ELECTRO-QUASISTATIC BODY COMMUNICATION FOR BIOPOTENTIAL APPLICATIONS

by

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This thesis is dedicated to my parents Dr. Sriram Ramalingam, Dr. Pradnya Sriram and my sister Divya Sriram.

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ABSTRACT

The current state of the art in biopotential recordings rely on radiative electromagnetic (EM) fields. In such transmissions, only a small fraction of this energy is received since the EM fields are widely radiated resulting in lossy inefficient systems. Using the body as a communication medium (similar to a 'wire') allows for the containment of the energy within the body, yielding order(s) of magnitude lower energy than radiative EM communication. The first part of this work introduces Animal Body Communication for untethered rodent biopotential recording and for the first time this work develops the theory and models for animal body communication circuitry and channel loss. *In vivo* experimental analysis proves that ABC successfully transmits acquired electrocardiogram (EKG) signals through the body with correlation >99% when compared to traditional wireless communication modalities, with a 50x reduction in power consumption. The second part of this work focusses on the analysis and design of an Electro-Quasistatic Human Body Communication (EQS-HBC) system for simultaneous sensing and transmission of biopotential signals. In this work, detailed analysis on the system level interaction between the sensing and transmitting circuitry is studied and a design to enable simultaneous sensing and transmission is proposed. Experimental analysis was performed to understand the interaction between the Right Leg-Drive circuitry and the HBC transmission along with the effect of the ADC quantization on signal quality. Finally, experimental trials proves that EKG signals can be transmitted through the body with >96% correlation when compared to Bluetooth systems at extremely low powers.

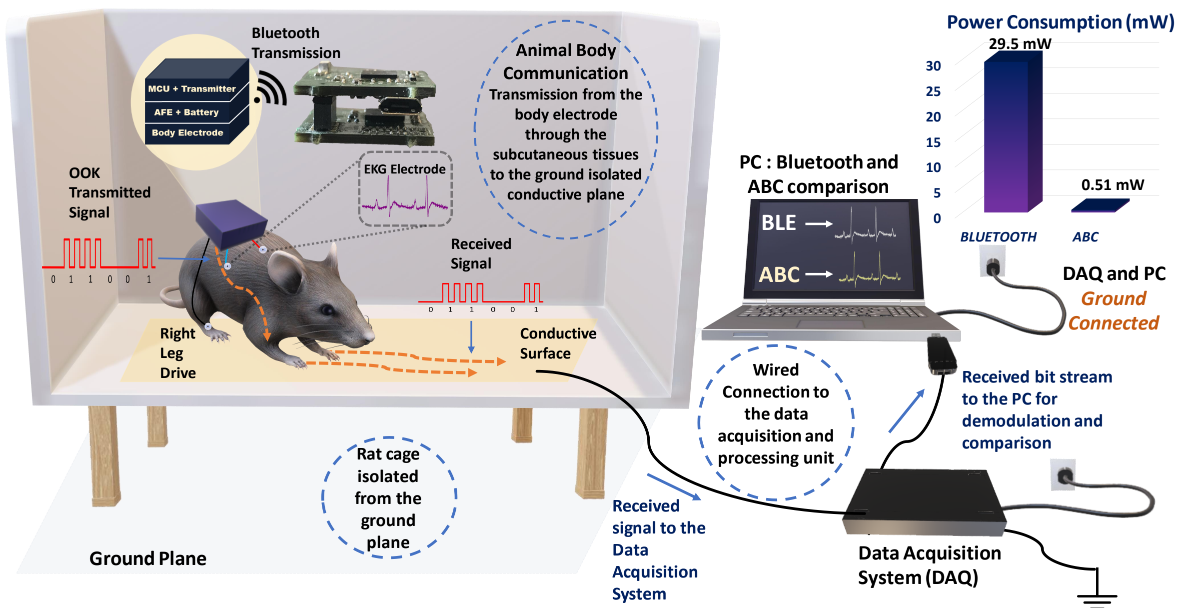
1. INTRODUCTION

Chronic monitoring of biopotential signals has paved the way for a better understanding of neural pathways along with improved therapeutic treatments. Recent proliferation in small form-factor wearables has enabled a new domain of continuous health monitoring. This coupled with miniaturized biological sensors, both in the wearable and the implantable domain has resulted in gathering valuable information regarding the body. Surface biopotential signals such as EKG, sEMG (Surface Electromyography), EEG (Electroencephalogram) have been studied as a means of understanding the behavior of the body. Neural recording systems interfaced with the peripheral nervous system have been extensively explored as a method to acquire meaningful data that is used to predict and understand the motor, sensory, proprioceptive, and feedback functions of the brain.

The use of animals in biological research and medicine has been a longstanding practice given the similarity between the animal and human anatomy and physiology. The current state of the art in animal signal recording includes miniaturized wearable or implantable devices with stimulation and recording capabilities. These devices placed on the body of the animal or implanted inside the animal body, transmit data to an external unit capable of receiving and processing this information. A vast majority of animal recording systems still rely on tethered units especially in cases when continuous long-term information is a priority. Tethered systems are not limited by the data rates and are a gold standard for reliable comprehensive information, this, however, does come with a few caveats. Tethered systems are limited by the bias and irritation introduced by these devices on the subject. Long experimental duration is possible, however, the experimental arena is hindered by the need for long wires which in turn results in restricted movement of animals. Noisy systems result from the animals tucking and biting at the wires. Tethered systems require signal conditioning electronics to be placed external to the body, long wires also act as a site for infection and require buffers to prevent signal attenuation [1]. To reduce these effects, wireless telemetry of signal information is needed. Wireless recording systems have since evolved from discrete modules to system on chip devices.

These small form-factor wireless devices eliminate the bias introduced by the tethered systems; however, it is limited by the high-power consumption due to the need for up-conversion of the baseband signal to higher radio frequencies [2] and loss due to radiative communication. Animal studies, in particular, require the animal to wear a heavy battery pack to meet this high-power requirement. The need for constant replacement of batteries limits the experimental duration and causes undue stress on the animals which in turn corrupts the data [3]. The advancement in the field of wireless power transfer allowed for a longer experimental duration without the need for heavy battery packs or constant replacement of batteries [4]. However, due to the inherent high-power consumption of the sensing node with electromagnetic communication, high-power needs to be harvested, increasing the on-device harvester size significantly.

To overcome these constraints there is a need for a low power communication modality capable of withstanding the continuance of the experiment, along with having an unbiased model in which the animals are free to move in their natural environments. In this work, we introduce a novel communication modality that uses the animal body as a medium to transmit information. This system eliminates the bias introduced by the tethered systems and has a significant size, weight, area, and power benefits compared to electromagnetic communication systems. We demonstrate this **Electro-Quasistatic Animal Body Communication (EQS-ABC)** as a low loss, efficient channel which addresses the aforementioned drawbacks of both tethered and wireless EM communication systems. Using the body of the animal as a 'wire'ensures signal confinement resulting in significantly lower losses when compared to traditional wireless technologies. Here, we demonstrate ABC using a rodent model and explain the theory and biophysical models of ABC, followed by ABC demonstration with a sub-inch^3 [1"x1"x0.4"], custom-designed sensor node in the subsequent sections. Fig. 1.1, describes the concept of the ABC setup, surface biopotential signals are acquired by a custom-designed sensor node that then transmits the signal using ABC through the subcutaneous tissues of the animal body using EQS-ABC. These signals are picked up by a receiver connected to the ground isolated conductive surface. In this setup, we also transmit the signals using Bluetooth as a method to compare the ABC transmitted signal with an established communication modality. In this pilot study, we use the concept of body communication and extend it into the animal domain enabling long term benefits in energy consumption along with size, weight, and area benefits. The low power requirement enables the use of smaller batteries or coils in the case of energy harvested nodes. We show the concept of ABC applied to animal biomedical studies, this modality can be extended into the neuroscience domain. This work explores the recent advances in Electro-Quasistatic Human Body Communication (EQS-HBC) and adapts it to facilitate animal biopotential recording.



Overview of Animal Body Communication on a Rodent Model. Custom designed sensor node is placed on the back of the rat. This sensor node is capable of sensing and transmitting the surface biopotential signals via Bluetooth and Animal Body Communication. The sensed signal is transmitted through the body to the conductive surface in the form of OOK (On-Off Keying) sequences. The specially designed rat cage is isolated from the ground surface. A conductive surface is placed on the base of the rat cage which is then connected to a Data Acquisition System (DAQ) which receives the transmitted signals. The Bluetooth receiver and DAQ are connected to a PC for processing, with the DAQ and PC ground referenced. In this model Bluetooth communication acts as a validity check for ABC. This figure was created using the software Paint 3D by Microsoft Corporation (Version 6.2009.30067.0).

Figure 1.1. Animal Body Communication

2. STATE OF THE ART IN WIRELESS BIOPOTENTIAL RECORDINGS

The first biopotential discovery dates back to 1666 when Francesco Redi measured the EMG from a specialized muscle in the electric eel[5], the field of animal biopotential recordings evolved from tethered systems to wireless systems in the year 1948 when Fuller and Gordon first used radio communication for biopotential signal transmission [6]. Presently, multi-channel recording devices with wireless power transfer is being implemented, this coupled with smart devices and experimental arenas permits in-sensor analytics. The evolution and detailed comparison of the state of the art in biopotential recording has been described in a later section.

Biopotential signals, both non-invasive (skin surface) and invasive, have been studied as a means of building bio-electronic medical devices. The central nervous system controls the body and this control can be observed by studying the changes in the peripheral physiological factors such as changes in the heart rate, muscle activity, and breathing. To study these changes, long term monitoring of these physiological signals is necessary[7]. EKG is one of the most widespread diagnostic tools in medicine and the similarity between human and rat EKG[8] has permitted the study of various physiological conditions and cardiac diseases [9], [10]. Along with EKG signals, other surface biopotentials such as sEMG and EEG are studied in rats, analysis of these signals is used in sleep studies, epilepsy, locomotive analysis, and effect of spinal cord injuries [11], [12].

The study of the brain along with the body is essential in understanding the control mechanisms of the brain on physiology. Sican Liu described a novel neural interface system for simultaneous stimulation and recording of EEG/EMG and ENG (Electroneurogram) signals [13]. Along with surface biopotential signals, invasive recording allows for localized, high fidelity signal analysis. Neural biopotential signal analysis is a topic of extensive research in experimental neuroscience, with the aim of improving the quality of life of people with severe sensory and motor disabilities. Wireless neural recording systems have been described in insects, rodents and non-human primates. In rodents particularly, various neural interface systems which include bidirectional communication has been explored[14], [15]. Applicationspecific integrated circuit (ASICs) for neuro-sensing applications has been described for implantable neurosensors[4], [16]–[18].

Chronic multi-channel neural recording is a powerful tool in studying dynamic brain function. Multi-electrode arrays permit recording of more than one channel simultaneously enabling neuroscientists to explore different regions of the brain in response to a particular stimulus. Bandwidth constraints limit the number of channels that can be recorded simultaneously resulting in a trade-off between the number of channels that can be simultaneously recorded, power requirements, and the form factor of the device. For example, Borton et al. designed an implantable hermetically sealed device that was capable of sending neural signal information via a wireless data link to a receiver placed 1 meter away. This system permitted 7-hours of continuous operation[17]. Chae et al. describes a 128 -channel 6mW wireless neural recording IC with on the fly spike detection for one selected channel. A sequential turn-on method is used to minimize the power requirement [19]. Similarly, Miranda et al. developed a 32-channel system that can be used for 33 hours continuously but requires two 1200 mAh batteries [20]. To achieve a meaningful experimental duration, the power consumption is often >10mW, generally dominated by the communication (radio) power. Thus, it is evident that wireless neural interfaces are power-hungry and there is a need for constant replacement of the batteries or selective channel selection in a chronic setting. To overcome these constraints wirelessly powered neural interfaces were developed, which eliminates the need for constant replacement of the batteries. Implantable devices, in particular, need wirelessly powered devices to reduce the need for a battery at the implant site. Enriched experimental arenas allow for the constant transmission of power facilitating chronic recordings. Yeager et al. developed a wireless neural interface, NeuralWISP capable of sending neural information over a 1-m range [21]. Lee et. al describes an EnerCage-HC2 to inductively transfer power to a 32-channel implantable neural interface[4]. Wireless power transfer though ensures longer experimental duration, one has to take into account the exposure to high electromagnetic fields along with concerns regarding excessive heat dissipation. Thus, it is evident that neural recordings are limited by size constraints and overall power consumption. This leads to the next advancement in wireless biopotential recording with electro-quasistatic animal body communication, which aims to use the animal body as the transmitting medium similar to the concept of human body communication. In the following chapters we describe the concept of body communication and also describe how the ABC differs from HBC while still having similar advantages.

3. ANIMAL BODY COMMUNICATION

3.1 Body Communication Basics

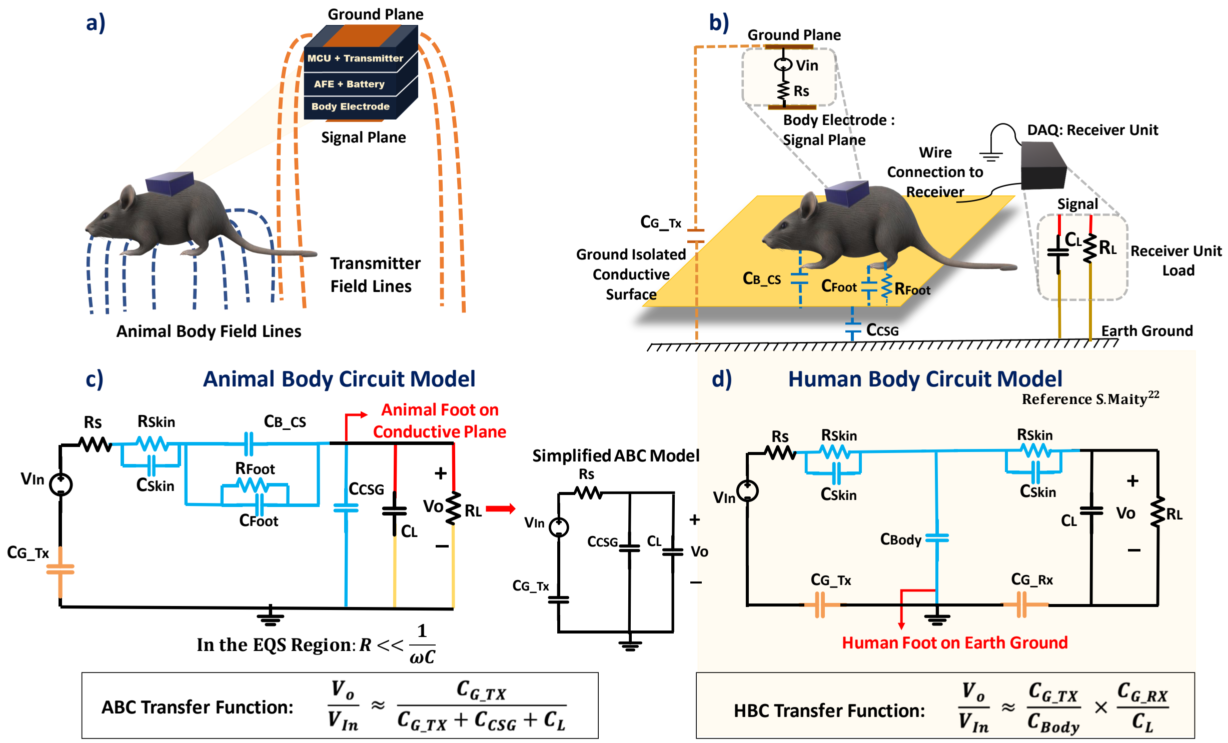
Body communication-based wearable technology has gained prominence over recent times as a communication modality for sending real-time information. Recent advances in using the human body as a channel for bio-physical communication has resulted in an energy-efficient secure information exchange modality [22]. HBC was first proposed as a method to connect devices on a Personal Area Network (PAN) by Zimmerman et al. [23], using a capacitively coupled HBC model where the return path is formed by the electrode to ground capacitance. The transmitter capacitively couples the signal into the human body which is then picked up at the receiver end. Galvanic coupling-based HBC introduced by Wegmueller et al.[24], the signal is applied and received differentially by two electrodes respectively. Since then extensive research on different modalities for HBC transmission has been explored and models to analyze HBC circuitry and channel loss has been proposed [25]–[27]. HBC utilizes the conductivity of the human body for a low transmission loss, high-efficiency transmission modality making it ideal for energy-constrained devices.Traditional wireless body area networks (WBAN) use EM signals that radiates outside the body all around us, resulting in only a fraction of the energy being received[28]–[30]. This radiative nature and high frequencies in WBANs are typically high energy and of the order of 10nJ/bit[31]. Recent advances have shown impulse-radio ultra wideband (IR-UWB) to be more energy efficient than traditional WBANs, with a energy of 1nJ/bit[32]. Now, if the body's conductivity is used, it provides a low loss broadband channel that is private (the full bandwidth is available for communication). This low loss and wide bandwidth availability along with the low-frequency operation results in ultra-low power body communication at 415 nW[33] as well as very low energy communication at 6.3pJ/bit[34]. Low-frequency HBC was not widely adopted due to the high loss at these frequencies because of resistive (50 Ω) termination[35]. Recently we demonstrated, by using capacitive termination, the loss in the EQS region is reduced by a factor of >100, making it usable[34], [36]. The first bio-physical model for EQS-HBC was developed by S. Maity[37] and a detailed understanding of the forward path[38] and return path[39] was described. Datta et al.[40] describes an advanced biophysical model to capture channel variability. EQS-HBC is presently the most promising low-power, low-frequency communication alternative for WBAN. It has also been shown that the EQS-HBC adheres to the set safety standards[41].

The state of the art in body communication has been restricted to human body communication. In this work we propose to utilize the recent developments in the concept of body communication and apply it to the animal body for biopotential and neural recordings, reducing the size, weight, area, and power of the device. We propose a capacitive termination EQS communication from a sensing node on the rat's body and also device an experimental arena to pick up these EQS signals most efficiently. This form of communication utilizes electro-quasistatic transmission through the conductive layers of the rat below the skin surface. The skin is a high impedance surface while the inner tissue layers are conductive. The transmission of the electro-quasistatic signals through the body with a capacitive return path at frequencies below 1 MHz ensures that the signal is contained within the body.

3.2 Animal Body Communication - Biophysical Theoretical Model

As already established, Human Body Communication has been explored as a viable communication model, extending this to an animal body allows for a low loss, efficient channel model, compared to the traditional wireless modalities currently used. Fig. 3.1 **a** and **b** depicts the concept of Animal Body Communication, the rat body capacitively couples with the signal plane. The transmitter placed on the body of the rat modulates this electric field to transmit OOK (On-Off Keying) sequences corresponding to the sensed biopotential signal. The experimental arena is designed such that the animal moves around on a conductive surface, which is isolated from the earth's ground. This surface picks up the EQS signals coupled onto the animal's body and is received through ground-referenced receiver. Hence, the received voltage is inversely proportional to the capacitance of the signal plane to ground (the less the capacitance the easier it is for the wearable device on the animal to modulate the potential of the animal body and the surface).

The circuit model for Animal Body Communication is described in Figure 3.1 **c**. At lower frequencies the skin impedance and the series body and foot impedance is negligible



a) Represents the field lines corresponding to the rat body and the transmitter ground plane. b) The rat body couples to the conductive plane and the associated capacitances are depicted. The conductive plane is ground isolated and forms the capacitance CCSG. The node consists of the ground plane which couples with the earth's ground to form the capacitive return path. c) The circuit model associated with the experimental setup is shown in the figure. The simplified model of the animal body communication circuit shows that the output voltage is proportional to the conductive plane to ground capacitance CCSG, return path capacitance C_{G_TX}, and load capacitance CL. d) Simplified Human Body Communication circuit model and transfer function as depicted by S. Maity[22]. The rat models in a) and b) were created using the software Paint 3D by Microsoft Corporation (Version 6.2009.30067.0).

Figure 3.1. Animal Body Communication model

compared to the capacitance between the signal plane and ground. Given the operation of ABC in the electro-quasistatic regime, these impedances can be neglected in the computation of the channel loss. From the simplified circuit model, the output voltage $\mathbf{V}_o$ and the input voltage $\mathbf{V}_{In}$ are related as follows:

$$\mathbf{Z}_{Skin}, \mathbf{Z}_{Body}, \mathbf{Z}_{Foot} \ll \frac{1}{\omega\ \mathbf{C}_{CSG}}$$

$$\frac{\mathbf{V}_o}{\mathbf{V}_{In}} = \frac{\mathbf{C}_{G\_TX}}{\mathbf{C}_{G\_TX} + \mathbf{C}_{CSG} + \mathbf{C}_L} \tag{3.1}$$

In Fig. 3.1 **c** and **d** we compare the animal body circuit model along with the established human body circuit model. The output voltage is a function of $\mathbf{C}_{CSG}$ as shown in equation

CIRCUIT MODEL COMPONENT COMPARISON BETWEEN ANIMAL BODY COMMUNICATION AND HUMAN BODY COMMUNICATION

SIMILAR COMPONENTS	DESCRIPTION
Source Resistance (R_S)	Source resistance of the transmitter
Skin Layer Resistance (R_{Skin})	Rat Body Skin resistance varies depending on the fur and other factors
Skin Layer Capacitance (C_{Skin})	Depending on the skin layer thickness, capacitance from the signal electrode to the conductive tissue layers of the rat body
Transmitter Ground to Earth Capacitance (C_{G_TX})	Return path capacitance from the earth ground to the ground plane on the transmitter
Load Capacitance (C_L)	Load capacitance of the receiver probes
Load Resistance (R_L)	Load resistance of the receiver probes

DISSIMILAR COMPONENTS	ANIMAL BODY COMMUNICATION	HUMAN BODY COMMUNICATION
Capacitance to Conductive Surface (C_{B_CS})	Capacitance from the rat body to the conductive surface	Does not exist in HBC
Body Capacitance (C_{Body})	Does not exist in ABC	Capacitance from the body of the human to the earth ground
Foot Resistance (R_{Foot})	Resistance of the rat foot to the conductive surface	Does not exist in HBC
Foot Capacitance (C_{Foot})	Capacitance between the foot of the rat to the conductive surface, varies depending on the distance of the foot from the conductive surface	Does not exist in HBC
Signal Plane Capacitance (C_{CSG})	Capacitance from the conductive surface to the earth ground	Does not exist in HBC
Receiver Ground to Earth Capacitance (C_{G_RX})	Does not exist in ABC	Return path capacitance from the earth ground to the ground plane of the receiver

Figure 3.2. Comparison between Animal Body Communication and Human Body Communication circuit components.

3.1 for ABC, while it a function of $\mathbf{C}_{Body}$ in case of HBC. The approximate value of C_{CSG} was found to be 50pF. This value was computed for an output voltage, V_o of 45mV, which was experimentally determined and an input voltage, V_{In} of 3.3V. The value of the return path capacitance was computed using the equation $C_{G\_TX} = 8\varepsilon_0 a$, where a is the radius of the ground plane [39]. This value was calculated to be 0.9pF for a radius of 0.0127m. The receiver load capacitance from the datasheet was found to be 14pF. Body communication-based systems heavily depend on the body surface and ground sizes. S. Maity describes the Bio-Physical Model for HBC[37], Fig. 3.2 compares the ABC model with the HBC model. Traditional HBC systems have the human body connected to a transmitter and a receiver placed on a different part of the body. The human body has a much larger surface area when compared to an animal. In this ABC setup, the sensor node is placed on the body of the rat, while the receiver is a large conductive plane. This large conductive plane ensures that the movement of the rat is not restricted, and data can be continuously recorded. In contrast, in human body communication, the body is on the earth's ground and there exists a trunk path to ground. Due to this, the output voltage is affected by the body capacitance, unlike in the animal body setup. Fig. 3.2 illustrates the key components of HBC and ABC. The capacitance of the body varies from ABC and HBC due to the fact that the ABC channel model consists of the additional conductive surface on which the rat is free to move. Another important component is the rat foot impedance, in ABC the rat's feet rest on the conductive surface. $\mathbf{C}_{Foot}$ and $\mathbf{R}_{Foot}$ change depending on the position of the rat's foot on the conductive plane.

In the human model, the received signal is collected from the body surface itself, thus the output voltage depends on the capacitive return path of both the transmitter and the receiver. In the ABC model, the conductive surface is ground isolated and connected to an oscilloscope which acts as the receiving unit. The transmitter couples to the floating body and the return path capacitance $\mathbf{C}_{G\_TX}$ from the earth's ground plane to the transmitter ground plane completes the loop, allowing for signal transmission. The receiver in ABC is the oscilloscope signal probe, which can be modeled as the load capacitance $\mathbf{C}_L$ in parallel with the load resistance $\mathbf{R}_L$. This oscilloscope is earth ground referenced and hence eliminates the capacitive return path of HBC. The low-loss in ABC coupled with low-carrier frequency communication (as a wire) enables ABC power consumption to be much lower when compared to wireless communication modalities such as Bluetooth. This reduced power enables longer duration experiments with small form factor devices.

3.3 System Design

The system architecture can be broadly divided into three blocks, the custom-wireless signal acquisition node, the Bluetooth receiver connected to the data logging system (computer), and the animal body communication receiver. The custom node consisted of two vertically stacked custom-designed printed circuit boards (PCB) which were populated with commercially available integrated circuits and discrete components. The top board in the stack contained the micro-controller and Bluetooth System on Chip (SoC), along with the antenna and matching network on the top layer. The bottom layer consisted of the power management system and charging connector. The analog front end was housed on the top layer of the bottom stack, with the bottom layer serving as the electrode for animal body communication.

A System on Chip (NRF52840, Nordic Semiconductors) which integrates an ARM Cortex-M4F micro-controller and a Bluetooth 5.0 transceiver was selected to form the core of the node since it would minimize the device footprint and power consumption. The SoC utilizes Bluetooth 5.0 - Bluetooth Low Energy (BLE), which is the latest version of the Bluetooth wireless communication. The on board 1MB flash memory and 256KB RAM was sufficiently large to store the sampled signals and implement in-sensor analytics in the future. Power efficiency was further improved by utilizing the on-chip DC-DC converters. A 3.7V 150mAh Lithium Polymer rechargeable battery is directly soldered onto the board, along with the battery management circuitry. In this custom node, we use a battery management integrated circuit, MCP73831 by Microchip Technologies. This linear charge management controller was selected for its small physical size and the need for a low number of external components.

The custom node collected the EKG signals from a zero-insertion force connector placed on the PCB. Signal conditioning and sampling of the EKG signal was performed by another SoC (ADS1298, Texas Instruments). This analog front-end chip incorporates a programmable gain differential amplifier and right-leg drive generation for conditioning EKG signals, which were subsequently sampled at 500Hz by a 24-bit analog to digital converter. The SoC was programmed to optimize signal acquisition quality and power consumption. The sampled signals were sent to the micro-controller through an on-chip Serial Peripheral Interface.

The sampled data was stored in a buffer in the micro-controller until the transmission window started. The samples were then converted to characters and transmitted as a string over Bluetooth after adding delimiters to differentiate between subsequent samples. For Animal Body Communication, the sample was transmitted in its original 24-bit binary integer form after creating packets by adding two bits (binary 1) at the start and end of the sample. Each bit in ABC was represented by on-off keying, wherein a 500kHz, 50% duty cycle square wave was turned on (binary 1) or off (binary 0). The amplitude of each bit is 3.3V, which is the output of the micro-controller. ABC data was transmitted at 25Kbps, which was significantly lower than the minimum required Bluetooth bandwidth of 45Kbps, which excludes the overhead added by the Bluetooth stack.

The custom-designed node was packaged in a 3D-printed housing of dimensions 25mm x 25mm x 10mm, which is equivalent to 0.39 cubic inches. It had a net weight of 20g and average power consumption of 29.5 mW (with Bluetooth transmission for data comparison purposes) which resulted in approximately 20 hours of battery life. This is 19 times smaller and has more than twice the battery life when compared to a commercial wireless unit (Bio-Radio). We expect a much longer lifetime when the Bluetooth transmission is turned off and only ABC transmission is turned on. The power required for sensing is typically orders of magnitude lower than the power required for communication, thus the system power is dominated by this communication power. The ABC transmission power is 50x lower when compared to the Bluetooth transmission power and this translates into an order of magnitude improvement in the device lifetime and reduction in the battery size.

The Bluetooth receiver was essentially another NRF52840 SoC connected via USB to the data logging system, which in this case was a computer. This setup was used instead of the inbuilt Bluetooth device of the computer since it would be easier to collate data from multiple transmitters.

The conductive signal plane is connected to the high impedance receiver probe. A computer-based oscilloscope, by Pico Technologies, was used as the ABC receiver. The OOK sequences are sampled at 3.9 MSamples/s and collected for post-processing.

3.3.1 Signal Processing

OOK sequences collected from the ABC receiver are sent to a computer for processing. Signals are first band-passed between 400kHz to 600 kHz with 80 dB attenuation software filters. Filtered sequences are demodulated using envelop detection and thresholding. Sequences are then decoded using the start and stop bit followed by software error correction. Bluetooth sequences in the form of ADC codes are converted to corresponding voltage values and compared to the received ABC signals.

3.3.2 Communication Protocols

1. Time Multiplexed Data

As discussed earlier, a requisite for animal body communication especially while recording surface biopotential signals is the need to time multiplex the sensing and transmission periods.

2. Error-Correcting Algorithms

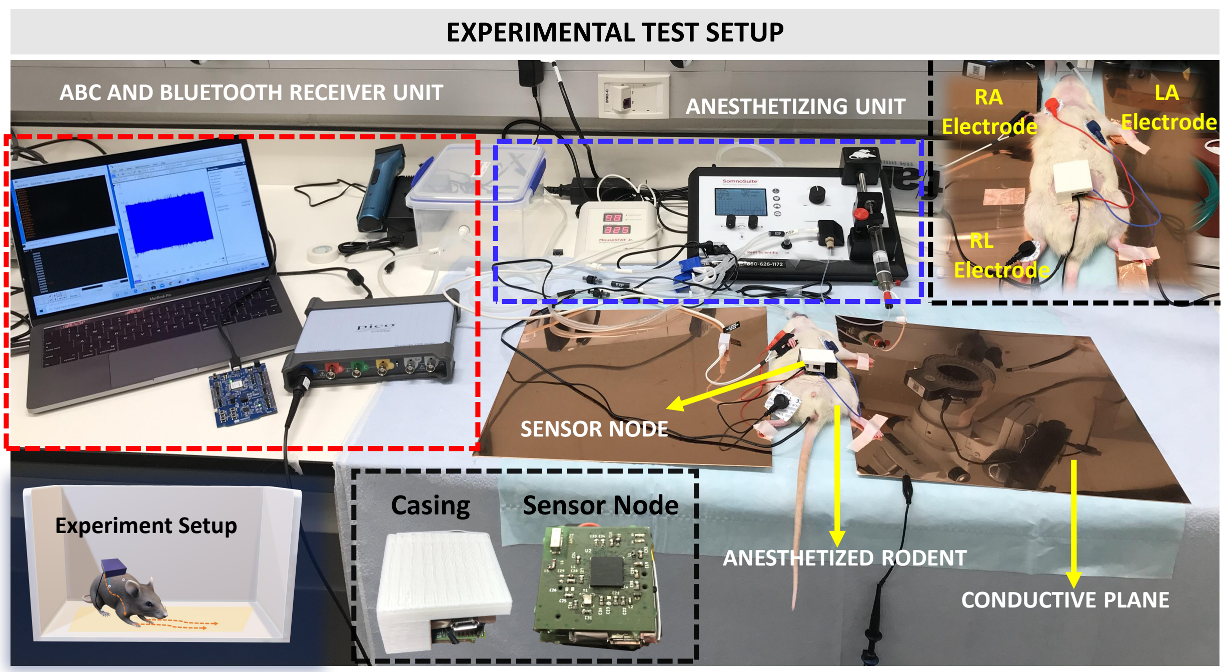
There is a possibility to bring in redundancy into the communication channel to ensure the robustness of this communication modality. We have shown that if the rat foot is lifted from the conductive surface, the received signal can still be picked up by the receiver. The goal of this paper is to ensure that long term recordings of freely moving animals can be obtained. To ensure that there is a successful transmission of data, error-correcting algorithms become a necessity.

Bi-modular Redundancy can be introduced by repeating packets over time. In the event of a jump or signal drop, repeated packets ensure that the signal information is faithfully transmitted. This technique reduces the data rate due to the added redundancy.

Block Codes a common error-correcting technique of encoding the data in blocks, such that the code is a linear combination of the message and parity bits in a linear block code.

3.4 Animal Body Communication Experimental Setup

The Animal Body Communication setup is tested on Sprague Dawley rats, experiments were performed on anesthetized rats. In this study, capacitive coupling is used as a means to achieve Animal Body Communication. The details of the sensor node are described in the methods section. Anesthetized rats are placed on a non-conductive surface, the sensor node, in a casing, is placed on the rat skin surface and patch connectors are used to connect to the surface electrodes. The feet of the rat are placed on a conductive copper plate, signals are acquired using the sensing unit, then transmitted via Bluetooth to a receiver connected to a computer as shown in Fig. 3.3. The device is capable of transmitting both over Bluetooth and through ABC simultaneously. Only the feet are connected to the conductive plane while leaving the body on a non-conductive surface. This depicts a case when the rat moves in a cage with only the feet on the bottom plane. ABC happens through the transmission of OOK sequences from the node through the body, to the conductive copper plate. These signals are picked up using an oscilloscope connected to the conductive plane. The oscilloscope signal probe is connected to the conductive plane while the ground probe is left floating. EKG signals are acquired using a three-electrode setup with the electrodes placed on the Right Arm (RA), Left Arm (LA), and Right Leg (RL). The RL serves as the right leg drive, common to EKG recording systems. Additional monitoring systems such as the anesthetizing setup and body vital measurement systems are present in this experimental setup not part of the communication setup. This setup aims to mimic the setup as described in Fig. 1.1. The copper plates act as the conductive surface which in an awake recording setup will form the base on which the rat is free to move.



The sensor node is placed on the rat skin surface and connected to the surface electrodes(Right Arm (RA), Left Arm (LA), and Right Leg (RL) for EKG sensing. The rat's feet are taped on a conductive copper plate, the plate is then connected to a receiver for ABC transmission. The Bluetooth receiver and the ABC receiver are connected to the computer for signal acquisition and processing. The setup also consists of the anesthetizing unit which delivers the anesthetizing drug and oxygen to rat. The rat model was created using the software Paint 3D by Microsoft Corporation(Version 6.2009.30067.0).

Figure 3.3. Experimental Test Setup

3.4.1 Surgery

All surgical procedures were performed under aseptic conditions at Purdue Animal Facility. 5% Isoflurane gas and oxygen were used to anesthetize the rat in an induction chamber, followed by a continuous flow of 2.5 % Isoflurane gas with oxygen delivered through a nose cone. The dosage of Isoflurane and the flow of oxygen is continuously monitored to ensure that the rat does not respond to the toe pinch while still maintaining a steady breathing rhythm and observable pink extremities. A heating pad is placed below the rat to maintain the body temperature and lubricating drops are added to the eyes of the rat to prevent drying. The skin surface is shaved and cleaned for the placement of the surface electrodes. The device is placed on a shaved surface on the belly of the rat with the signal plane touching the skin surface. The surface electrodes are connected to the device using patch connectors. The experiment was performed on 8 Sprague Dawley rats which is sufficient to show the science and working of ABC.

All procedures were approved by the Institutional Animal Care and Use Committee (IACUC) and all experiments were performed in accordance with the Guide for the Care and Use of Laboratory Animals. The experiments were closely monitored and reviewed by Purdue Animal Care and Use Committee (PACUC).

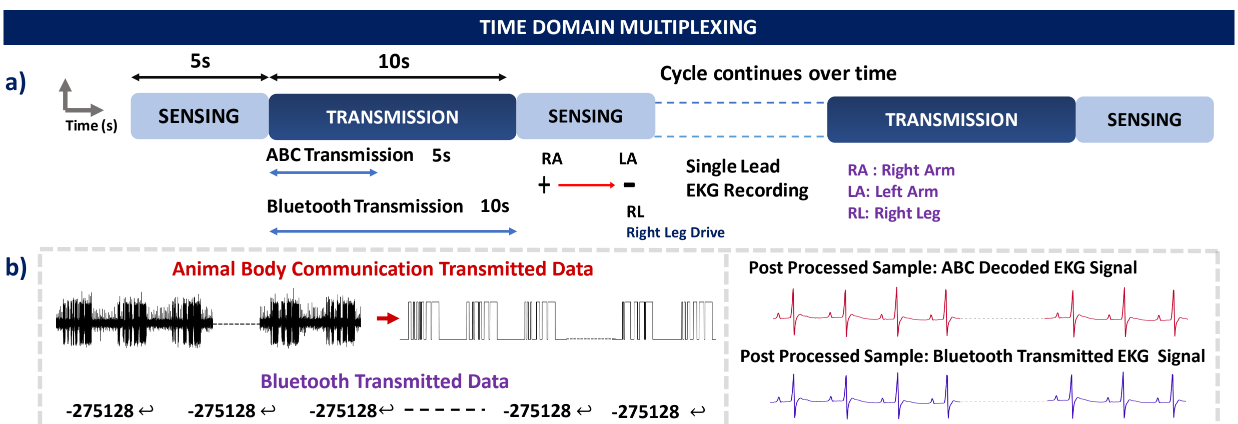
3.5 Results

Animal Body Communication was explored as a new modality for the transmission of biopotential signals. The sensing and transmitting devices are built using off the shelf components and consist of a communication module, a processing module, a power source, and an interface to connect it to the rat body. Surface electrodes are placed on the skin surface of the rat, after employing appropriate skin preparation techniques and then connecting the electrodes to the front end of the device.

Biopotential information is sensed and modulated for transmission, simultaneously transmitting the signal over Bluetooth and through the body of the rat as Animal Body Communication. Bluetooth has long been used as a wireless communication modality and widely cited in literature as a means to transmit biopotential information. In this work, we use this gold standard of communication to compare the biopotential information received from the ABC transmitter and Bluetooth module. In an ideal situation, a tethered system acts as the gold standard, however, body communication cannot be achieved when the system is ground connected (as in the case of a tethered system), with a ground connected system, the results would be optimistic and incorrect [37]. A correlation analysis is performed to compare both signals. Experiments were performed on a rat to prove the feasibility of Animal Body Communication.

3.5.1 Time Division Multiplexing

Biopotential signal measurements require the body to be grounded to improve the CMR of the entire system. Grounding the body eliminated the floating nature which is essential for body communication. Thus, to sense and transmit biopotential signals, time-division multiplexing is used. Such multiplexing between each sensing cycle and transmission cycle ensures that surface biopotentials can be sensed accurately and also transmitted via body communication.



Time multiplexed sensing and transmission cycles: a) Sensing cycles consists of acquiring the single-lead EKG signal using three electrodes, Right Arm, Left Arm and Right Leg. ABC Transmission starts at the end of the sensing cycle and has the same duration as the sensing cycle. Bluetooth transmission duration is almost twice the ABC transmission duration. Upon the completion of both transmissions, the sensing cycle restarts, and this cycle repeats. b) Post-processing steps on ABC transmitted sequence and Bluetooth transmitted sequence transmission.

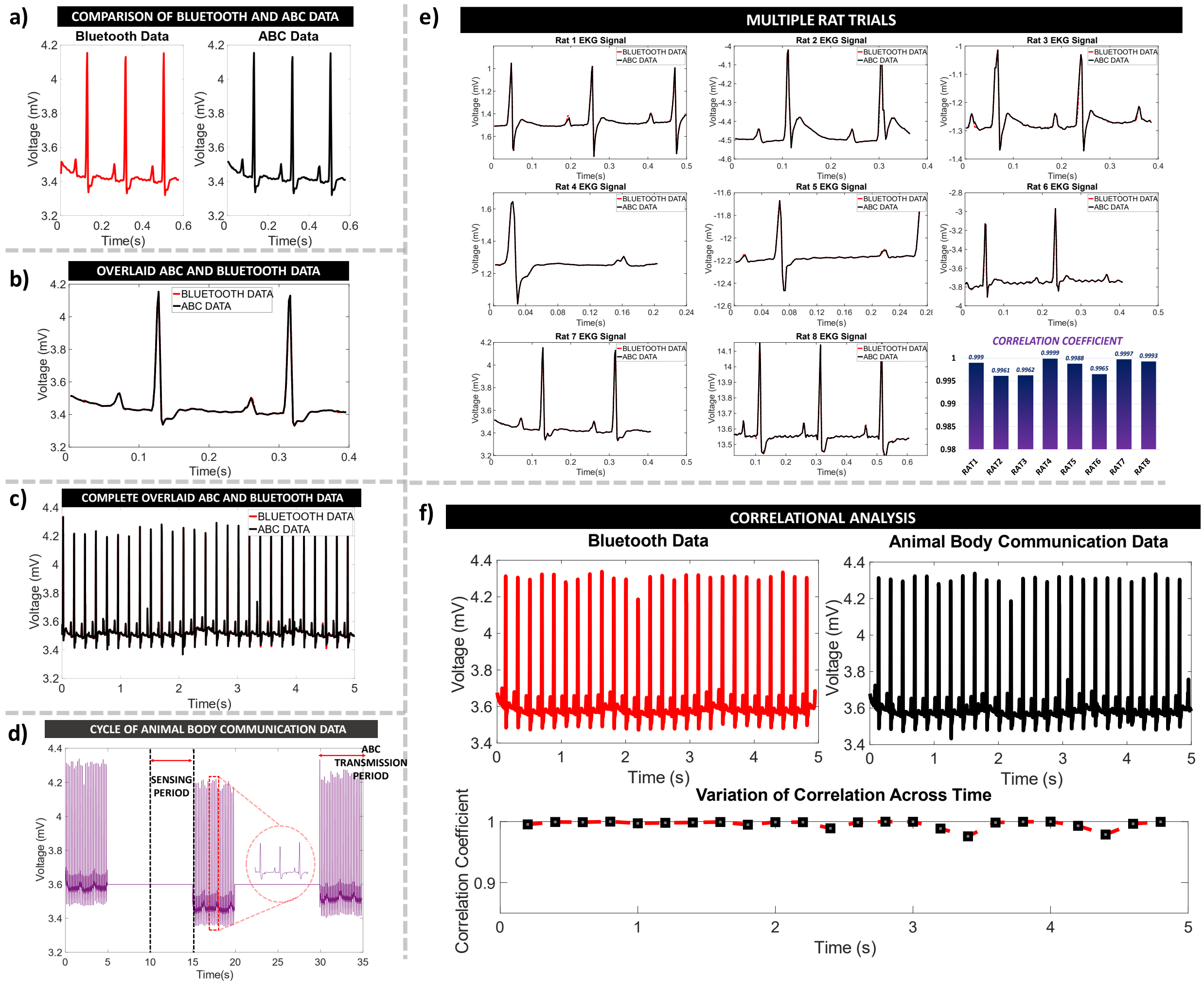
Figure 3.4. Time multiplexed sensing and transmission cycles

In the event of simultaneous sensing and transmission, given that the transmitter is placed on the surface of the body, the sensing electrodes pick up the OOK sequences used in the transmission, resulting in a corrupted sensed signal. To avoid this, sensing and transmission are time multiplexed. This technique is critical for body communication with surface biopotentials. Simultaneous surface biopotential sensing and EQS body communication should be possible and is part of the future work. Fig. 3.4**a** describes the time multiplexing cycles, data is sensed for a period of 5s followed by the transmission for 10s. The transmission of ABC and Bluetooth occurs simultaneously, however Bluetooth sequences take longer to transmit due to packet constraints resulting in a longer transmission time as compared to the sensing time. Following the transmission cycle, the sensing cycle repeats. ABC data is sent as OOK sequences which are then demodulated and decoded to retrieve the EKG sample as shown in Fig. 3.4**b**. Bluetooth samples are transmitted as characters corresponding to the ADC codes, which are then converted to corresponding samples to compare with the transmitted ABC signal.

3.5.2 Time Domain Correlational Analysis on Acquired EKG Signal

EKG signals are chosen for testing the animal body communication setup. The experiment was conducted on a total of 8 Rats over 2 months. This current set-up ensures continuous synchronized transmission of the biopotential signal from both the Bluetooth module and the ABC transmitter.

As mentioned before, the signals are time-multiplexed allowing Animal Body Communication. The EKG signal is sensed for a period of 5s followed by simultaneous transmission of ABC and Bluetooth. Fig. 3.5 shows the EKG sample comparison, 3.5**a** shows the Bluetooth and the ABC EKG data for a period of 0.6s, these two signals are overlaid in 3.5**b**, the PQRST peaks of the characteristic EKG signal align, similarly, the data is compared for all 8 rats and correlation coefficients across each trial is depicted in 3.5**e**. The correlation coefficients for all the rats was seen to be $>$ 99 %. In Fig. 3.5**c**, we can see the complete overlaid 5s sample. Time multiplexing results in an ABC transmission period followed by a wait time for the completion of the Bluetooth transmission and sensing. Fig. 3.5**d** depicts this time-multiplexed ABC data, with this cycle being continuous. Fig. 3.5**f** depicts the



a) Bluetooth and ABC transmitted signal. b) Overlaid Bluetooth and ABC transmitted signal data, depicting overlap of the EKG peaks. c) Complete 5s Bluetooth and ABC transmitted EKG Signal. d) Time multiplexed ABC transmission cycles, 5s transmission time followed by a 10s wait time to allow for Bluetooth transmission and next cycle sensing. e) Overlaid plots of EKG Signals from eight rats with correlational analysis between Bluetooth and ABC transmitted signals. f) Time varying correlational analysis of one 5s sensing cycle of rat EKG signal.

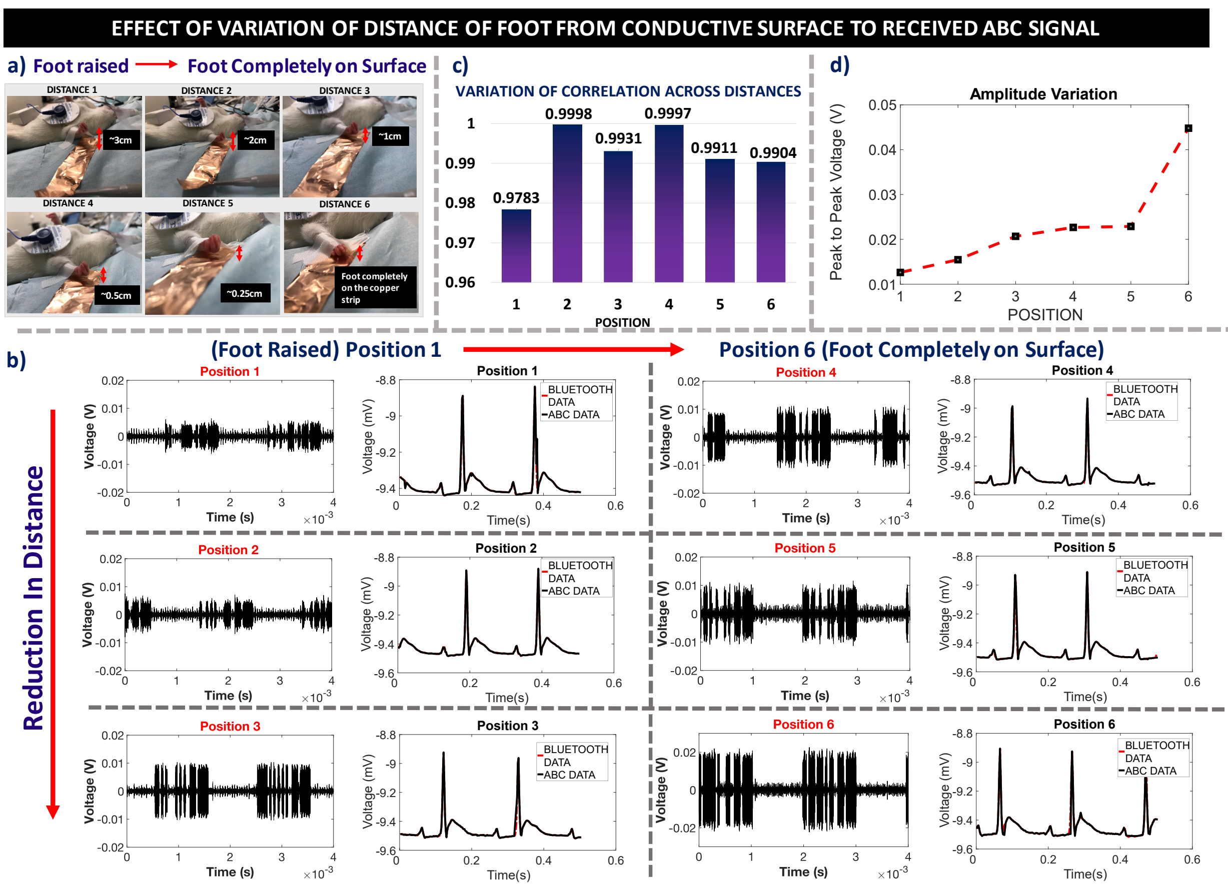
Figure 3.5. Rat Electrocardiogram (EKG) Analysis

variation of correlation across the entire 5s window, the correlation between Bluetooth and ABC is approximately 1 throughout the 5s window depicting a reliable transmission system.

Since we are using commercial off the shelf (COTS) components not designed for body communication, the sensitivity is significantly worse compared to what can be achieved with custom-designed transceivers. Due to this, the BER (bit error rate) of the system is higher. We are able to show that even with a high BER, good correlations between the Bluetooth transmitted data and ABC transmitted data. We have further elaborated on this in the Discussion section.

3.5.3 Effect of Distance of Foot from Conductive Surface to Received ABC Signal

A key component of animal body communication is the dependence of the received signal on body resistance and capacitance. Variation of the distance of the foot from the conductive surface changes the magnitude of the received signal which then tests the robustness of the system. Experimental analysis with only one foot on a conductive surface with varying



a) Experimental setup to measure the effect of distance variation on received OOK signal; In position 6, the rat foot is closest to the conductive surface and in position 1 the foot is furthest from the conductive surface. b) Received OOK signals of different distance variations and the decoded signals for the different distances c) Correlation between Bluetooth and ABC received signals as a function of distance, each depicting correlation >97\%. d) Variation in the amplitude of the received signal as a function of distance, for a transmitter amplitude of 3.3V

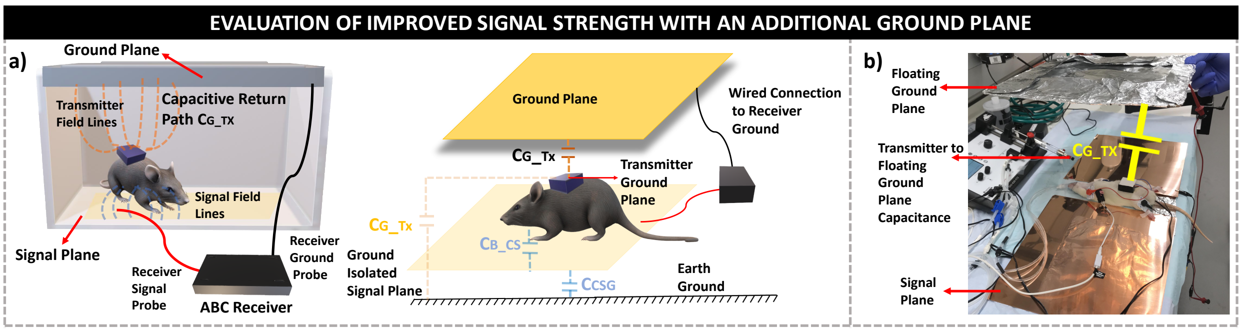
Figure 3.6. Effect of distance on received signal strength

distances shows that even with the foot raised, OOK sequences can be picked up from the conductive strip. The distance from the conductive surface was varied from 3cm (Foot Raised) to a negligible distance when the rat foot is taped to the conductive surface (Foot Completely on Surface). It is evident that as the distance from the conductive surface reduces, the amplitude of the coupled signal increases. However, even at large distances, though the signal amplitude is lower, the received Bluetooth and ABC signal can be decoded and display >97% correlation.

This case evaluated only with one foot coupling to the conductive surface. In reality, the entire rat body would couple to the conductive surface increasing the received signal. When the rat foot is raised above the conductive surface, the foot resistance R_{Foot} becomes infinite, however, even in that case C_{Foot} and C_{B_CS} exists as shown in Fig. 3.1 and the body as a whole will couple to the signal plane. Here C_{Foot} and C_{B_CS} are the capacitances of the foot to the conductive surface and the body to the conductive surface respectively. This ensures the necessary path for transmission of the signal. Since body communication works on capacitive coupling, even without complete contact with the conductive surface, the OOK sequences couple to the conductive surface. It is highly unlikely that the rat would have all feet raised above the conductive plane, for a long time. In the event of improper contact with the conductive surface or when the rat jumps, it is shown that the signals can still be received on the conductive plane and can be successfully decoded. In the event that the rat has all of its feet and body away from the conductive surface, which is not a common occurrence, C_{Foot} and C_{B_CS} would reduce and the signal may be lost. For such cases, bi-modular redundancy can be introduced in the system in which case, the lost data could be retrieved by transmitting it at a later instance. This form of error correction used for short burst errors, can ensure robust transmission. In Fig. 3.6 the variation of the distance of the rat foot from the conductive surface is shown, position 1 is furthest away from the conductive strip, while in position 6, the rat foot is completed taped on the conductive surface. The amplitude of the received signal increases with the reduction in distance for a set transmitter voltage of 3.3V. It can be seen that in all cases the sequences can be decoded, and all show high correlations with Bluetooth.

3.6 Discussion

Capacitive coupling from the transmitter ground plane to the earth's ground ensures the return path necessary for animal body communication.



a) Experimental setup depicting the electric field lines from the transmitter ground plane to the external ground plane; Capacitive return path from the transmitter ground to the external ground plane. b) *In vivo* test setup with a hand-held external ground plane. The external ground plane is placed above the rat body similar to the experimental setup, mirroring the top of a rat cage. *The rat models in a) were created using the software Paint 3D by Microsoft Corporation (Version 6.2009.30067.0).*

Figure 3.7. Effect of an External Ground Plane

The presence of a large conductive signal plate prevents the existence of such a capacitive path to ground. The addition of a conductive plane connected to the receiver ground placed above the rat body provides the necessary return path. The transmitter ground plane along with this floating ground plane forms the capacitance $\mathbf{C}_{G\_TX}$. In the setup with a rat cage, as shown in Fig. 3.7**b** the top and bottom surfaces of the rat cage are made conductive, with the top plate connected to the receiver ground, while the bottom plate, which acts as the signal plane is connected to the signal probe of the receiver. During *in vivo* tests, the ground plane consisted of a hand-held conductive plane above the anesthetized rat body. Only the feet of the rat are connected to the signal plane, with a slot in the conductive plane to allow for the placement of the rat. Fig. 3.7**a** describes the need for the addition of the conductive ground plane in a model rat cage. Similar to Fig.3.1**b**, the capacitive coupling from the device ground plane to the external ground plane provides the necessary return path. The sensor node placed on the body of the rat has the transmitter ground plane on the top surface and the signal electrode touches the body of the rat. The addition of this floating ground plane allows for the use of a large signal plane, providing a larger experimental arena for the rat to move on without being limited by the loss of the signal return path.

3.6.1 Limitations and Scope for Future work

Some neuroscientific behavioral experiments involve swimming or require the animal to walk on treadmills and mazes. Due to the nature of the signal path, a modified setup would be needed to accommodate a conductive plane. In some cases, such as swimming, this may not be possible. However, there is a possibility to extend this setup into cases involving mazes with a special setup where the maze bottom surface is made conductive to receive the ABC transmitted signals. Similarly, in the case of treadmills, a copper strip can be stuck on the belt which can then be connected to the receiver. Conductive textile could be used as the plane through which ABC signals are received. Also, given that the signal electrode needs to be interfaced with the body of the animal, this could act as a limitation in certain applications. For this setup, we consider Bluetooth as the gold standard and compare the ABC signal with the Bluetooth signal. For the receiver, we use an oscilloscope-based system to recover the data. The sensitivity of this system is low, similar to traditional oscilloscopes which results in low SNR and higher BER. The SNR_{dB} of the received signal was computed to be in the range of 7-8dB. Based on this SNR, the BER of the system for OOK modulation is of the range of 10^{-3} to 10^{-2} as stated by Salehi and Proakis [42]. Our system has a similar BER of 10^{-2}. Even with a high BER, the system achieves good correlations between the two communicated signals. With a custom-designed receiver with higher sensitivity, it is possible to achieve a much lower BER of the order of 10^{-4} for a 500kHz carrier[33]. In some of our previous works, we have shown efficient receivers which can be used to efficiently collect the signals [43]–[47].

In this system, we use time-division multiplexing to achieve ABC communication. There is a need for simultaneous sensing and monitoring in many neuroscientific studies. The basic physics of body communication does not change, and we have evaluated that body communication does not affect the actual electrophysiological signal. Given this, there is a path to simultaneous sensing and transmission which will involve a change in the engineering design of the current system. It is also possible to extend this system to support data recordings from multiple animals. For animals that are not singly housed, Frequency Division Multiple Access (FDMA) can be used, which allows us to use different carrier frequencies that can be separated on the receiver end allowing continuous transmission from multiple animals on a common conductive plane. For Electro-Quasistatic body communication, the carrier frequency is below 20MHz. The IEEE 802.15.6 standard for Wireless Body Area Networks (WBAN) specifies short-range, wireless communication in the vicinity of, or inside a human. The standard specifies the center frequency at 20MHz with a bandwidth of 5MHz double-sided supporting 2.5Mbps with OOK. For a 16 QAM (Quadrature amplitude modulation) system, the data rate can be as high as 2.5×10^6 x 4. Thus, this standard specifies communication at extremely low power and data rate up to 10Mbps. In this work, we have focused on single-channel recording up to 50Kbps. In the future, increasing the carrier frequency would allow us to increase the data rate up to 10 Mbps.

3.7 Conclusion

To conclude, in this work we demonstrate a novel communication modality in the animal studies domain and demonstrate how the advances in Electro-Quasistatic Human Body Communication (EQS - HBC) can be adapted to animal biopotential recording. Biopotential signals were acquired from the rat and transmitted using Animal Body Communication. The theory and channel model for animal body communication was developed and a custom-designed sensor node was built and tested *in vivo*.

The correlation between standard wireless transmission systems and ABC was found to be > 99 % in these tests. The power consumption for Bluetooth transmission was observed to be 29.5 mW, while the power consumption for ABC transmission was found to be 0.5 mW. This depicts a > 50x reduction in power. If a custom-designed IC is built with only ABC transmission, the device size and power can be further significantly reduced, along with the possibility to make these high bandwidth systems. The effect of variation of distance of the foot of the rat from the receiver signal plane was observed and it is clear that reliable signals can be received even with improper contact or raised feet, adding to the reliability of this communication channel. A modified test setup was explored as an additional technique to ensure robust communication. While in this study, EKG was the chosen biopotential, it can be extended to neural signal acquisition and transmission, where low power communication

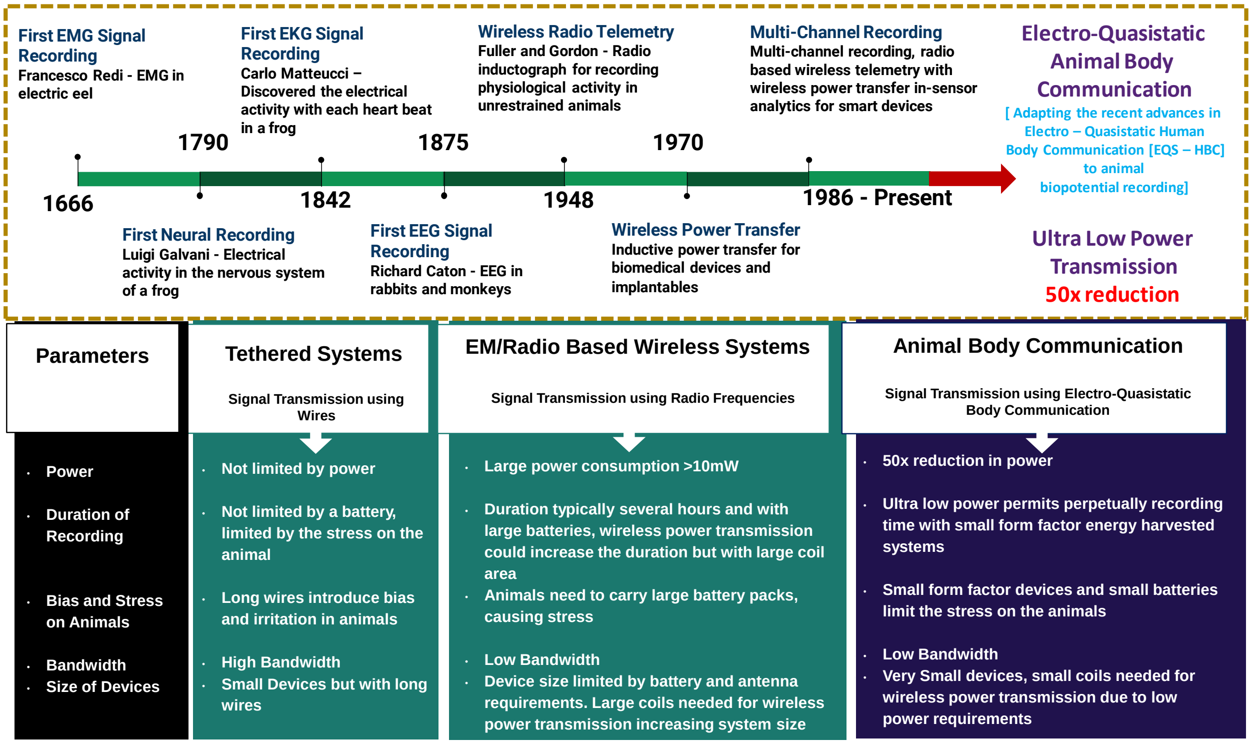


Figure 3.8. Evolution of Animal Biopotential Recordings

modalities are essential. In Fig. 3.8 the evolution of animal biopotential recording was studied [5], [6], [48]–[53], the key differences between tethered, wireless and EQS-ABC was compared and it was found that EQS-ABC can prove to be the next advancement in this domain, allowing for an ultra-low power, efficient channel model.

Most of the materials in the chapters above have been extracted verbatim from the paper: S. Sriram, S. Avlani, M. P. Ward, and S. Sen, "Electro-quasistatic animal body communication for untethered rodent biopotential recording," Scientific Reports, vol. 11, no. 1, pp. 1–14, 2021.

4. SIMULTANEOUS SENSING AND TRANSMISSION

Recent proliferation in small form factor wearables has paved the way for continuous health monitoring. State of the art in wireless technology has enabled miniaturized sensors that can be embedded in watches or wearable patches to monitor certain biopotential signals. Continuous monitoring of vital signs using wearable devices is especially beneficial to individuals with chronic conditions and allows for the timely detection of changes in health conditions. The ubiquitous nature of smart watches or smart phones has enabled universal access to continuous health monitoring systems. Some of these personal devices have been synonymous to personal trainers or trackers that help individuals keep a check on their health.

4.1 Need for Continuous Monitoring of Biopotential Signals

The need for continuous monitoring is needed to track changes in the patient's health as well as detect any sudden changes that may occur either during sleep or during levels of heightened activity. Wearable devices are battery powered and need to be charged timely in order to facilitate longer duration of recordings. It has become vital to have small devices with large battery life capable of withstanding the continuance of the experiment. Most wearable devices rely on Bluetooth or Bluetooth Low Energy for communication of the biopotential signals to a hub station or any other smart device.

Current state of the art in wearable technology includes smart watches such as the Apple Watch, Fitbit Sense, Samsung Galaxy Watch to name a few. These devices are capable of recording the Electrocardiogram (ECG) signals by placing the fingertip on the crown or dial of the device allowing for an on-demand ECG signal. These devices record single lead, two electrode ECGs with one electrode below the watch surface, touching your skin surface and the second electrode is the fingertip. Though popular among the public, such devices only record 30s worth of ECG information and do not continuously monitor the patient's ECG. Medical grade devices, such as the Holter monitors are specifically employed for continuous monitoring of the heart rhythm and detect any abnormalities that may be present in the ECG. Holter monitoring is a common technique to record heart activity for a period of 24 to 72 hours. Holter systems are generally bulky and used only by medical professionals to monitor heart activity. Recently, VitalConnect introduces the VitalPatch capable of recording heart activity continuously for at least 6 days.

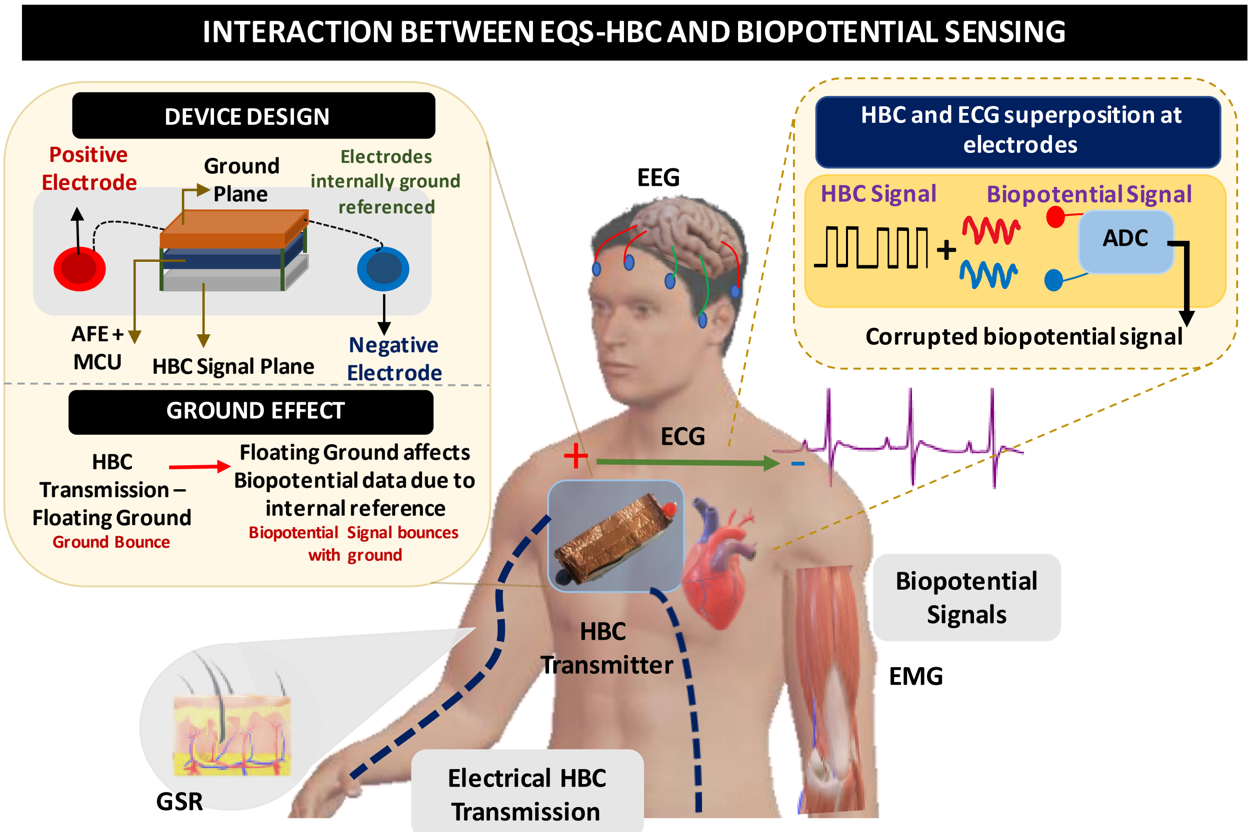


Figure 4.1. Simultaneous Sensing and Transmission of Electrocardiogram Signals

For biopotential recordings, longer duration information is vital for diagnostic purposes. Furthermore, multi-channel recordings requires large amount of data transfer which then again consumes larger amounts of power. Most smart devices rely on radiative electromagnetic (EM) communication for the transmission of the data. These communication modalities are power hungry due to the need for up-conversion the baseband signal to higher frequencies and due to the loss due to radiative communication. Thus, there is a need for a low power communication modality capable of withstanding the continuance of the experiment and in the wearable form factor. Along with having a low power communication modality, a secure communication modality is necessary when transferring medical data. It has been seen that pacemakers can be hacked and tampered with [22]. A secure communication modality should be safe from hackers such that the information remains confidential.

Vital sign monitoring has gained popularity in recent times as a means to keep track of one's health and fitness. Surface biopotential signals can be easily acquired by placing electrodes on the skin surface and measuring the potential difference through those electrodes. As mentioned, fitness trackers and watches are capable of monitoring ECG signals on demand. However there is a need for continuous monitoring of biopotential signals which would allow for a concrete diagnosis from the medical professionals.

This work for the first time describes the interaction between Human Body Communication (HBC) based transmission and surface biopotential signal acquisition. It describes the methods for simultaneous sensing and transmission of HBC and the effect of the drive circuitry on body communication. Here we provide details analysis on the system level interaction between the sensing unit and transmission unit and also experimentally prove the safety of HBC for transmitting biopotential signals. Finally we conduct experiments with the custom designed sensor node to sense and transmit ECG signals using both Bluetooth and HBC. Keeping Bluetooth as the gold standard for communication, we evaluate the performance of HBC in simultaneous sensing and transmission.

4.2 Current State of the Art in Biopotential Signal Transmission using HBC

Wireless communication modalities such as Bluetooth have been well established for biopotential signal communication and most commercially available devices utilize Bluetooth communication to transmit the biopotential signal wirelessly. The power and security benefits of HBC has been well established in literature as shown in [22], [54], [55]. These power benefits in particular aid in wearable health monitoring where miniaturized low power devices is necessary [56]. The use of HBC to transmit external signals has been shown in literature [57], [58], however, the use of HBC to sense and transmit biopotential signals is still not well determined. When dealing with surface biopotential signals, the issue arises when sensing and transmitting signals simultaneously. The HBC transmitter is placed on the body and transmits the OOK sequences through the body, the sensing electrodes pick up these sequences along with the biopotential signal. This results in a corrupted biopotential signal. Wang et al. [59] described a technique to use the same electrodes for sensing and transmission. In this technique, ECG signals acquired from the subject was transmitted through the body using impulse radio On-Off Keying. A smart switching between the sensing and transmitting electrode was employed to sense and transmit the signals. In this work, they also use a ground electrode for transmission of HBC signals, which would result in a concentration of the signal near the transmitter.

The current state of the art in biopotential recording with HBC is the use of time division multiplexing. In this technique, the sensing and transmit cycles are multiplexed. First, during the sensing cycle the surface biopotential signal is sensed and stored in the memory of the microcontroller. Following the sensing cycle, the biopotential signals are transmitted through the body. In the previous work, we demonstrate this technique using Animal Body Communication as seen in [60]. Using time division multiplexing, the acquired ECG signal from the rat can be transmitted at 50x lower power than radiative EM communication such as Bluetooth and with high correlation with Bluetooth transmission.

Though literature has shown the use of HBC to transmit biopotential signals using a time multiplexed approach, this is limited by the amount of continuous data that can be stored in the memory of the microcontroller before transmitting. Such an approach though continuous over time, does not allow for simultaneous sensing and transmission which is essential in many biopotential applications. Tang et al. [61] describes concurrent body communication and EEG sensing, however it is unclear the interaction of body communication on biopotential sensing. In their work, they focus on the common mode rejection system and do not establish how concurrent sensing and transmission is established. In this work, we describe the interactions involved in simultaneous sensing and transmission as well as experimentally demonstrate sensing and transmission using ECG signals.

4.3 Challenge with EQS-HBC and Biopotential Sensing

In HBC, the body's conductivity is used as a low loss broadband channel, to transmit signals. In Electro-Quasistatic Human Body Communication (EQS-HBC), the operating frequency is below 1MHz allowing for ultra-low power body communication at 414 nW [33] along with low energy consumption of 6.3pJ/bit [34]. The use of lower frequency for HBC transmission was not favourable due to the higher channel loss in these frequencies due to the resistive 50 Ω termination [35]. In order to use this low frequency region for communication, a capacitive termination allows for a reduction in the loss in the EQS region by 100x as shown by Maity et al. [34], [38] and Das et al. [36]. Thus, these findings make this region usable for HBC and result in ultra low power transmission. In this work, we use a capacitively terminated EQS communication. The HBC transmitter is placed on the body, touching the skin surface while the ground of the transmitter is left floating. The skin surface is a high impedance region, while the internal tissues layers are conductive. The signals pass through the body and can be picked up by a receiver placed on the body. The channel characterization and optimal design of excitation and termination configurations is shown in [62], [63]. In capacitive HBC, the entire body is modulated to a potential $\mathbf{V}_o$ given by the following transfer function,

$$\frac{\mathbf{V}_o}{\mathbf{V}_{In}} = \frac{\mathbf{C}_{G\_TX}}{\mathbf{C}_{Body}} \times \frac{\mathbf{C}_{G\_RX}}{\mathbf{C}_L} \tag{4.1}$$

Using capacitively coupled HBC, the transmitted signals can be picked up from anywhere on the body. This system varies from galvanic HBC, where the electric field lines are concentrated in proximity to the sensor. Detailed analysis of the behaviour of capacitive and galvanic HBC has established in literature [37], [64], [65]. When using EQS-HBC , the transmit signals are below 1MHz, these signals couple onto the body surface which can be picked up by a receiver placed on the body. The issue then arises that any electrode placed on the body would be able to pick up these HBC signals. When the ECG sensor is placed on the body to pick up the ECG signals, it also picks up the HBC signals.

ECG signals are recorded using a differential setup, where the potential difference between two electrodes produces the desired signal. Since the HBC signals modulates the entire body to a common potential, the HBC signals gets eliminated by the differential amplifier. This can be clearly seen when dealing with a sensor and transmitter that do not share a common ground, i.e are two different devices. When the sensor and transmitter share a common

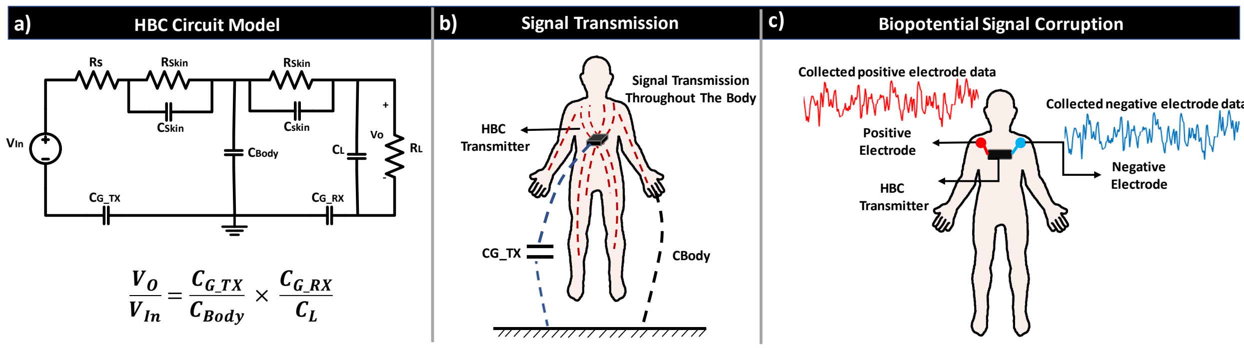


Figure 4.2. Effect of EQS-HBC on Biopotential Signal Sensing

on-board ground, while dealing with capacitive HBC, this ground plane bounces based on the transmitted OOK sequence. Due to this, the sensing unit also has a varying ground, which results in a corrupted signal. The large swing introduced by this HBC signal is much greater than the biopotential signal under consideration. The resulting signal as seen by the ADC is the low voltage biopotential signals superimposed on a high amplitude varying ground. When the differential amplifier receives this signal, the output is a noisy ECG signal, since the coupling on both the positive and negative electrode is the same and get subtracted internally. This is the reason why, in the case of two different sensor and transmitters, a clean ECG signal is obtained. However, in the case of a common ground, the bouncing ground plane results in higher quantization errors, resulting in noisy output. Detailed explanation of this is provided in section 4.5, where we describe the system design consideration.

The second issue when dealing with simultaneous sensing and transmission, is the affect of the Right Leg Drive (RLD). Extensive analysis has been performed on the affect of the RLD and explanation on how it affects capacitive HBC. The detailed analysis has been provided in the next section.

4.3.1 Interference Concerns with Human Body Communication

A common question that arises when dealing with biopotential signal recording and HBC is the effect of HBC transmission on the body's biopotential signals. Literature [41] has shown that HBC complies with the safety standards. In this work, we evaluate the effect of HBC signals on the sensed biopotential signal shape and evaluate if HBC effects the biopotential signals. To evaluate these effects, two sets of experiments were performed, first using a medical grade system similar to those used in hospitals and secondly testing sensing and transmission using the custom designed sensor node.

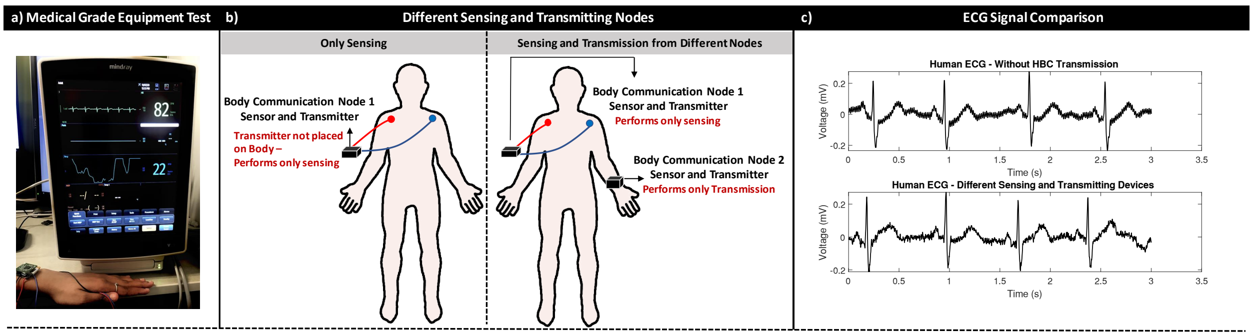


Figure 4.3. Safety of Human Body Communication

Medical Grade System Test

To evaluate this setup, the subject was connected to the vital signs monitoring system by MindRay technologies. A single lead ECG signal is recorded similar to what the custom designed sensor is capable of performing. The HBC transmitter is placed on the body of the subject. This transmitter transmits OOK signals through the body of the subject. It is observed that the transmission of the OOK signal does not affect the ECG strip and clean ECG signals are obtained. The results of this setup are described in Figure 4.3 a).

Different Sensing and Transmitting Nodes

Medical grade systems have highly efficient filters capable of eliminating any interference. In order to test the system with the custom designed sensor node, the sensor node was used to sense the ECG signal and a different sensor node was used to transmit the signals as shown in Figure 4.3 c). The sensed signal does not change when HBC signals are transmitted using a different device as depicted in Figure 4.3 c).

Thus, from these experimental analysis it can be established that HBC transmission does not effect the inherent biopotential signal. Any observed interaction or biopotential corruption is only in the electronics of the custom board and does not affect the body potentials. For simultaneous sensing and transmission from the same sensor node, hardware and software filtering techniques allow for the transmission of biopotential signals as described in later sections.

4.4 Right Leg Drive (RLD) Experiments

Biopotential signal amplifiers utilize a right leg drive circuit to reduce the common mode interference. In this technique, a known potential is driven back into the body, eliminating the floating nature of the body. Capacitive HBC relies on this floating nature body to transmit signals through the body. Thus, there is a trade off between the need for the right leg drive and the use of HBC to effectively transmit signals through the body.

While dealing with ECG signals, experimentally it was observed that the signal quality did not significantly change with or without the RLD. This is as expected in cases where a wearable is used to sense the biopotential signal. Furthermore, software filtering approaches allowed for the improvement in the signal quality. Most wearable devices do not include a RLD electrode and are capable of reproducing good fidelity signals using signal processing techniques.

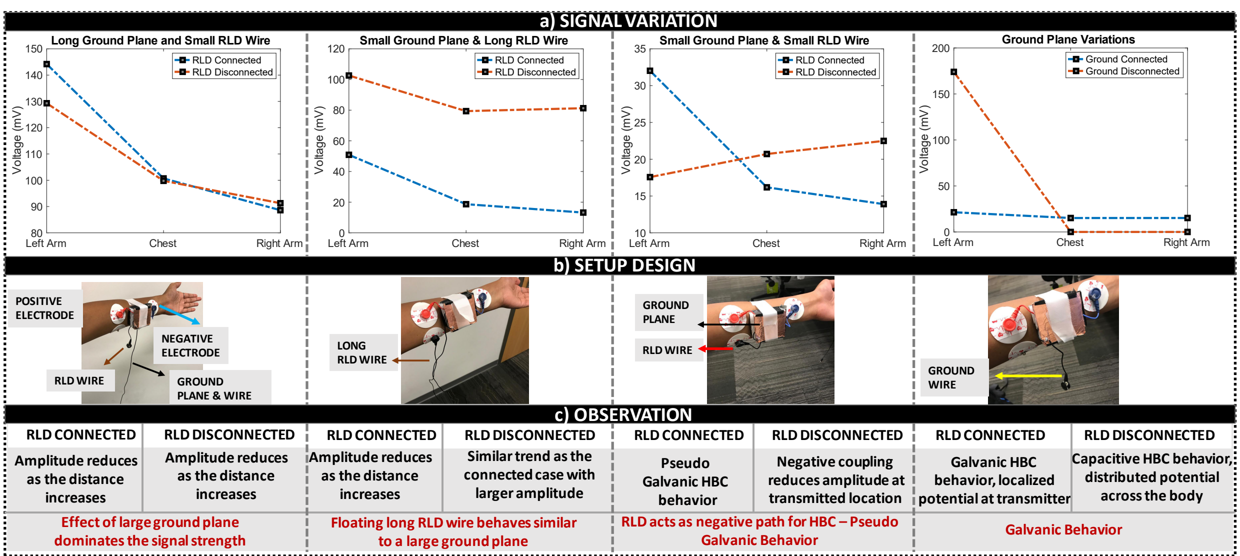


Figure 4.4. Analysis of the effect of the RLD

The effect of the RLD circuit on HBC transmission has not been explored before, this work for the first time provides an explanation for this interaction. It can be seen that the RLD circuitry affects the HBC signal transmission however it does not affect the biopotential signal quality. Thus, experimentally the elimination of the RLD can be justified.

In order to evaluate the effects of the RLD, experiments were performed where the RLD wire was connected or left floating. The experimental paradigm, involved connecting the device and the sensing electrodes to the forearm of the subject and the receiver is placed in three different locations: left palm, chest and right palm. Here, the variation in the RLD signal as well as the ground plane is taken into consideration. Due to the technique of operation of HBC, the variation of the ground plane changes the amount of received signal. This setup, only tries to observe the effect the RLD and does not necessarily collect a meaningful biopotential signal. The different cases in this experiments can be summarized as below.

4.4.1 Long Ground Wire with a Small RLD Wire

In this experiment, the device is placed on the left arm, and with a long ground wire and a short RLD wire. The receiver is placed on the same arm as the transmitter (left arm). The device design is explained in the following section. It is observed that when the RLD wire is connected to the body, with the ground wire floating, the peak to peak amplitude of the received OOK signal reduces as the distance from the receiver increases. This can be attributed to the effect of inter-device coupling [40]. In inter device coupling, the coupling of the signal from the transmitter to the receiver is greater than the signal through the body itself. When the receiver is placed on the chest or right arm, the received signal reduces. Due to the large ground wire, the signal amplitudes are much higher than what it would be in an ideal case. When the RLD is connected, the amplitude of the received signal at the left arm increases when compared to the case when the RLD disconnected. However, in this case the received signal amplitudes are dominated by the large ground plane.

4.4.2 Small Ground Plane with a Long RLD Wire

In this experiment, the device is modified to eliminate the large ground wire and only includes a small ground plane, however the small RLD wire was replaced with a long RLD wire. In this experimental setup, similar to the previous case, when the receiver is placed on the same arm as the transmitter the signal amplitude increases. When moving away from the receiver the signal amplitude reduces, however a variation is observed when the RLD wire is connected to the body versus when it is not. When the RLD is disconnected, the signal amplitude in all three location is higher than when it is connected to the body. It is inferred that a floating RLD wire aids to the floating ground plane and results in an increases ground plane surface area. When the RLD wire is connected to the body, this pseudo ground plane, changes the coupling to a pseudo-galvanic HBC from a capacitive HBC. The RLD wire provides a return path into the device allowing for a differential applied signal through the body.

4.4.3 Small Ground Plane and Small RLD Wire

In this case, the behaviour of the RLD requires further analysis. When the RLD is connected to the body, similar to the previous cases, the amplitude of the signal is higher for the left arm and drops off at the chest and right arm. This behaviour is similar to a galvanic HBC, where the fringe fields are picked up by the receiver. When analysing it in the circuital perspective, during simultaneous sensing and transmission, the RLD circuitry and the HBC circuitry both act as drivers and try to modulate the body's potential. As a result, one acts as the source and the other inevitably acts as the sink. In these experiments, it was observed that based on the behaviour of the signal transmission, the HBC signal are localized in the region of the transmitter resulting in a pseudo galvanic behaviour. The signal plane on the body, applies the OOK signal onto the body, when then finds a return path through the RLD. When the RLD is disconnected from the body, a more uniform distribution of the signal is observed across the body.

4.4.4 Ground Plane Variations

To further understand the behaviour of the RLD, a control experiment where the RLD is disconnected and the behaviour of the system is evaluated using only a ground wire. Connecting the ground wire onto the body results in a very large signal when the receiver is placed in close proximity to the transmitter and drops off to zero when moving away from the transmitter.This behaviour is consistent with literature on Galvanic HBC. When the ground wire is disconnected from the body, a uniform distribution of the signal is observed across the body, this is consistent with capacitive HBC.

In Figure 4.4, the variations in the amplitude of the received signals is depicted. In all the trials, the variations in the ground plane significantly affects the amplitude of the received signal. This is as expected and has been shown in previous literature [66]. However, when the RLD is connected to the body, the amplitude increases as the distance between transmitter and receiver reduces. These observations provide an understanding on the interaction between the RLD and the HBC signal transmitter.

Based on these experiments, certain conclusions can be drawn:

1) RLD circuitry affects the transmission of capacitive HBC when the sensor and transmitter are part of the same device. The RLD acts as a pseudo return path in the board and results in localization of the transmitted biopotential signal as seen in the above cases. This stems from the fact that two drivers on the same board are trying to modulate the body potential, eventually resulting in one source and one sink. The effect of the RLD circuitry is seen only when the transmitter and receivers are placed at a distance. Close proximity of the transmitter and receiver will result in high amplitude signal being received, which is an optimistic response to the actual HBC behavior.

2) Pseudo Galvanic response when RLD is connected when HBC signals are being transmitted. The localization of the HBC signals near the transmitter when the RLD is connected indicated a pseudo galvanic behavior wherein, the RLD acts a sink to the HBC signal. Moving away from the transmitter results in a reduction in the signal amplitude. This effect is contrary to capacitive HBC where the entire body is modulated to a common potential.

3) For biopotential signal acquistion and transmission, it is necessary to be able to pick up the signals from anywhere on the body. To allow this, there is a need for capacitively coupled HBC. Based on the above mentioned cases, it is observed that the RLD affects the HBC transmission.

4) For a wearable form factor device, it can be seen that absence of the RLD does not affect the biopotential signal quality and software processing techniques can yield clean signals.

4.5 System and Device Design

A custom designed sensor node capable of sensing and transmitting ECG was used. This device is capable of transmitting the signal through both Bluetooth and HBC. The signals are simultaneously transmitted over Bluetooth Low Energy and though HBC. Bluetooth is used as the gold standard to compare the transmitted HBC signal. The device construction is a modification of the device setup as shown in [60].

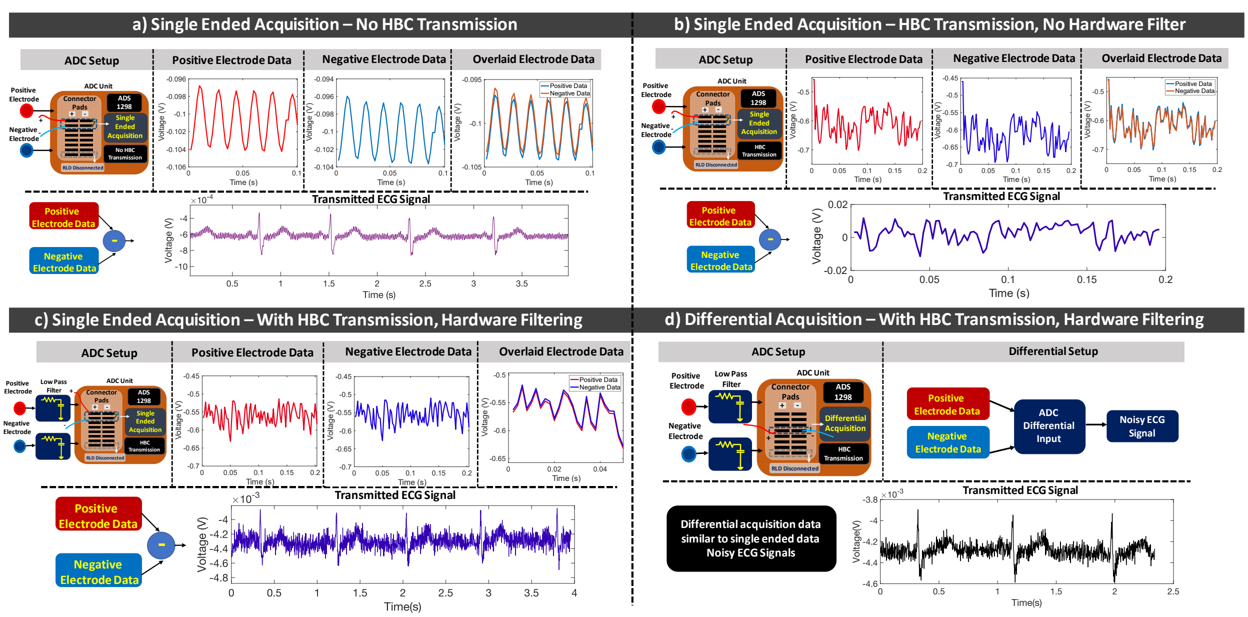


Figure 4.5. System Design Considerations

4.5.1 System Design Considerations

Simultaneous sensing and transmission of ECG signals requires analysis of the interaction of the biopotential signal transmission and the effect of the HBC transmission on biopotential signal acquisition. To understand these interactions, the effect of the sensed ECG signal is visualized. ADS1298 [Texas Instruments] is used as the ADC to acquire the biopotential signals. This includes a differential input setup, with configurable inputs. In the current design, a single lead (single channel) ECG is recorded without the RLD unit. As previously established, the presence of the HBC signal does not affect the biopotential signal and is thus a safe modality of communication. However, there exists an interaction between the acquired ECG signal and the transmitted HBC during simultaneous sensing and transmission. Such an interaction occurs in the system level and does not question the physics of HBC as a transmission modality. To understand this interaction, the following cases are evaluated and the outcomes in each case evaluated.

Single Ended Acquisition - No HBC Transmission

To evaluate the effect the HBC signal on the biopotential signal acquisition, data is individually sensed at both the positive and negative interface. The zero-insertion force connector, which is designed to acquire the signals differential, is modified for single ended acquisition allowing analysis of each electrode interface. To evaluate the ideal case of signal transmission, single ended biopotential signal recording is recorded without HBC transmission. External subtraction of the signal results in the recorded ECG signal. In this case, it can be seen that even without the RLD clean ECG signals can be obtained.

Single Ended Acquisition - HBC Transmission, No Hardware Filter

Similar to the previous case, single ended data from each electrode is recorded, where the electrodes are directly connected to the inputs of the ADC. In this case, the node is placed on the body of the subject and HBC signals are transmitted through the body. It is observed that in this case, even though the interference in each electrode is the same (as seen in the overlaid plot), the positive and negative data does not result in the ECG signal as seen in Fig. 4.5 b). It can be inferred that without a hardware filter, the HBC signals are directly picked up the ADC. This HBC signal being higher in amplitude than the biopotential signals can saturate the ADC resulting in a noisy signal.

Single Ended Acquisition - HBC Transmission, Hardware Filtering

Each electrode is first connected to a first order RC low pass filter with a cut-off frequency of 230Hz. The node is placed on the body and HBC transmission occurs through the body. In this case, it is observed that both the positive and negative biopotential signal is superimposed on a noisy interference. This interference is equal on both the electrodes as observed in Fig. 4.5 c). When subtracting the two electrode plots, the ECG signal is obtained. This signal is noisier than the case without HBC transmission. This effect can be attributed to the signal dependent quantization noise of the ADC and the residual aliased HBC signal. There is a 10x increase in the amplitude of the input signal to the ADC when HBC is transmitting versus when HBC is not. Though noisy signal are obtained, these signals can be filtered out using software filtering techniques.

Differential Single Ended Signal Acquisition

In differential signal acquisition, the positive and negative electrodes are directly connected to the differential input of the ADC. The output is then analysed to observe the interaction of the HBC signal and the biopotential signal. It is observed that a noisy ECG similar to the case with single ended signal acquisition. Comparative analysis of the sensed signal with and without HBC transmission showed a higher interference only when HBC signals are transmitting. Through this interference is common in both the electrodes, the average amplitude of the signal is larger and the biopotential signal is dominated by the interference. Based on the previous experimental analysis, it was established that the superimposition of the noise on the positive and negative data was uniform. This uniform interaction should have resulted in a clean, noise free ECG similar to the case when HBC is not transmitting.

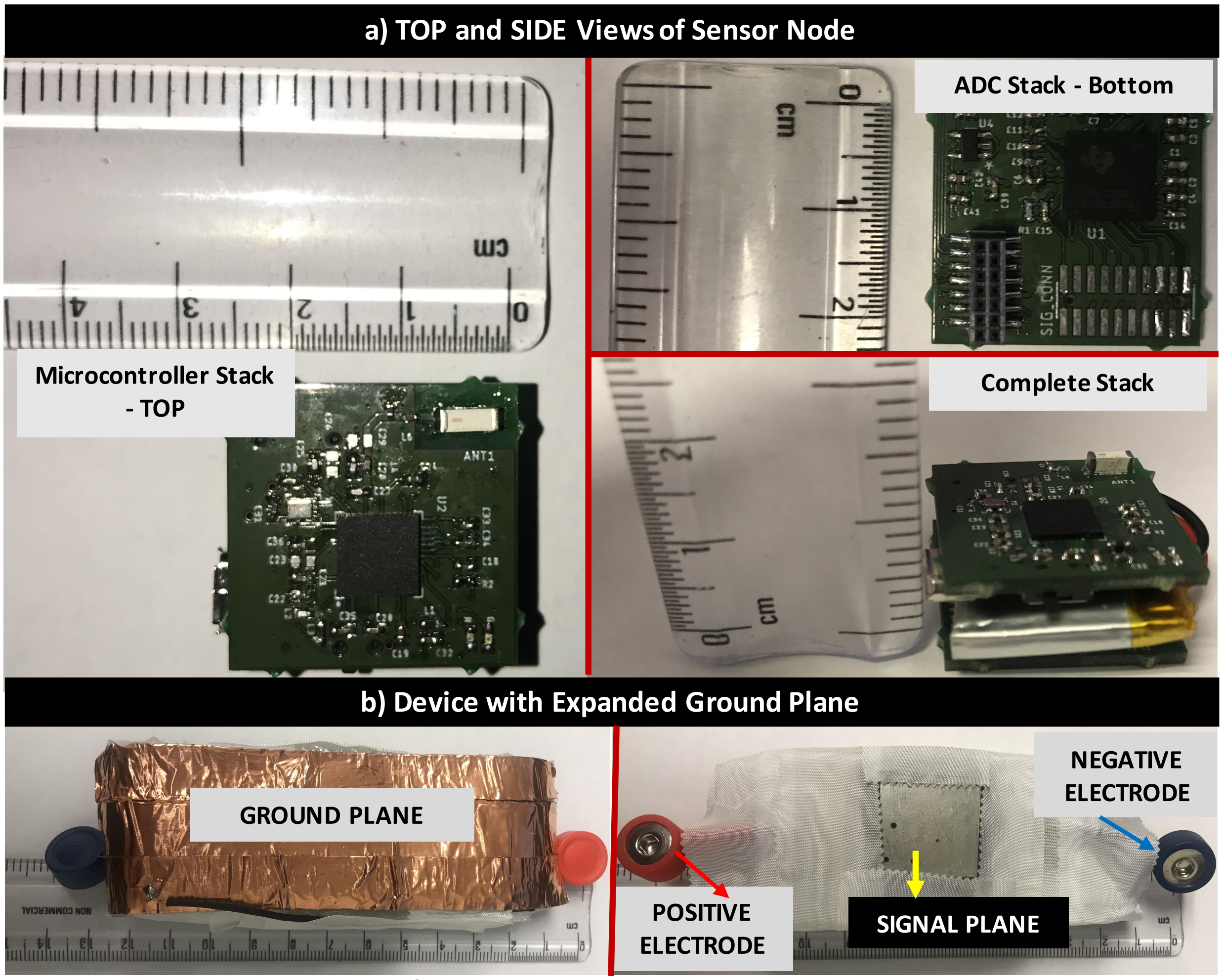
Based on these experimental analysis, certain conclusions can be drawn on the effect of the HBC signal on the sensing unit. By analyzing the single ended setup, it is observed that the interference couples equally to both the positive and negative electrode. This interference is 10x greater in amplitude than the biopotential signal amplitude, the overlaid plot depicts how both the positive and negative electrode data is affected equally. In the event, when HBC is not transmitting, this large interference is not observed and clean ECG signals are obtained. In the differential setup, a similar noisy ECG signal is observed, though the interference to both the inputs is identical, the ECG signal is noisy when HBC is transmitting. When HBC signals are transmitting, that is when the signal plane is placed on the body, the floating ground couples to the ADC as well. This ground bounce is what we observe as interference on the biopotential signals. Subtraction should have eliminated this interference, however a low amplitude biopotential signal is riding on a high potential noise signal, the ADC quantization noise increases resulting in a noisy output signal.

When HBC signals are not transmitting, the effect of ground bounce does not exist and this results in clean ECG signals. Based on the analysis in the previous section on the safety of HBC signal in transmitting biopotential signals, it is clear that HBC signal transmission does not affect the inherent biopotential signal and any interaction that exits is on a system level design and not on the human body. Post processing techniques to filter the ECG signal can result in clean ECG signals. Based on these observation, the final system design consists of the positive and negative electrodes differentially connected to the ADC. Based on the effect of the RLD on HBC transmission, RLD is eliminated from the system design. In a small form factor wearable system, RLD is not needed and noise free ECG signals can be obtained even without the RLD. Following the acquisition of the biopotential signal, software filtering techniques are employed to eliminate noise from the ECG signal.

4.5.2 Device Design

The sensor node is a sub-inch^3 custom designed sensor capable of transmitting biopotential signals over Bluetooth and HBC. This custom node consisted of two vertically stacked printed circuit boards. The top layer consists of the microcontroller stack along with the

Bluetooth transmitter, while the bottom layer consists of the ADC (ADC1298, Texas Instruments) along with the sensing pads, this SoC is particularly designed for biopotential signal recording.



a) Custom designed sub-inch^3 sensor node capable of simultaneous sensing and transmission of ECG signal using HBC. b) Complete device setup to include patch connectors for ECG sensing and expanded ground plane for HBC transmission.

Figure 4.6. Device Design

The bottom stack also contains the HBC signal plane which couples onto the body surface. The input to the ADC is a differential input from the body. In Figure 4.6, the designed sensor node is depicted along with the patch connector to connect onto the body. In Figure 4.6 b), the red and blue patch connectors represent the positive and negative electrodes which connect to the body using Ag-AgCl hydrogel electrodes. Each input signal is first passed through a passive RC low pass filter to eliminate high frequency signals. ECG signals are below 500Hz, a first order filter is capable of eliminating the high frequency HBC signals. The signal plane in between the two sensing electrodes acts as the HBC signal plane. This specific geometry also allows for equal distribution of the HBC signal to both the sensing electrodes, which results in efficient common mode cancellation.

In addition to the signal plane, the top surface of the setup, consists of an expanded ground plane. The trade off between the size of the device depends on the distance between the two sensing electrodes needed for ECG acquisition and the size of the ground plane to allow for capacitive HBC.

The setup is a compact design which can be adhered to the chest. The device design also consists of an expanded ground plane. The size of the ground plane is determined by the amplitude coupling to the body and the sensitivity of the receiver. It has also been shown that placing the transmitter on the torso results in body shadowing which reduces the signal coupling on the body [40]. In this work, the receiver is a computer-based oscilloscope by Pico Technologies. The high impedance receiver probe is connected to a conductive band on the subjects arm. Due to the lower sensitivity of the oscilloscope, a larger ground plane is needed. With a custom designed receiver with higher sensitivity the overall size of the ground plane can be reduced.

4.5.3 Principal of Operation

ECG signals are acquired using the positive and negative electrodes which are connected to the body using hydrogel electrodes. The device is placed on the chest with the signal plane touching the skin surface. HBC signals are transmitted through the body and can be picked up by the receiver. The channel loss is dependent on the return path capacitance C_{G_TX}, this is the capacitance from the transmitter ground to the earth ground as depicted in Figure 4.2. The floating ground plane capacitively couples to the earth ground to complete the loop for HBC transmission. Larger the ground plane, lower the impedance and hence lower the loss. Detailed analysis of the bio-physical model can be found in [37].

4.6 Simultaneous Sensing and EQS-HBC Transmission Results

In this experimental paradigm, the subject wears the device on the chest with the ECG electrodes connected to the body using patch connectors. The Bluetooth receiver is connected to the computer and the high impedance receiver probe of the oscilloscope is connected to a band on the subject's wrist to collect HBC transmitted signals. Once the device is turned on, it is capable of sensing ECG signals and transmitting these signals over Bluetooth and HBC. Unlike the time-division multiplexing approach, in such a setup, the device is capable of sensing and transmitting signals simultaneously.

The Bluetooth signal is transmitted as a string of characters representing the ADC codes along with the necessary deliminator to distinguish between samples. Bluetooth transmission is used only for the purpose of comparison with the HBC transmitted signal. HBC communication consists of the transmission of the 24 bit-binary sequence along with a start and stop bits added to this sequence.Each bit in HBC was represented by on-off keying, wherein a 500kHz, 50% duty cycle square wave was turned on (binary 1) or off (binary 0). In this setup, HBC is transmitted at 25kbps with an ability to increase up to 10Mbps.

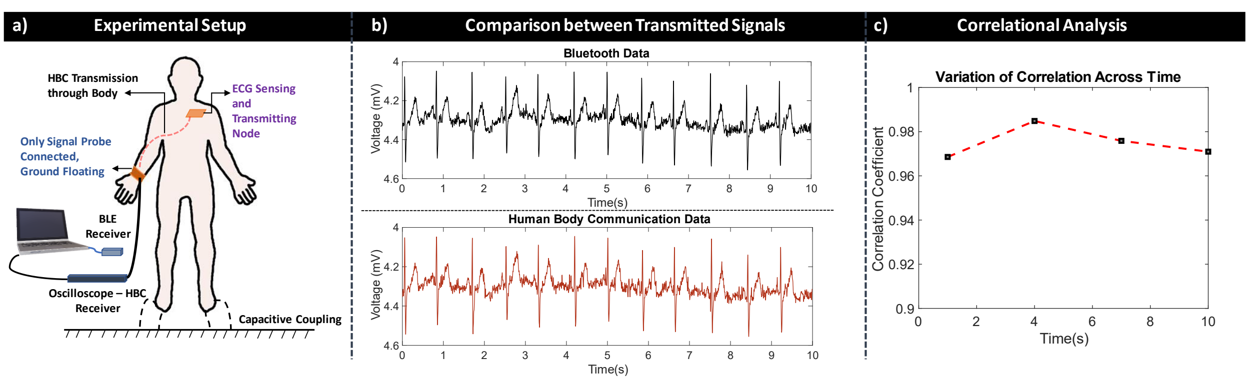


Figure 4.7. Experimental Results

4.6.1 Post Processing of HBC Sequences

Data from Bluetooth receiver is in the form of data packets which represent the ADC codes corresponding to the sample values. The HBC receiver (oscilloscope), samples the data at 3.9 MSamples/s. These OOK sequences are then processed in MATLAB to represent the corresponding samples. The data from the oscilloscope if first band passed filtered between 400KHz - 600KHz with 80dB attenuation software filters. After filtering, envelope detection followed by thresholding techniques are used to demodulate and decode the signals. Software error correcting algorithms are employed, following which the HBC data is compared to the Bluetooth transmitted data.

4.6.2 ECG Signal Processing

As explained in the previous sections, elimination of the RLD does not significantly affect the ECG signal quality. However, due to effects of ground bounce during HBC transmission, it is necessary to filter these signals.

Hardware Filter

The ECG signals are first low passed filtered using a first order RC filter with a cut off frequency of 230Hz. The data from the patch connectors are connected to these filters and the output of this is connected to the ADC input. This low pass filter, eliminated the high frequency HBC signal signal from aliasing into the biopotential signal.

Software Filtering

Data from both Bluetooth and HBC is filtered to eliminate 60Hz line interference and quantization error introduced due to HBC transmission. The data is low pass filtered at 250Hz and a notch filter is used to eliminate the 60Hz noise. Further, QRS complexes in the ECG signal are detected and smoothening techniques are employed to eliminate spurious spikes in the ECG signal.

4.6.3 Correlation Between ECG and HBC

Bluetooth data is considered as the gold standard for biopotential signal communication. Literature has established Bluetooth as a robust communication modality for biopotential recordings. For medical grade setups, wired setup are generally preferred to prevent any packet losses, however with body communication, the body cannot be ground connected and thus comparison with a ground connected system is not feasible. In this work, we compare

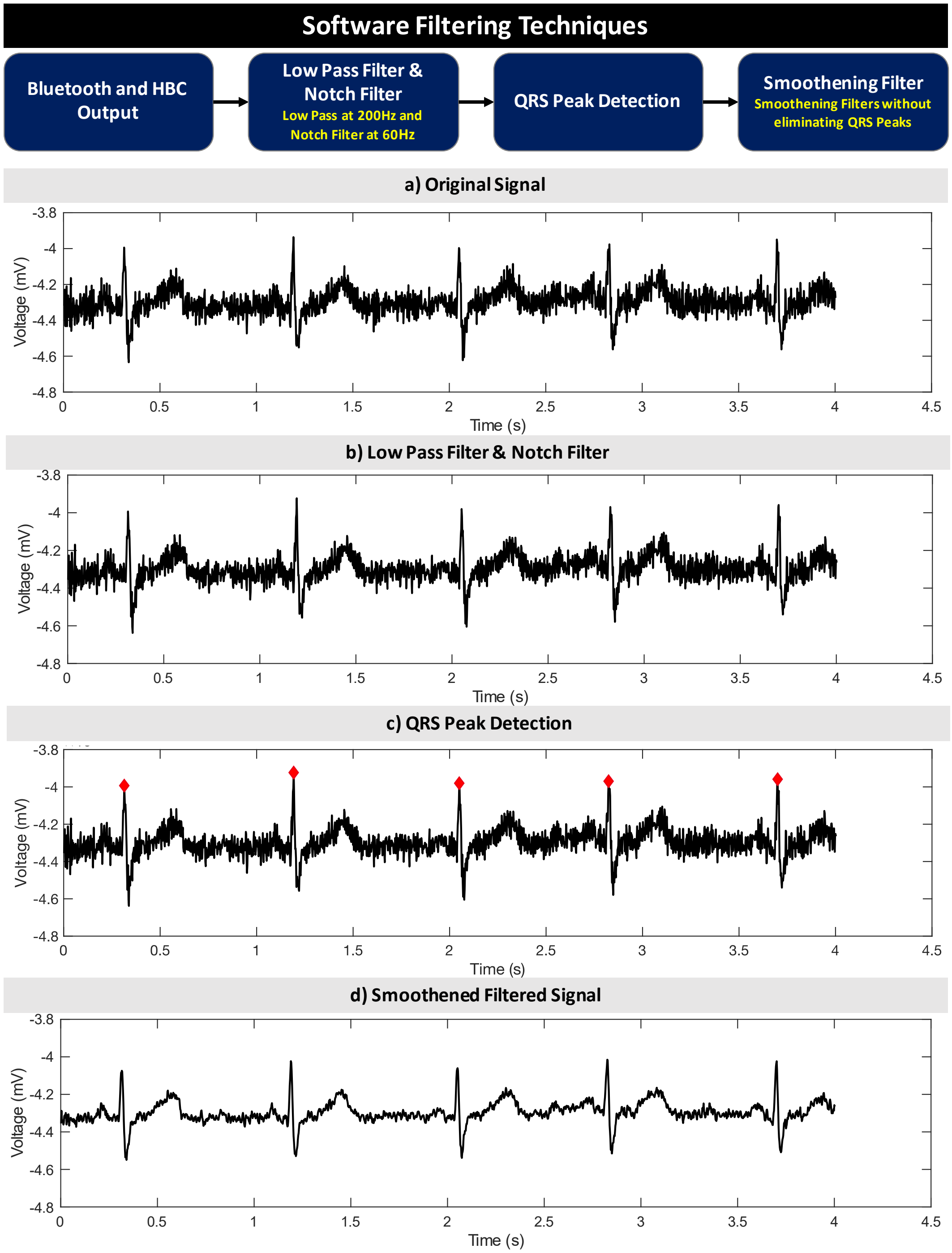


Figure 4.8. Software Filtering Techniques

the ECG signal as transmitted by Bluetooth and HBC. It is found that correlations of > 96 % are achieved.

4.7 Conclusion

This work for the first time analyses the techniques for simultaneous sensing and transmission of biopotential signals. The interaction between the RLD circuitry and the HBC transmission was studied and a pseudo galvanic behaviour was observed. Further analysis on the effect of signal dependent quantization noise provides an explanation for the degradation in the signal quality with HBC transmission. Hardware and software filtering techniques provide improvement in the signal quality, with hardware filtering being a necessity for simultaneous sensing and transmission. Correlation of >96% between Bluetooth and HBC was determined from experimental tests. Thus, to conclude this work describes the a technique for simultaneous sensing and transmission of biopotential signal using HBC, enabling an extremely low power and secure communication modality.

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