5s), FMRI (4-5s)	EEG (0), MEG (0)	ECoG (0),
Wireless Protocol	Depending on the implanted electrode arrays	Bluetooth, ZigBee, UWB, Wi-Fi	Bluetooth, ZigBee, UWB
Sampling Frequency	μECoG and ECoG (1000-2000Hz)	EEG (250-1000Hz)	ECoG (1000-2000Hz)
Amplitude	From 1 to 500μV	From 1 to 50μV	From 50 to 100μV
Spacing	0.2-10mm	3cm	0.2-10mm
Bandwidth	From 1 to 500 Hz	From 0 to 60 Hz	From 0 to 200 Hz
Activity Measured	Electrical	Electrical, Hemodynamic, Magnetic fields associated with electrical activity	Electrical

3.3 Specific Absorption Rate (SAR)

Currently, the neurological control of a robotic limb for disabled patients has been verified in clinical trials with systems where the wired array of electrode to an external body unit through a pedestal secured to the skull. The wired connection severely restrict the quality of life of patients that they need, as well as, there is also a risk of infection [8]. This emphasizes the crucial need of wireless BMI system by taking to account the healthcare advantages and challenges. Recent research on wireless BMI is concentrating on communication by means of back scattering power to avoid useless power consumption in active transmitters in the brain implant. Previous research shows that the miniaturized millimeter size loop antenna was implanted on top of the brain beneath the skull and the optimum frequency for the transfer of wireless power, it lies somewhere in between 100 to 400 MHz. In all wireless systems, it is important to make sure that they follow some standard and regulation like US FCC regulation; it states that SAR level should be around over a volume containing 1 grams of tissue must be at or below 1.6 W/kg. The wireless power transmit antenna should also be able to transfer high power level without breaching the Specific Absorption Rate (SAR) limitation in the human body [9].

Specific Absorption Rate (SAR) determines how much power a volume of tissue absorbs, for whole human body heat pressure and extreme restricted tissue heating for frequencies between 3 KHz and 300 GHz. We are also following the above mentioned US-FCC, SAR regulation, for the proposed system, that will be explained in next chapter. SAR is defined as the Joule heating per volume mass induced by an electromagnet field, Equation 3.1.

$$SAR = (\sigma \times E_{rms}^{2}) / \rho \qquad (3.1)$$

where as,
SAR = Specific Absorption Rate
σ = Conductivity of various human tissues (S/m)
E_{rms} = RMS of electric intensity of the body
ρ = Biological density of human tissue (kg/m^3)

According to IEEE standards, the 1 g limit is for whole human body except the wrists, feet, ankles and hands, which should not exceed to 10 g SAR of 20 W/kg, it’s the similar value that International Commission on Non-Ionizing Radiation Protection (ICNIRP) has for limbs [9, 20].

Moreover, the heating of tissue can also results from power dissipation of the implanted microelectronic device. A power density of a 500 $\mu W/mm^2$ results in a 1° C increase in surrounding tissue [19]. For that reason, we should take care to take account of the effects from both electronic power dissipation and SAR in the calculation of temperature change in body tissue.

3.4 Implant Requirements

Here are the some implant requirements, for the use of wireless communication inside the human body. In order to find out the particular requirements for the implant devices, it will be used to decide, that how and which kind of wireless communication approaches are appropriate. The important requirement includes the size of implant, energy restrictions, frequency range and its side effects, and the absorption of waves in human body. Here are the some tables listed below with comparison and considering these main requirement issues.

Table 3.2 *Maximum allowed Specific Absorption Rates (SAR) [17]*

Frequency	Whole Body Average (W/kg)	Localized Head/Torso average over 1 g (1cm^3) tissue (W/kg)	Localized limbs average over 10 g (10 cm^3) tissue (W/kg)
100 kHz to 10 GHz	0.08	1.6	4

Table 3.3 *Maximum allowed Electric Field Strength [17]*

Frequency	Strength Electric Field: (V/m) (rms)
3 kHz to 1 MHz	280
1 to 10 MHz	280/f
10 to 300 MHz	28
300 MHz to 1.5 GHz	$1.585f^{0.5}$
1.5 to 10 GHz	61.4

Table 3.4 *Maximum allowed Power Density [17]*

Frequency	Power density, S (W/m²)
30 to 400 MHz	2
400 MHz to 2 GHz	f/200
2 to 10 GHz	10

Table 3.5 *Maximum allowed Magnetic Field Strength [17]*

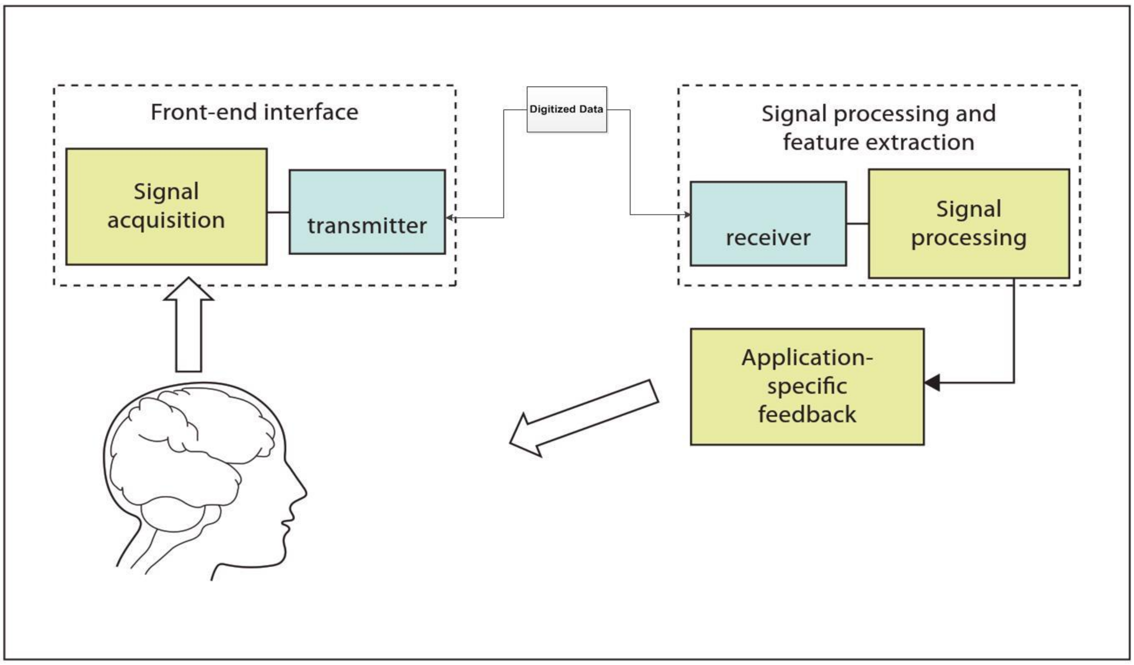
Frequency	Strength of Magnetic Field: (A/m) (rms)
3 kHz to 1 MHz	2.19

1 to 30 MHz	2.19/f
30 to 300 MHz	0.073
300 MHz to 1.5 GHz	$0.0042f^{0.5}$
1.5 to 10 GHz	0,163

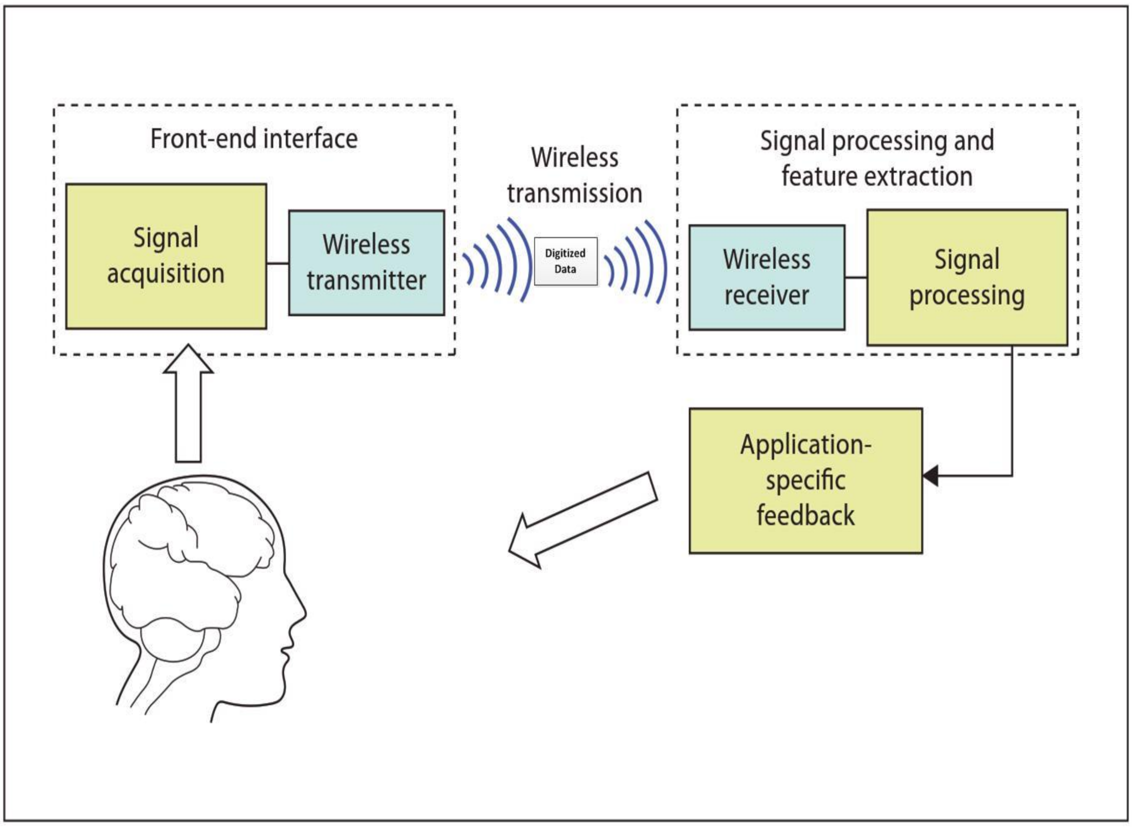
3.5 Wired and Wireless BMI

BMI systems can be divided in to two types according to their connection between sub units, shown in the Figure 3.6, the wired and wireless BMI systems.

Many conventional BMI systems are wired, starting from the input power to the head wearable device and the acquisition units of wired BMI system normally have a heavy and bulky amplification and data processing units. The wired connection between electrode arrays and data acquisition unit is usually complicated because of considerable number of cables, it makes the system very bulky. Due to all these limitations, the preparation time for processing and measuring neural activity through EEG method is typically very long and time consuming. As a result, the patient's usage of this BMI device is limited due to wired connection restrictions. The implementation of such kind of system for rehabilitation of patients has made it difficult to have a practical usage rather than just laboratory scale experimentation. The main objective and need of a wireless BMI system is to restrict the use of cables between input power source and electrodes, between the signal acquisition unit and the signal processing units and finally between signal processing and main processing module, by using modern wireless communication units and protocols, to enhance the portability of BMI system. As a result, the wireless transfer of neural information till the end user provides a room that this system can be implemented for new applications as well as for medical purposes [1, 5]



(a) Wired BMI Data Acquisition



(b) Wireless BMI Data Acquisition

Figure 3.6 *Wired vs wireless data acquisition [21]*

Comparison Criteria between Wired and Wireless BMI

1. BMI system can be compared by using such possible combinations of characteristics.
2. Method of measuring the activity.
3. Measured activity or Potentials.
4. Data Resolution.
5. Degree of freedom (user specific Implementation).
6. Average or single trial.
7. Types of signal preprocessing.
8. Method of feature extraction and Translation or Classification.
9. Type of Wireless Protocol (Data rate or Electrode arrays dependent).
10. Type of application.
11. Input Power.

3.5.1 Advantages of Wireless over Wired BMI

Here are the some benefits of Wireless BMI over wired BMI system:

1. A wireless BMI system can effectively decreases the initial connection complications such as bulkiness, wires and equipment management related to the traditional wired BMI systems.

2. A wireless BMI system would be able to offer users with more autonomy in the movement of their robotic hands or legs etc. Thus they also can complete their work with more freedom in a more convenient way.

3. A BMI system built with a circuitry of low power, training circuits and miniaturized signal acquisition, so that the BMI system can be combined with any light weight wear-able device like a headband, baseball cap or to wear sunglasses to take full advantage of wear-ability and portability.

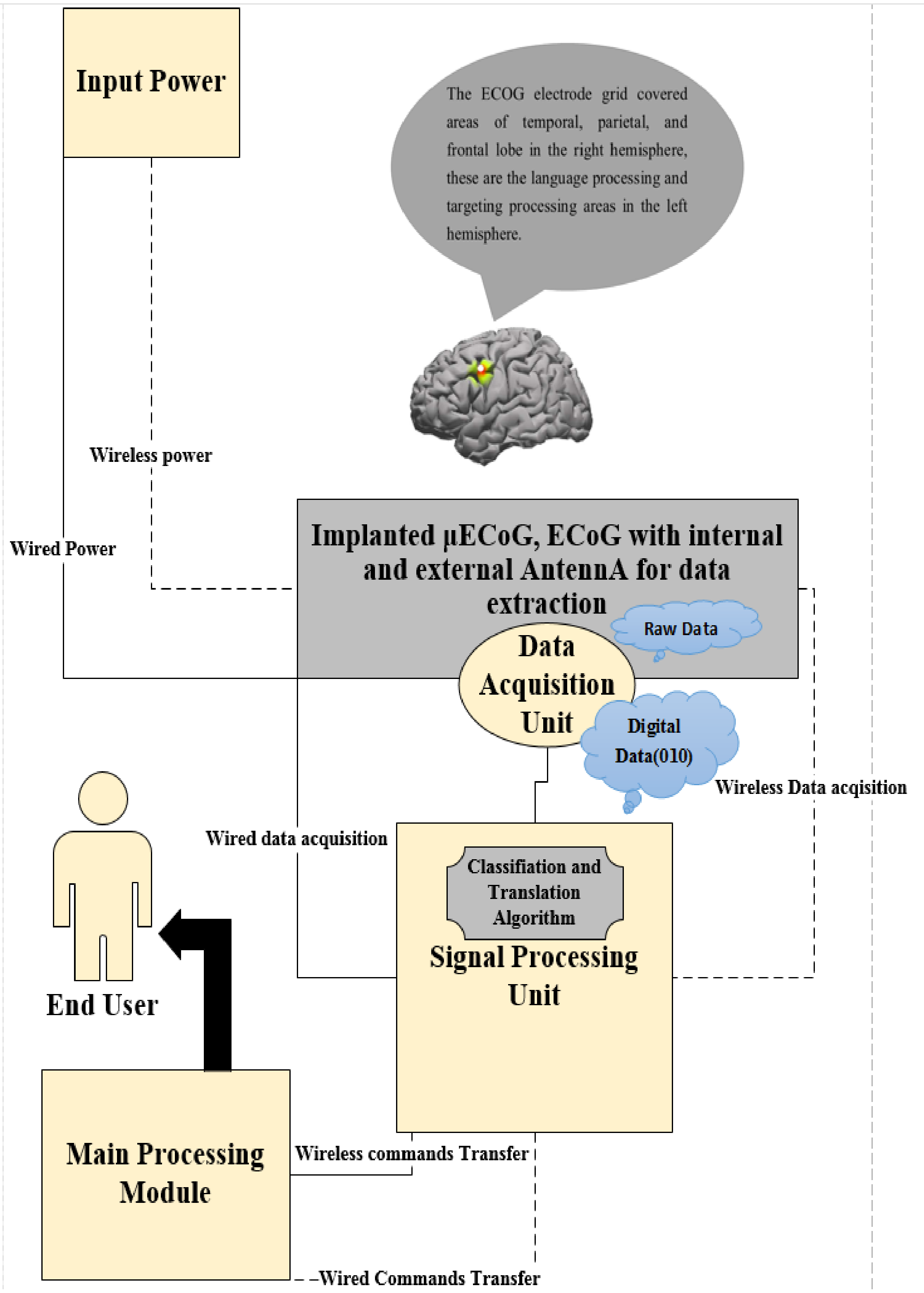


Figure 3.7 *Wired vs Wireless connected BMI Modules*

3.5.2 Issues in a wireless BMI system need to improve

Although, wireless BMI systems provides some great advantages, but still there are numerous problems that need to be determined and fixed like, more compact and improved system design by considering the under mentioned points.

1. Implant-ability restrictions
2. Excavation of more suitable applications for users
3. Enhance the signal quality by improving data acquisition technique.

Researchers are trying to develop and introduce different applications related to medical and health care but such contributions are still needed to become more mature [1].

4. PROPOSED BMI SYSTEM

This chapter describes a complete wireless BMI system, consisting of hardware working with a wireless power unit, signal processing and translation unit with classification of that BMI system till the end user command by considering all possible challenges and advantages.

4.1 Introduction

In the recent years many researchers have focused on a BMI system with wireless power transmission, portability, fast data acquisition and implant-ability. In a wireless power transmission system, the rectenna system consists of two main modules called the rectifier and the antenna. By keeping in mind the end goal to understand the vision of completely independent BMI frameworks, the neural implantable devices should be successful in their capacity, as well as, to meet the clinical safety restrictions [22, 23]. As seen in Figure 4.1, µECoG is an invasive intra cortical neural recording method through implanted microelectrode arrays. In the EEG, electrodes are located outside the skull on the surface of the cortex. In a BMI system, it is complex to analyze the brain waves because it carries a large amount of information. Data acquisition unit can receive this particular information through wired or wireless system. The EEG has a sampling frequency of 250 Hz to 1000 Hz and the ECOG data is collected with a sampling frequency of 1000 Hz to 2000 Hz [24]. A higher digitization rate of 1000 Hz or more would also be able to provide a really good time based resolution to study the brain activity [24]. The neural recordings will also need to go through a process of pre-signaling for feature extraction and translation algorithm. Brain signal pre-processing can be done by using three methods. These methods are Basic Filtering, Adaptive Filtering and Blind Source Separation [25, 26]. The data from acquisition unit can be transferred through a wireless ZigBee/UWB/WiFi module, depending upon the number of electrode arrays used in BMI system.

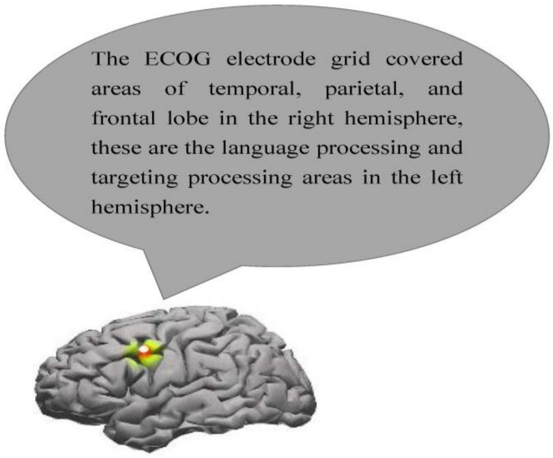


Figure 4.1 *Implanted Electrode Array in Brain [22]*

In my proposed BMI system level concept, there is complete description of a Wireless BMI end-to-end system, from the hardware working with a wireless power unit, data processing and characterization of a BMI system till the end user command.

4.2 Architecture of BMI system

Here are the basic modules in the Architecture of a BMI system.

4.2.1 Wireless Input Power Unit

In last few years, researchers have tried to develop a miniaturized head mountable or invasive BMI device [27]. The main issue they faced is to transmit the required input power to bring the implanted or head mountable device in an active state. It is the limiting factor in practical implementation, by taking this restriction in mind; many researchers have tried to develop methods to extract energy from external resources. It includes, light, pressure, thermal, motion, momentum and vibration [27].

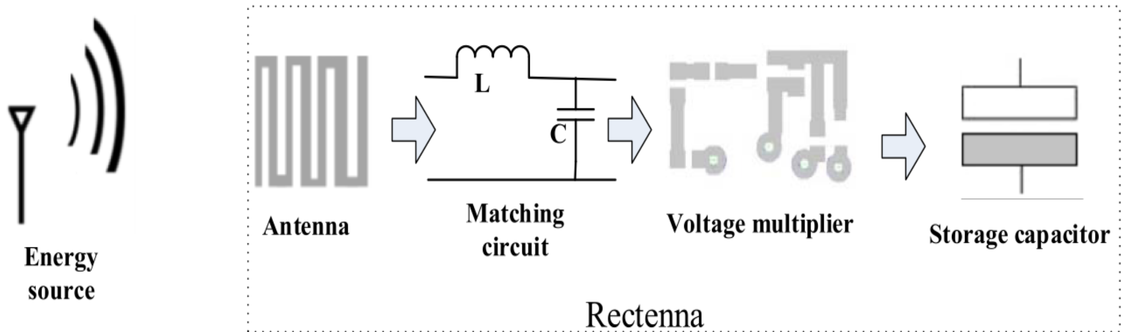


Figure 4.2 *EM energy harvesting system [27]*

Figure 4.2 shows an EM energy harvesting system through which RF energy can be harvested for wireless transmission. As we can see that on the reception side of energy harvesting system, an antenna captured the RF waves that are the significant portion of the rectenna system. The Alternating Current (AC) is produced on the output terminal with the help of receiving antenna and afterword the rectifier transforms the AC to DC power. Now it is possible to save this converted DC in a super capacitor, or we can use it directly to supply power to the load.

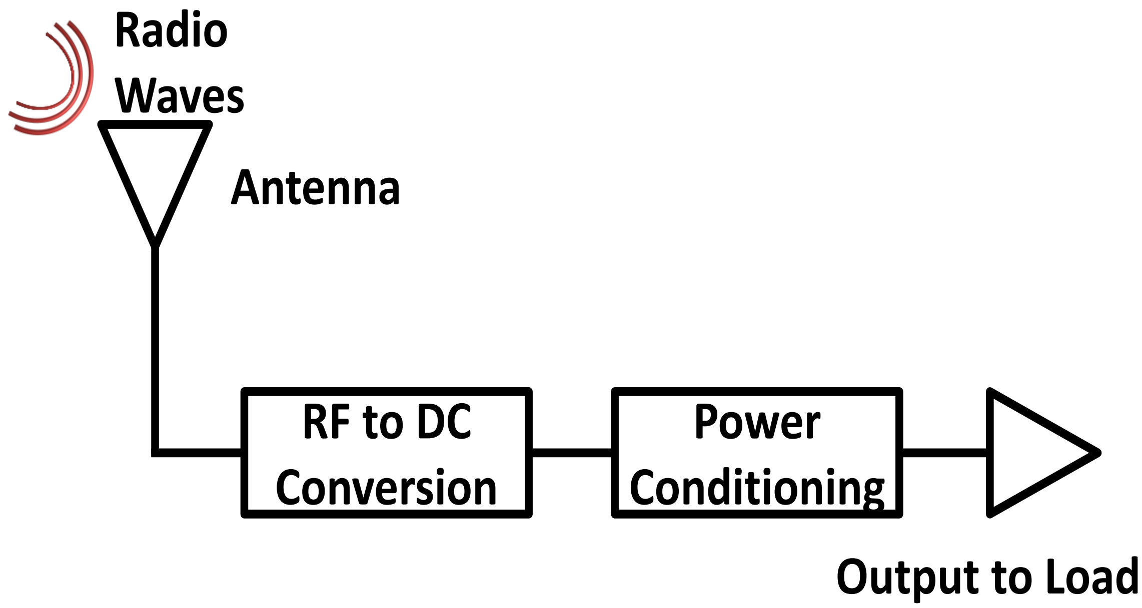


Figure 4.3 *Wireless rectenna system block diagram.*

There are also some other ways to transmit power to implanted BMI devices like bio fuel and cell phone battery [28]. As seen in Figure 4.3, the suggested way to transmit power wirelessly to a multi-channel electrode array [29] follows the design of reference [27]. The Rectenna transmit power via microwave source to operate a passive head mountable or implanted device at a resonance frequency of 915 MHz with a simulated bandwidth of 18 MHz (907-925 MHz) [27]. The proposed power supply rectenna array has a peak transformation efficiency of 75.6 %, and the systems overall efficiency is 33 % [27].

4.2.2 Implantable μECoG and Data Acquisition

1. **Implantable microsystem**

   As shown in the Figure 4.4, the ECoG are also the intracranial EEG in which placed electrodes usually perform the recording directly from the brain surface. Here we are suggesting a low invasive μECoG wireless device for 4096 channels with multiple connections of electrode arrays with Large Scale Integrated Circuits (LSI) (64Ch*16units) with Time Division Multiplexing (TDM) of the recorded data [29]. The multiple connections of arrays can be chronically implanted and powered well without violating the SAR < 1.6 W/kg limit under the U.S. FCC regulation [29, 30]. The ECoG systems efficiency depends upon the inductive coupling of the internal and external antennas, the miniaturized size of the antenna, the maximum allowed input power to external antenna under SAR limits [22].

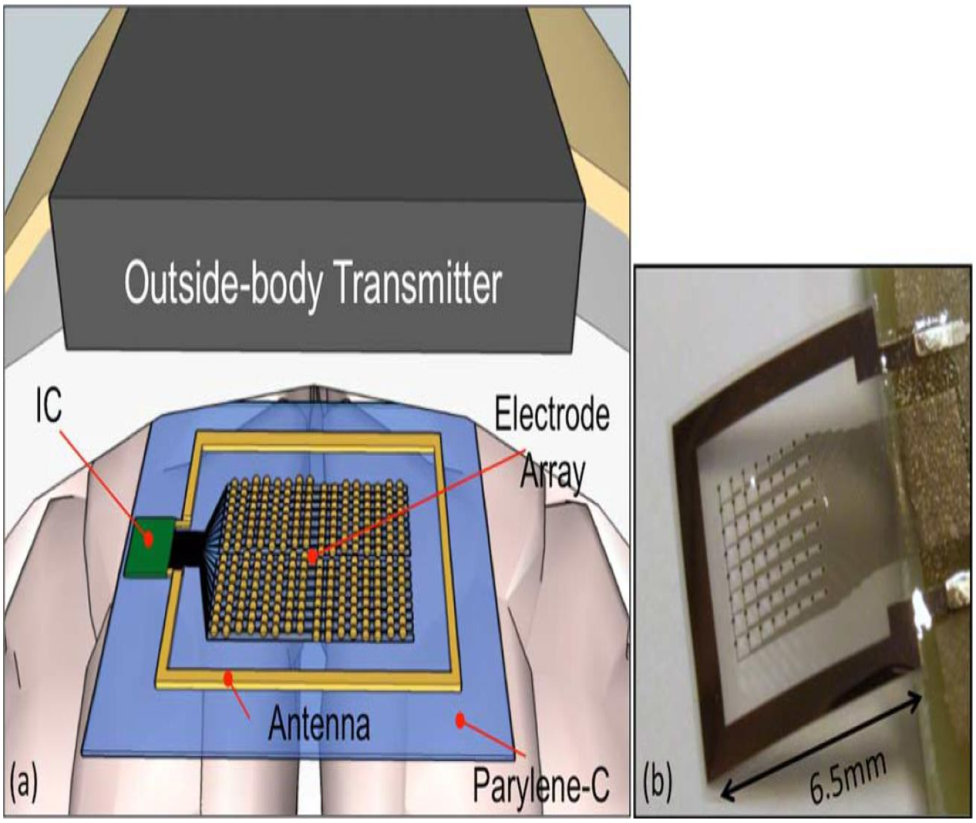
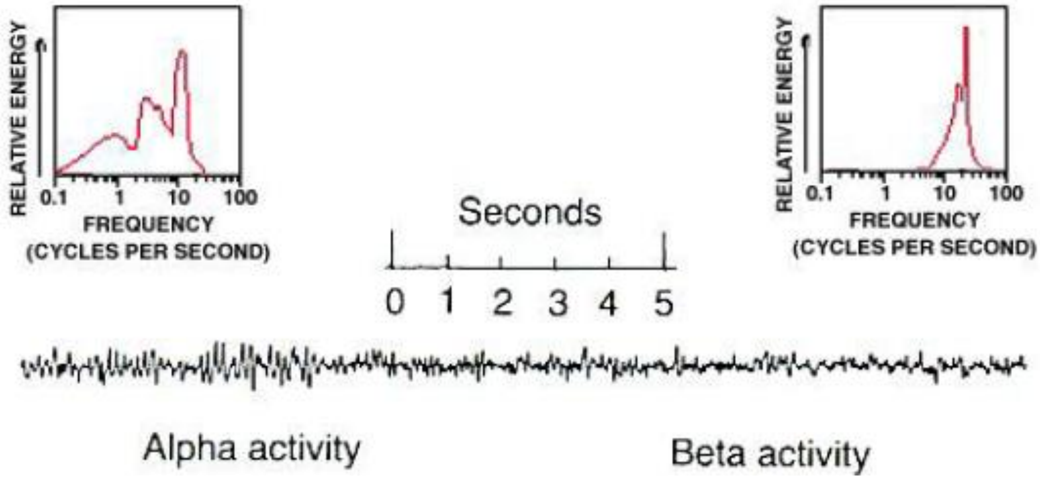


Figure 4.4 *µECoG system concept and micro-fabricated components [22]*

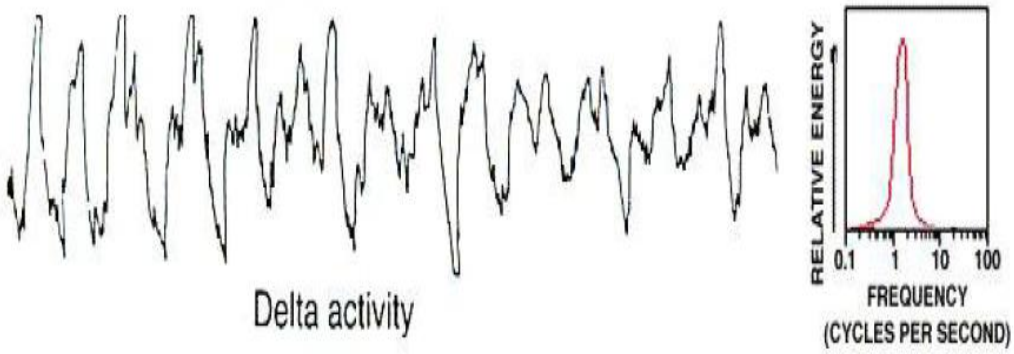
2. Signal Processing & Brain Waves

In BMI signal processing, the brain wave signals analysis is very complex because it carries large amount of data received from electrodes. Based on their emanations the brain waves are categorized into the following types, Alpha-Beta activity, Theta, Delta activities as shown in the Figure 4.5 [31].

The block diagram in Figure 4.6 is showing the signals acquisition and signal processing units, where signals are amplified and then sampled [32]. Signal processing has two main parts feature extraction and translation algorithms. Support vector machine (SVM) [23, 33] or Fishers discriminant algorithm [34] can be used to distinguish between different mental tasks like amplitude of an evoked potential, firing rate of a cortical neuron etc. The featured signals are translated by algorithms like common spatial algorithm to change it into control signals for certain user application. The information is then transmitted wirelessly to a PC over wireless link. Econnectome is free available software in market and can be used to analyze the brain activities through brain imaging and mapping the electrophysiological signals including ECoG and EEG [26, 35].



(a)



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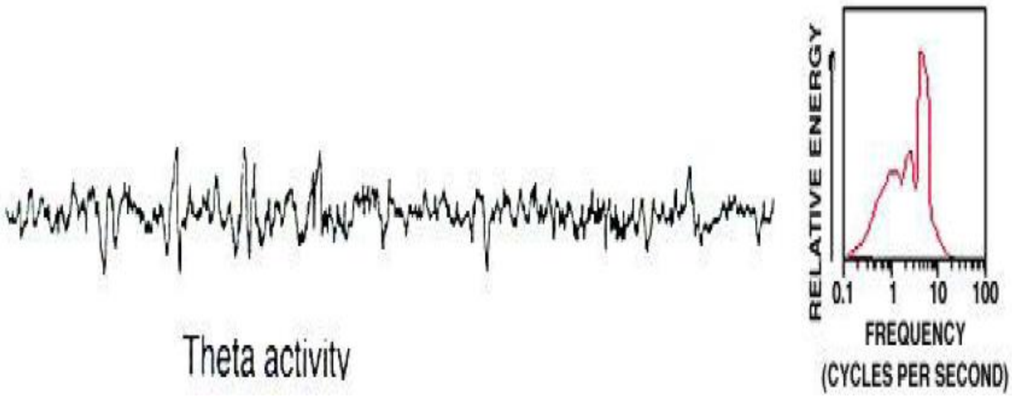

(c)

Figure 4.5 *Showing Brain wave activities [26]*

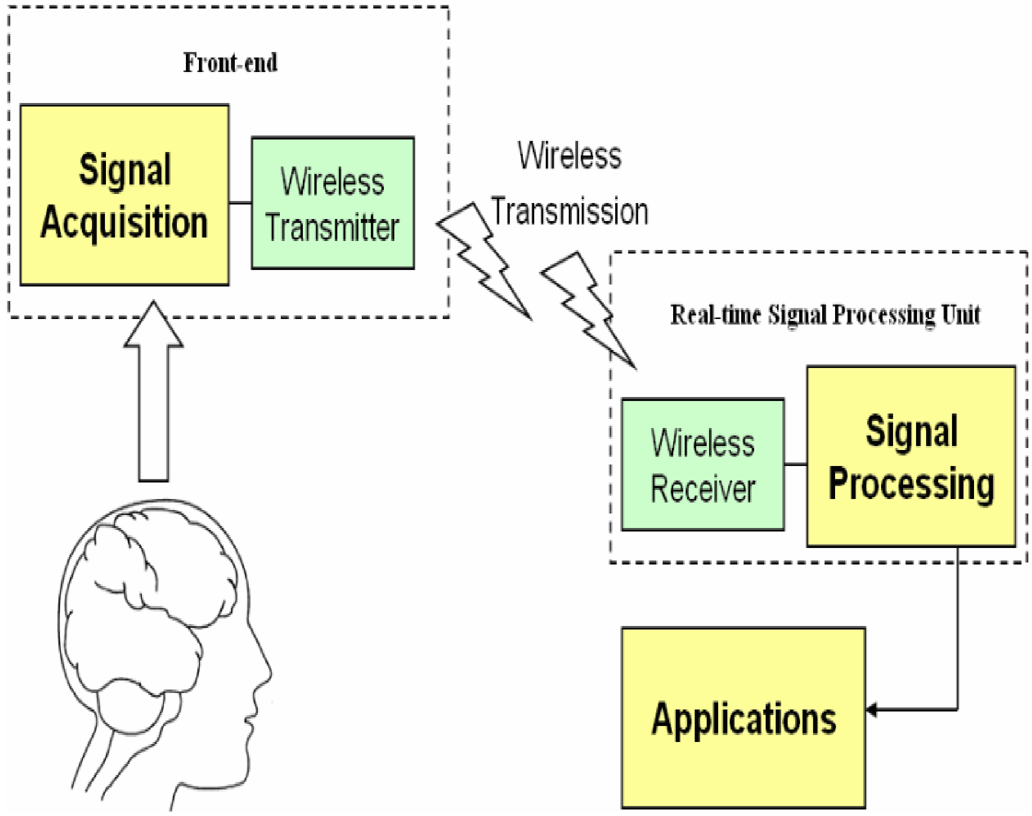

Figure 4.6 *Brain Signal Acquisition [43].*

4.3 Transmission Protocols/Medium

A Wireless Body Area Network (WBAN) is a specially designed wireless sensor network to operate autonomously and to connect medical sensors and devices with implants or outside the human body that provides a long term health monitoring system within a hospital or remotely [36]. Around 5000 to 10000 neurons communication are necessary for BMI to move a human muscle and 100000 neurons required to move a complete human body [37]. In this thesis, an integrated system is proposed to help patients by sending their commands after signal processing for a rapid intrusion and to perform a particular task by the targeted muscle or any body part [38]. The system is based on collecting the µECoG signals through a small portable device with external antenna in the data acquisition unit. After acquiring the data, it is transferred for signal processing to identify the feature extraction. These extracted features are further transmitted in the form of commands by translation algorithms to the Zigbee/UWB/WiFi transceiver module [39] [40].

Table 4.1 *Comparison between wireless protocols*

Standards	**Zigbee**	**UWB**	**Wifi**
Frequency Band	868, 915MHz, 2.4 GHz	3.1 to 10.6 GHz	2.4 GHz, 5 GHz
Max Data Rate	250 kbps	110 Mbps	54 Mbps
Nominal Protocol Range	10-100 m	10 m	100 m
Channels Band-width	0.3/0.6 MHz to 2 MHz	500 MHz to 7.5 GHz	22 MHz
Radio Frequency Channels	1/10 - 16	1-15	14 at 2.4 GHz
Protocol Network Topology	All	Star	Medium de-pendent
Data Protection Techniques	16 bit CRC	32 bit CRC	32 bit CRC
Power consump-tion	Very Low	Low	High
Battery Life	Rechargeable(hours)	Rechargeable (hours)	NA

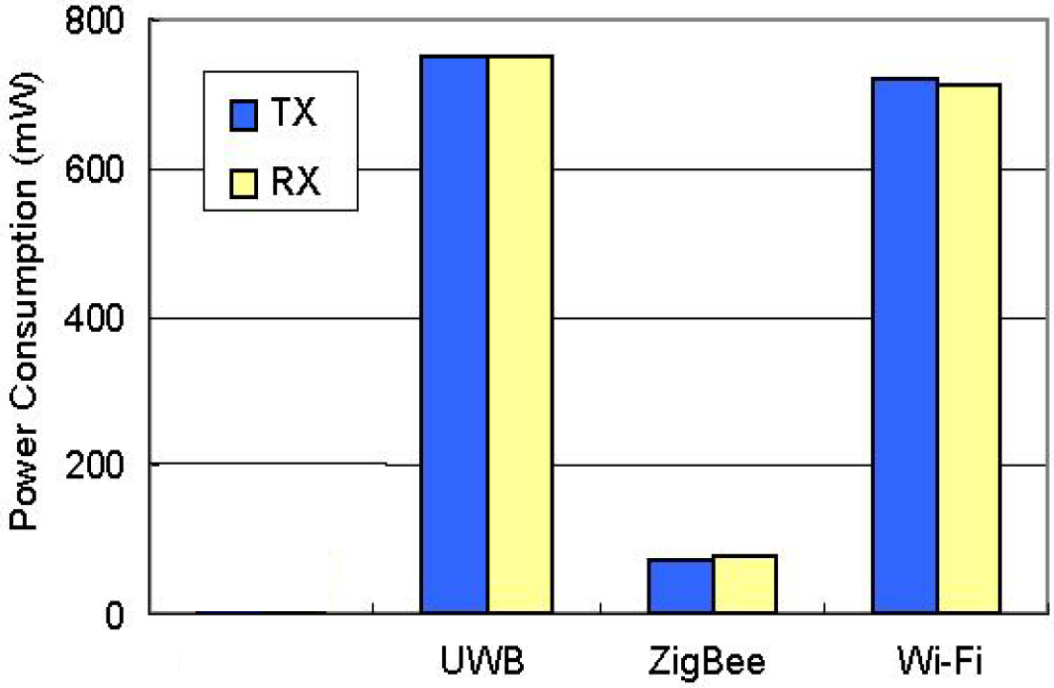

Figure 4.7 *Comparison of the power consumption for each protocol.*

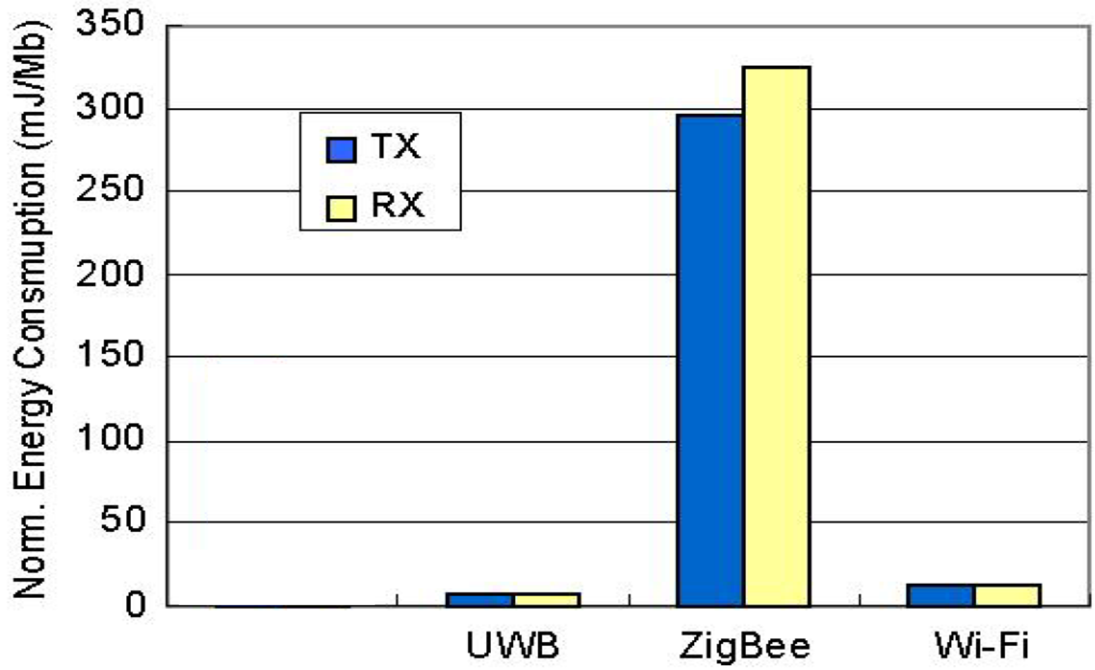

Figure 4.8 *Comparison of the normalized energy consumption for each protocol.*

In Table 4.1 and Figure 4.8 [41, 42] comparison we can see that ZigBee is very suitable for low data rate applications with limited power consumption like wireless remote devices or battery operated sensor networks. Contrary for high data rates WiFi and UWB could be a better solution just because of their low normalized power consumption.

4.4 Block diagram of proposed BMI system

Figure 4.9 shows the proposed end-to-end wireless BMI system architecture that provides a convenient way of communication between the human brain and physical devices by translating different patterns of brain activity into commands in real time scenario.

For the implementation of this whole structure, we consider a wireless input power with implanted μECoG. Data acquisition unit that transfer signals for signal processing of brain signals can be mapped into intentions to perform a particular action. After processing of brain signals, the data is transferred wirelessly with the help of Zigbee/UWB/WiFi hardware implementation. Table 4.2 shows the specifications of BMI multi-channel array electrodes.

Explanation of the diagram is given in the points:

1 EM (Wireless) input transmission power through rectenna system at a distance of 20 cm from an EM source we can transmit at least 26.77dBm (475.33mW) depending on number of electrodes.

2. Implanted μECoG system with frequency range 0.1 Hz to 500 Hz with amplitudes ranging from 1μV to 1mV connected with internal antenna.

3. External antenna for wirelessly transfer of acquired raw data with the help of Zigbee (250 Kbps), UWB (70-110 Mbps), Wifi (54 Mbps). We can transfer at least 400 kbps 128 channel ECoG data for data classification and translation.

4. Signal Processing module for feature extraction and translation algorithm (digitized data)

5. Wireless Transfer of commands for different kinds of robotic movement.

Table 4.2 *BMI multi-channel arrays specifications*

Features	**Technical Specifications**
Number of channels	64 till 4096 channels
Supply voltage	3.3 v
Bandwidth	Depending upon the Zigbee/UWB/WiFi

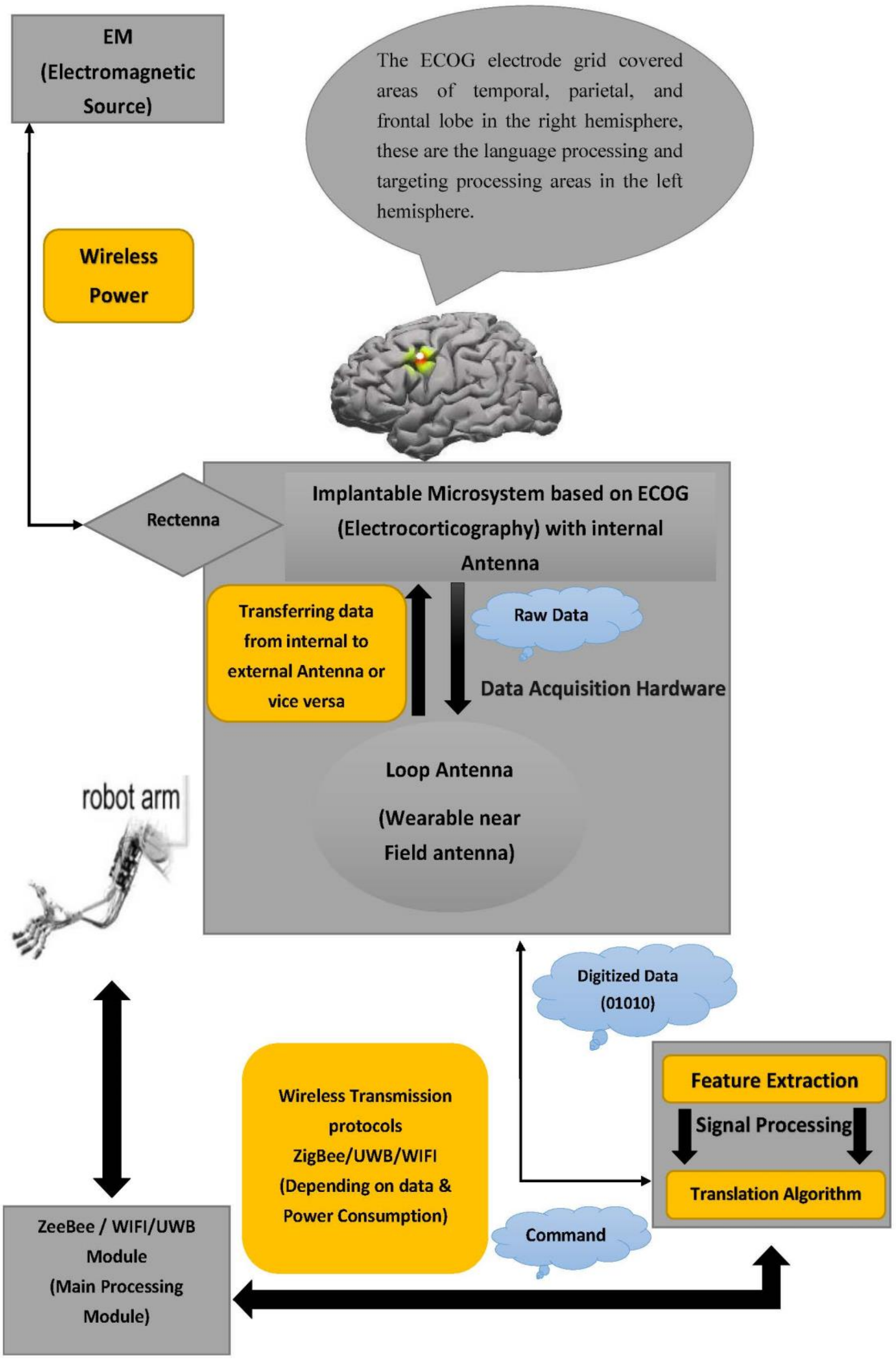

Figure 4.9 *Proposed Wireless BMI Structure end-to-end*

4.5 Discussion

BMI is quite helpful for disabled people as it proposes a communication medium, and restores an injured or damaged motor control function. BMI research has started to catch the attention of medical sciences as well as the common public, since this innovative technology has presented the opportunity of a more enhanced kind of user experience. By recording, monitoring and understanding the real time of bio-potential signals from the motor control areas of the brain; it is now possible to monitor the brain activities and it is helpful for the diagnosis of patients who have neurological disorders, for e.g. epilepsy. By using different methods; such as invasive, noninvasive and minimally invasive observation of the electrical activity of the specific cortical area, to detect and identify the neural activity patterns helps in the diagnosis of neurological diseases and disabilities.

The main idea behind this thesis is provide a more convenient and feasible way to move their robotic arms, or legs etc. A goal directed approach is used to make this novel complete wireless BMI system.

1. Less prone to skin in case of invasive BMI.
2. Light weight head wearable BMI system for signal extraction.
3. Efficient and reliable transfer of power to that head wearable or portable equipment.
4. Effective, efficient and least errorless way of signal extraction.
5. Wireless transfer of neurological signals after signal processing to the main processing module for end user command.

5. CONCLUSION AND FUTURE WORK

In recent years, researchers in the field of brain machine interface gave assurance to thoroughly change the field of medicine. People suffering from different devastating brain disorders, as a result in lack a way to regain their free mobility. BMI is quite helpful for disable people as it can propose them a communication medium, and restore an injured or damaged motor control function.

BMI research has started to clutch the attention of medical sciences as well as the common public, since this innovative technology has presented the opportunity of a more enhanced kind of user experience. By recording, monitoring and understanding the real time of bio-potential signals from the motor control areas of the brain, it is now possible to monitor the brain activities and it is helpful for the diagnosis of patients who have neurological disorders for example epilepsy. By using different methods, like invasive, non-invasive and minimally invasive observing of the electrical activity of the specific cortical area, to detect and identify the neural activity patterns, helps in the diagnosis of neurological diseases and disabilities. For a real time application of a BMI system in our daily life, head mountable and portable wireless BMI systems are very critical, instead the use of heavy and old fashioned wired systems.

Recently, numerous wireless BMI systems have been prepared with improved technology by taking the idea from wired BMI systems. A convenient way to power up the head mountable or implanted device, data acquisition unit and for a communication between brain and effected body part, there is a wired or wireless medium required, these are the compulsory parts of a complete BMI system.

In this thesis, we have discussed a review of current state-of-the-art of BMI invasive, noninvasive and minimally invasive systems as well as compared wired and wireless BMI, with all possible challenges and progresses involved in the system. In contrast of all these I proposed an end-to-end wireless BMI system based on available literature that provides a feasible way for paralyzed patients to communicate and control their muscles and robotic body parts by using their brain waves. According to such idea, the above mentioned circuits and systems can enable a high power efficient and wireless BMI development. From a medical point of view an implantable wireless system is necessary for the applications of invasive BMI to reduce the risk of infection.

5.1 Future Work

Despite of all the recommended work stated above according to the novel idea, the BMI device would react autonomously according to the intentions of human being and would work with small commends (neural activity time frames).

The ongoing research in medical communication is expected to improve in coming years. In the future, we implement the proposed system step-by-step starting from wireless power transfer to activate the implanted device for the extraction of neurological signals by considering all challenges and advantages.

REFERENCES

[1] Seungchan Lee, Younghak Shin, Soogil Woo, Kiseon Kim and Heung-No Lee (2013). Review of Wireless Brain-Computer Interface Systems, Brain-Computer Interface Systems - Recent Progress and Future Prospects, Dr. Reza Fazel-Rezai (Ed.), ISBN: 978-953-51-1134-4, InTech, DOI: 10.5772/56436. Available from: http://www.intechopen.com/books/brain-computer-interface-systems-recent-progress-and-future-prospects/review-of-wireless-brain-computer-interface-systems

[2] Tan, Desney, and Anton Nijholt. "Brain-computer interfaces and human-computer interaction." Brain-Computer Interfaces. Springer London, 2010. 3-19.

[3] J. D. Bronzino. 1995. Principles of Electroencephalography. In: J.D. Bronzino ed. The Biomedical Engeneering Handbook, pp. 201-212, CRC Press, Florida.

[4] Raymond Carl Smith, “Electroencephalograph based Brain Computer Interfaces”, A thesis presented to University College Dublin (NUI) Dublin, Ireland, Feb 2004.

[5] A. Lenhardt, “A Brain-Computer Interface for robotic arm control”, Universität Bielefeld, 2011.

[6] Mak, J.N.; Wolpaw, J.R., "Clinical Applications of Brain-Computer Interfaces: Current State and Future Prospects," Biomedical Engineering, IEEE Reviews in , vol.2, no., pp.187,199, 2009 doi: 10.1109/RBME.2009.2035356

[7] Borikar, Shweta Sanjay, Snehal Ramesh Kochre, and Yugandhara D. Zade. "Brain Computer Interface." National Conference on Engineering Trends in Medical Science (NCETMS) – 2014.

[8] M. Krauledat, “Analysis of nonstationarities in EEG signals for improving brain computer interface performance,” Ph.D. dissertation, Tech. Univ. Berlin, Germany, 2008.

[9] Moradi, Elham, et al. "Measurement of Wireless Link for Brain–Machine Interface Systems Using Human-Head Equivalent Liquid." Antennas and Wireless Propagation Letters, IEEE 12 (2013): 1307-1310.

[10] Yeager, Daniel James. Wireless Neural Interface Design. Ph.D. dissertation, UNIVERSITY OF CALIFORNIA, BERKELEY, 2014.

[11] F. Carpi, D. De Rossi, Noninvasive brain–machine interfaces, ESA Ariadna Study 05/6402, ESA Contract 19706/06/NL/HE,2006.

[12] Javaid, Muhammad Adeel. "Brain-Computer Interface." Available at SSRN 2386900 (2013).

[13] Lee B, Liu CY, Apuzzo ML. A primer on brain-machine interfaces, concepts, and technology: A key element in the future of functional neurorestoration. World Neurosurg. 2013;79(3–4):457–471. http://dx.doi.org/10.1016/j.wneu.2013.01.078

[14] Emily B.J.Coffey, Anne-Marie Brouwer, EllenS.Wilschut, JanB.F.vanErp, “Brain–Machine Interfaces In Space: Using Spontaneous Rather Than Intentionally Generated Brain Signals”, Acta Astronautica 67 (2010) 1–11, http://dx.doi.org/10.1016/j.actaastro.2009.12.016

[15] Leuthardt, Eric C., et al. "A brain–computer interface using electrocorticographic signals in humans." Journal of neural engineering 1.2 (2004): 63.

[16] Muller, Rudolf, et al. "A Minimally Invasive 64-Channel Wireless μECoG Implant." Solid-State Circuits, IEEE Journal of 50.1 (2015): 344-359

[17] Den Bakker, Wouter. "Optimal Wireless Communication Method for Communication inside the Human Body." Proc. 19th Twente Student Conference on IT. 2013.

[18] Chai, Rifai. "Advanced computational intelligence strategies for mental task classification using electroencephalography signals." (2014).

[19] Biederman, Will. "Power Conditioning and Stimulation for Wireless Neural Interface ICs." Ph.D. dissertation, University of California, Berkeley, (2014).

[20] Gosselin, M.-C.; Vermeeren, G.; Kuhn, S.; Kellerman, V.; Benkler, S.; Uusitupa, T.M.I.; Joseph, W.; Gati, A.; Wiart, J.; Meyer, F.J.C.; Martens, L.; Nojima, T.; Hikage, T.; Balzano, Q.; Christ, A.; Kuster, N., "Estimation Formulas for the Specific Absorption Rate in Humans Exposed to Base-Station Antennas," Electromagnetic Compatibility, IEEE Transactions on , vol.53, no.4, pp.909,922, Nov. 2011 doi: 10.1109/TEMC.2011.2139216

[21] C-T. Lin, L-W. Ko, M-H. Chang, J-R. Duann, J-Y. Chen, T-P. Su, and T-P. Jung, “Review of wireless and wearable electroencephalogram systems and brain-computer interfaces—a mini-review,” Gerontology,vol. 56, pp. 112–119, 2010.

[22] R, Muller., Le, Hanh-Phuc., Li, Wen., P, Ledochowitsch. S Gambini, S., Bjorninen, T., Koralek, A., Carmena, J. M., Maharbiz, M. M., Alon, E., Rabaey, J. M. 2015. A Minimally Invasive 64-Channel Wireless μECoG Implant. IEEE Journal of Solid-State Circuits. 50, (Jan. 2015), 344-359. DOI= http://dx.doi.org/10.1109/JSSC.2014.2364824

[23] Hirata, Masayuki, et al. 2011. A fully-implantable wireless system for human brain-machine interfaces using brain surface electrodes:W-HERBS. IEICE transactions on communications. E94, 9 (2011), 2448-2453.DOI= http://dx.doi.org/10.1587/transcom.E94.B.2448

[24] Ramon, Ceon,. Mark, D. Holmes. 2015. Spatiotemporal phase clusters and phase synchronization patterns derived from high density EEG and ECoG recordings. Current opinion in neurobiology. 31, (2015), 127-132. DOI= http://dx.doi.org/10.1016/j.conb.2014.10.001

[25] Dauwels, Justin., Francois, Vialatte. 2010. Topics in Brain Signal Processing. Proceedings of the Second APSIPA Annual Summit and Conference. (Dec 2010), 939-943.

[26] Rajyalakshmi, M., Rao, T. Kameswara., Prasad, T. V. 2012. Exploration of Recent Advances in the Field of Brain Computer Interfaces. IOSR Journal of Computer Engineering. 8, (Nov-Dec. 2012), 19-24.

[27] Hosain, M. K., Kouzani, A. Z., Samad, M. F., Tye, S. J. 2015.A Miniature Energy Harvesting Rectenna for Operating a Head-Mountable Deep Brain Stimulation Device. IEEE Access. 3, (Mar. 2015), 223-234. DOI= http://dx.doi.org/10.1109/ACCESS.2015.2414411

[28] Goff, Alan Le., Holzinger, Michael., Cosnier, Serge. 2015. Recent progress in oxygen-reducing laccase biocathodes for enzymatic biofuel cells. Cellular and Molecular Life Sciences. 72, 5 (Jan. 2015), 941-952. DOI= http://dx.doi.org/10.1007/s00018-014-1828-4

[29] Suzuki, Takafumi., et al. 2014. Super multi-channel recording systems with UWB wireless transmitter for BMI. IEEE 36th Annual International Conference of Engineering in Medicine and Biology Society. (2014), 5208 – 5211. DOI= http://dx.doi.org/10.1109/EMBC.2014.6944799

[30] Bjorninen, Toni., et al. 2013. Electromagnetic modelling and measurement of antennas for wireless brain-machine interface systems. IEEE Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO). (Dec. 2013), 1-3. DOI= http://dx.doi.org/10.1109/IMWS-BIO.2013.6756196

[31] Alshbatat, Abdel Ilah N, et al. 2014. EEG-based Brain-computer Interface for Automating Home Appliances. Journal of Computers. 9, 9 (Sep. 2014), 2159-2166. DOI= http://dx.doi.org/10.4304/jcp.9.9.2159-2166

[32] Lin, Chin-Teng., et al. 2009. Wearable and wireless brain-computer interface and its applications. 13th International Conference of Human Computer Interface. 5638, (2009), 741-748. DOI= http://dx.doi.org/10.1007/978-3-642-02812-0_84

[33] E. Hortal,. et al. 2015. SVM-based Brain–Machine Interface for controlling a robot arm through four mental tasks. Neurocomputing. 151, (Mar. 2015), 116-121. DOI= http://dx.doi.org/10.1016/j.neucom.2014.09.078

[34] Contreras-vidal, Jose L., et al. 2015. METHODS FOR CLOSED-LOOP NEURAL-MACHINE INTERFACE SYSTEMS FOR THE CONTROL OF WEARABLE EXOSKELETONS AND PROSTHETIC DEVICES.U.S. Patent No. 20,150,012,111. (8 Jan. 2015).

[35] Wolpaw, R. Jonathan., et al. 2002. Brain–computer interfaces for communication and control. Clinical neurophysiology. 113, 6 (Mar. 2002), 767-791. DOI= http://dx.doi.org/10.1016/S1388-2457(02)00057-3

[36] Bhandari, Sabin, and Sangman, Moh. 2015. A Survey of MAC Protocols for Cognitive Radio Body Area Networks. Sensors. 15, 4 (Apr. 2015), 9189-9209. DOI= http://dx.doi.org/10.3390/s150409189

[37] Kuan, Y., Y. Lo,. Y. Kim., M.F Chang., W. Liu. 2015. Wireless Gigabit Data Telemetry for Large-Scale Neural Recording. IEEE Journal of Biomedical and Health Informatics. 19, 3 (May. 2015), 949-957. DOI= http://dx.doi.org/10.1109/JBHI.2015.2416202

[38] Ahmed, Khaled Sayed., M. El-Metwally, Shereen. 2015. Portable Low-Cost Heart Attack Detection System Using ZigBee Wireless Technology. Bioinformatics and Biomedical Engineering. Springer International Publishing. 9043, (2015). 155-162 DOI= http://dx.doi.org/10.1007/978-3-319-16483-0_15

[39] Ghamari, Mohammad., et al. Comparison of Low-Power Wireless Communication Technologies for Wearable Health-Monitoring Applications (Paer is accepted but not officially published yet)

[40] Darif, A., Saadane, R., Aboutajdine. D. 2014. An efficient short range wireless communication technology for wireless sensor network. Information Science and Technology (CIST). (Oct. 2014), 396-401. DOI= http://dx.doi.org/10.1109/CIST.2014.7016653

[41] Jin-Shyan Lee., Yu-Wei Su., Chung-Chou Shen. 2007. A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi. IEEE 33rd Annual Conference of Industrial Electronics Society. (5-8 Nov. 2007), 46-51. DOI= http://dx.doi.org/10.1109/IECON.2007.4460126

[42] Hernandez, Oziel., et al. Position Location Monitoring Using IEEE® 802.15. 4/ZigBee® technology. Beyond Bits. 4. 67-69. [Online]. Available= http://www.freescale.com/beyondbits

[43] Lin, Chin-Teng., et al. 2009. Wearable and wireless brain-computer interface and its applications. 13th International Conference of Human Computer Interface. 5638, (2009), 741-748. DOI= http://dx.doi.org/10.1007/978-3-642-02812-0_84