BodyWire-HCI: Enabling New Interaction Modalities by Communicating Strictly During Touch Using Electro-Quasistatic Human Body Communication

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Communication during touch provides a seamless and natural way of interaction between humans and ambient intelligence. Current techniques that couple wireless transmission with touch detection suffer from the problem of selectivity and security, i.e., they cannot ensure communication only through direct touch and not through close proximity. We present *BodyWire-HCI*, which utilizes the human body as a wire-like communication channel, to enable human–computer interaction, that for the first time, demonstrates selective and physically secure communication strictly during touch. The signal leakage out of the body is minimized by utilizing a novel, low frequency Electro-QuasiStatic Human Body Communication (EQS-HBC) technique that enables interaction strictly when there is a conductive communication path between the transmitter and receiver through the human body. Design techniques such as capacitive termination and voltage mode operation are used to minimize the human body channel loss to operate at low frequencies and enable EQS-HBC. The demonstrations highlight the impact of *BodyWire-HCI* in enabling new human–machine interaction modalities for variety of application scenarios such as secure authentication (e.g., opening a door and pairing a smart device) and information exchange (e.g., payment, image, medical data, and personal profile transfer) through touch (https://www.youtube.com/watch?v=Uwrig2XQIH8).

CCS Concepts: • **Hardware → Wireless devices**; *Wireless integrated network sensors*; *Emerging interfaces*; • **Human-centered computing** → Interaction paradigms; *Interaction devices*;

Additional Key Words and Phrases: Human Body Communication (HBC), Human Computer Interaction (HCI), HBC-HCI, Security, Strictly Touch Based Communication, Electro Quasi-Static HBC

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1 INTRODUCTION

Decades of rapid advancement in semiconductor technology has enabled computing in cheap, small form factor everyday devices. Human users are now submerged in a sea of computers, with which they are constantly interacting. User interaction with the surrounding environment is one of the key aspects of ubiquitous computing. Communication between devices during a touch-based interaction will significantly enhance the effect of a touch event and open up new interaction modalities in human–computer interaction (HCI). The standard method of achieving this is through coupling touch (Figure 2(a)) and communication (Figure 2(b)) separately. That can be done by utilizing a touch sensor (example: capacitive touch sensor) along with some wireless communication protocol such as Bluetooth, Near Field Communication (NFC) (Figure 2(c)). These protocols use radio waves, utilizing air as the communication medium. Wireless radio wave communication suffers from the problem of security and selectivity, as the signal gets transmitted through air medium and is available to any device within a certain range. As a result, information may get communicated when the devices are in close proximity, even before touch. Thus, communication strictly during a touch event i a secure and selective manner is difficult to achieve with radio communication.

Imagine if it is possible to communicate securely and selectively, strictly during a touch event (Figure 2(d)). Human Body Communication (HBC) [56, 65, 70] potentially provides such a secure, selective, and natural way of touch-based interaction between users and the environment, turning everyday objects into an interactive computing platform. HBC uses the human body as the communication channel for interactions between devices on and around the body. The transmitter couples the signal into the body through a metal electrode. The signal then goes through the skin layer and gets transmitted through the conductive tissues and fluids within the body and is picked up at the receiver end when it is in contact with the skin. As a communication method, HBC provides the following three key advantages over radio wave communication: (a) security, (b) selectivity, and (c) enhanced device lifetime.

The security aspect of HBC comes from the fact that the signal transmission is contained primarily within or in close proximity to the human body. Hence, an attacker cannot snoop any ongoing HBC transmission without either touching or coming in close proximity to the person. In radio wave transmission, this is not possible, as the signal is radiated from the transmitter into the air medium and any malicious attacker who is within the range of the transmission can pick up the transmitted signals. The human body as a communication medium can potentially provide this additional physical layer of security which is not present in radio wave communication.

The selectivity aspect of HBC also follows from the signal confinement within the body of the person, who is transmitting. Hence, multiple receivers in close proximity will not be affected by each other, as the signal intended for a particular receiver will not get picked up by an adjacent receiver. However, for radio wave wireless communication, selectivity between adjacent receivers is strongly dependent on the transmit power and sensitivity of the receiver. Communications intended for one receiver will be effectively broadcasted to other receivers in close proximity. In HCI scenarios, which require high selectivity between multiple spatially close sensors. Wireless radio communication can trigger multiple receiver devices at one time. Appropriate modality of HBC can provide appropriate selectivity in these scenarios, solving the problem of multiple receivers triggering simultaneously.

Radio wave communication suffers high loss around the body due to absorption and multi-path reflection effects. Moreover, the operating frequency of radio wave communication needs to be in the range of 100s of MHz to GHz due to the physical size limitation imposed of the antennas. Small devices are restricted to having small antennas, which makes the operating frequency higher.

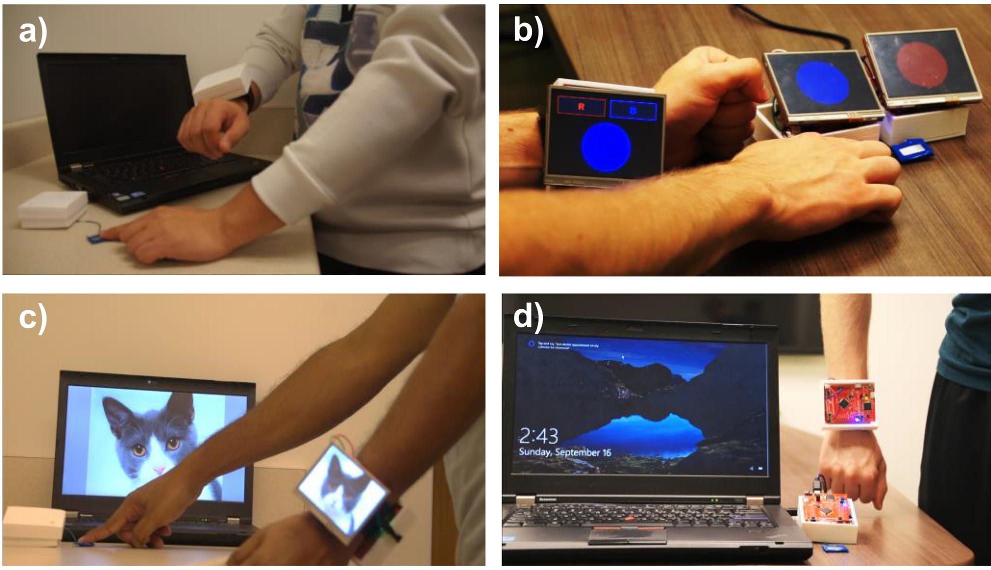

Fig. 1. *BodyWire-HCI* utilizes Electro-Quasistatic HBC technique to communicate through the body without radiating signal out of the body enabling selective and secure communication strictly through touch. (a) A wearable transmitter communicating with a receiver connected to a laptop which enables human computer interaction. (b) Demonstration showing selectivity of *BodyWire-HCI* transmission. (c) Information exchange between a wearable and a computer. (d) Secure Authentication through *BodyWire-HCI*. Link to demo: https://www.youtube.com/watch?v=Uwrig2XQIH8.

The high operating frequency increases the power consumption in radio wave communication reducing the battery life of small form factor wearable devices. In HBC operation, no antenna is required for signal transmission, as the signal is coupled to the body. Hence, the operating frequency of HBC is not limited by any physical parameter. Therefore, systems utilizing HBC can operate at lower frequencies which make them power efficient compared to wireless systems using radio waves, subsequently increasing the lifetime of the devices and systems.

These potential advantages, coupled with the natural and seamless integration of touch in everyday life, make HBC a promising alternative to radio wave communication for acting as the communication medium during interactions between a wearable and any computing device in the surrounding environment (Figure 1). Coupling communication strictly with a touch event can open up new interaction modalities utilizing everyday conductive objects as potential touch sensors. HCI through HBC can enable different applications such as authenticating a door with touch through transfer of a key, transferring data between a computer and smart watch, and information exchange between smart watches of two people during a meeting or some other social gathering [56]. In this article, we develop an HBC system that utilizes electro-quasistatic transmission of electrical signals through the human body to achieve enhanced selectivity and security by minimizing signal leakage out of the body into the air medium. The receiver and transmitter communicate with each other only when both devices are in direct contact with the human body and there is no communication even when the devices are in very close proximity to the body. Electro-quasistatic Human Body Communication (EQS-HBC) transmission requires operating at a low frequency range to minimize signal leakage out of the human body. Previous studies characterizing the human body channel as a communication medium have shown the body to be a high loss channel at low frequencies, making it undesirable to operate HBC systems at low frequencies.

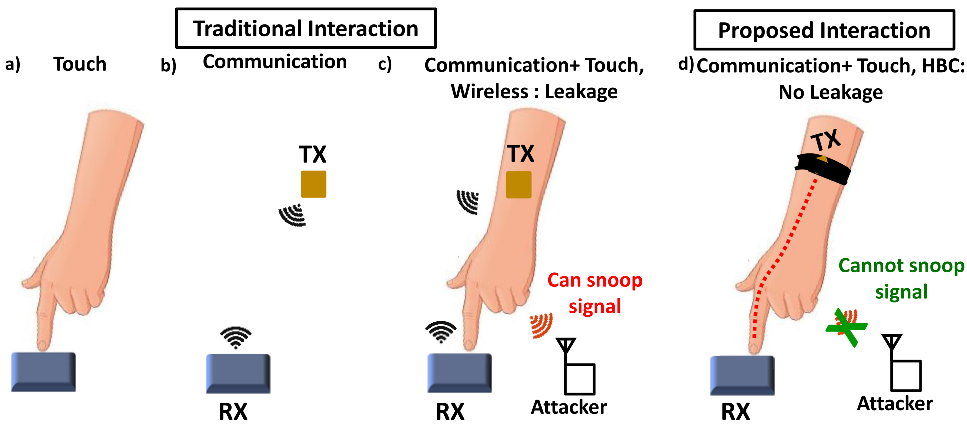

Fig. 2. Different possible interaction scenarios between a body worn wearable and off-body computing device. (a) Only Touch: a touch sensitive surface is used to detect a touch event. (b) Only communication: a wearable and machine communicating with each other through wireless communication. (c) Communication while touch through wireless communication radiates the signal, resulting in communication even without touch and also enabling data snooping from an attacker. (d) Communication during touch through HBC confining the signal within the body enabling communication strictly during touch.

Hence, certain system design techniques have to be followed to enable HBC signal transmission at low loss at these low frequencies to minimize signal leakage. The main contributions of this article are the following:

A. Technical Advancement of EQS-HBC for HCI:
   - EQS-HBC HCI Device Development: This article develops the first EQS-HBC device for HCI applications, using the fundamental theory developed previously [14]. The channel loss introduced by the body determines the amount of signal at the receiver end and is dependent on different factors specific to the device design, such as the form factor, the size of the ground plane, the proximity between the device ground and signal plane, location of the body, and quality of signal coupling into the body. We design a wearable EQS-HBC device taking these different factors into account.
   - EQS-HBC Channel Characterization for reliable communication: Detailed characterization of the channel is carried out for different conditions such as transmitter/receiver electrode size (Figure 7) and posture of the human body (Figure 11). These are necessary to determine the requirements of the receiver such as sensitivity and reliable data rate of communication. This helps design a receiver that can work under different conditions. This article has focused on these evaluations to further the understanding of the EQS-HBC channel and make informed design decisions for the *BodyWire-HCI* prototype, such that it is possible to reliably send data strictly through touch.
   - Interaction Aware Signal Leakage Evaluation: The selectivity property requires further evaluation of signal leakage on multiple electrodes in close proximity to each other. This article also focuses on how the user's technique of interacting with the devices can potentially affect these signal leakages and hence the selectivity property.

B. Computer Human Interaction Demonstration through EQS-HBC:
   - EQS-HBC Demonstration: This article develops an EQS-HBC HCI device to show the first Commercial off-the-shelf (COTS) component-based demonstration of EQS-HBC. The different design considerations for such a system is also discussed in detail. The

designed EQS-HBC system is used to demonstrate three applications towards computer–human interaction.

—Strictly Touch Based, Selective Communication: This article demonstrates how the signal confinement property of EQS-HBC can be extended to strictly touch–based communication and selectivity. These properties are then applied to demonstrate three applications towards computer human interaction scenarios.

—Simultaneous multi-user multi-touch identification: The low signal leakage of *BodyWire-HCI* enables simultaneous multi-user multi-touch user identification, not possible with current HBC technology because of cross-device interference due to leakage.

The rest of the article is organized as follows: Section 2 provides background information about how the human body can be utilized as a communication channel for interactions strictly through touch and discusses the previous demonstrations of HBC identifying the open problems. Section 3 discusses the fundamental techniques used in *BodyWire-HCI* system to enable HBC transmission with minimal leakage. Section 4 characterizes the human body channel as a communication medium and determines the range of loss with variation among subjects and parameters such as electrode size. Section 5 provides the design goals of the prototype, while Section 6 describes the safety aspects and limitations of the *BodyWire-HCI*. The demonstrations of the *BodyWire-HCI* system are shown in Section 7 and Section 8 concludes the article.

2 MOTIVATION

2.1 Touch–Based Communication

Touch has been widely used as a medium for humans to communicate with devices around them. Touchscreen displays on mobile devices and computers provide an interactive way to communicate with those devices. Touch has also been used as an interaction technique for 3D interactive environments [5, 22] and haptics. Touch-based interaction has even been recommended for older users due to its limited cognitive, spatial and attentional demand [8, 67]. However, adding interaction along with touch, which enhances the effect of touch, is seen as a promising application area [4, 9]. One example of such application is using mobile phones to interact with larger public displays [23]. Paying through mobile applications is also one such example where the user has to authenticate himself/herself by touching a fingerprint sensor and subsequently use NFC-based communication to finish the payment. Enhancing touch-based interaction by combining it with communication can increase the convenience of such applications significantly. In this article, we utilize HBC to enable communication strictly during touch, enhancing the effect of touch-based interactions.

BodyWire-HCI essentially utilizes electrical signal transmission through the body to provide a way for humans to interact with devices. There is a large body of work in the HCI field which utilizes the interaction of human body with electrical signals or electric fields. Finding Common Ground [20] offers a comprehensive summary of Capacitive Touch Sensing in HCI. Field mice [60], Smartskin [53], Diamond Touch [16], Swiss-cheese extended [19], Opencapsense [34], DGTS [21], Platypus [66], Tile Track [62], Cohn et al. [12], and Gong et al. [18], and the like use electric field sensing to identify the location of single/multiple touches using an array of transmitter and receiver devices. *BodyWire-HCI* doesn't enable us to detect touch location and it is not possible to get the resolution achieved through Electric Field Sensing (EFS). Instead, it augments touch sensing by adding communication during touch. Implementations such as Skintrack [68], Aurasense [69], High5 [32], Living Wall [6], iSphere [35], Multi-Touch Skin [50], Humantenna [14], and Your noise is my command [13] enable gesture recognition utilizing the interaction between an electric field and the human body. Biometric authentication/identification has also been implemented

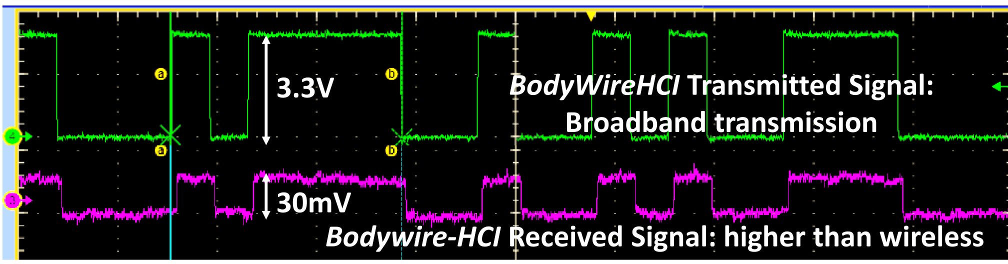

Fig. 3. Signal Attenuation characteristics of HBC. The transmitter sends out a 3.3V signal, which is then transmitted through the body and gets attenuated to a 30mV signal at the receiver end, showing a human body channel loss of about 40dB. The channel loss is dependent on the size of the device, location of the device on the body and body posture and can go up to 70dB.

through touch-based interaction between humans and computers, such as Fiberio [26], Biometric Authentication [29], On Demand Biometrics [27], Wearable key [46], Bodyprint [28], Capacitive Fingerprinting [24], Touche [72], Handsdown [55], and Carpicio [33]. These implementations use biometrics for identifying an individual. We demonstrate authentication/ identification as a possible application of *BodyWire-HCI*. However, in this case a password/key is sent through the covert channel through the body and allows an additional method of authentication and augment with biometrics to achieve multi-factor authentication. TAP [51], Touchcomm [63, 64], Earthlings Attack! [61], Wearable key [46], Skintrack [68], Aurasense [69], CarpetLAN [17], and so on, utilize the body as the communication medium to interact between devices and is the closest and most directly related set of work compared to *BodyWire-HCI*. However, no other HBC work has shown communication strictly during touch because of significant radiation during in body data transmission through HBC. *BodyWire-HCI* is the first system to achieve strictly touch–based communication through its low frequency operation and progresses state of the art HBC implementations. In the next subsection we look into the fundamentals of HBC and discuss a few of the circuit and system level implementations of previous HBC systems.

2.2 Background – HBC Basics

HBC, also commonly referred to as Body Coupled Communication or Intra-Body Communication was first proposed by Zimmerman [70] as a method of communication for devices in Personal Area Networks. A battery-operated transmitter is used to couple a small amount of modulated displacement current into the human body and transmit it through to the receiver. This kind of HBC technique is termed as Capacitive HBC, since the closed loop circuit in this scenario is formed by a capacitive return path through coupling between the transmitter and receiver ground planes with the surrounding environment. However, this results in the signal getting attenuated at the receiver end, as shown in Figure 3. Wegmueller et al. [65] proposed Galvanic HBC, where the transmitted signal is applied to the human body between two electrodes connected to the body and picked up at the receiver end through two similar electrodes. However, it has been established that in Galvanic HBC the signal gets attenuated more for longer distance communication within the body (example: left arm to right arm/arm to torso). Recently there have been studies about Magnetic HBC [52], where magnetic fields are used to communicate between devices on the body. However, this requires bulky coils at the transmitter and receiver end to pick up the magnetic field. Hence, the receiver and transmitter device sizes become big and are not suitable for the design of a wearable form factor device. Hence for our demonstration, we have used Capacitive HBC as the type of HBC transmission.

Table 1. Categorization of Previous Literature Focused on Touch-based Communication

Electric Field Sensing	Gesture Recognition	Biometrics	Human Body Communication (HBC)	
[12], [16], [18], [19], [20], [21], [34], [53], [60], [62]	[6], [13], [14], [32], [35], [50], [68], [69]	[24], [26], [27], [28], [29], [33], [46], [55], [72]	HCI: [17], [25], [30], [46], [49], [51], [61], [63], [64], [68], [69] Circuit: [3], [10], [11], [37], [40], [41], [54] Channel Char: [1], [39], [42], [44]	Electro-QuasiStatic HBC (Strictly Touch)
				This Work

BodyWireHCI is the first system which enables Strictly touch–based communication through signal confinement. Comparison of *BodyWire-HCI* with State-of-the-Art Touch–Based Communication Techniques.

2.3 Related Work – HBC

There have been previous studies showing both system level and circuit level implementations of HBC based systems for interactions between wearable devices and computers as classified in Table 1. Microchip Technology's Bodycom system [73] shows interactions between a wearable transmitter on a pocket and other everyday objects such as a car/home door, power drill, and the like. The devices are able to communicate when the transmitter is kept in the pocket, showing that direct touch is not a strict requirement for communication. [74] shows the demonstration of a ring being used as an intermediate device for exchanging data between two computers. The data is downloaded from a computer into the ring while touching a pair of electrodes attached to the computer. But in this scenario the communication is done by the touch of two fingers, which forms a closed path between the transmitter and receiver through the electrodes, making it unusable for wearable devices, like a smartwatch/smart-band. The demonstrations in [30] show the transfer of an image between a mobile transmitter and a receiver terminal connected to the wall. It also shows that even when the transmitter and receiver are a few centimeters away from each other, they can still communicate with just the transmitter being held in hand and the receiver not in contact with the body. [71] shows applications where the color of the clothing of a person or a ball changes depending on the color displayed at the transmitter end. Various demonstrations of cabinet unlocking and authentication on doors are shown in [49]. However, in these cases, the demonstrations work when the person is not in direct contact with both the transmitter and receiver devices. [63] shows multiple applications utilizing HBC for HCI, such as playing interactive games by touching or walking on custom electronic floor tiles. The authors show that even when the person wearing the transmitter is standing on one floor tile, there is signal leakage into the adjacent floor tiles. In addition to this the experiments show communication between the wearable and the floor tiles through the shoes of the user, proving that touch is not a strict necessity for communication. The demonstrations in [25] show the usage of commodity devices such as smartphone and touchpads to transmit secret keys through the body for user authentication. The achievable data rate in this scenario is a few hundred bits per second, which is sufficient for the authentication demonstrations shown but not sufficient for information transfer.

The studies discussed so far focus on system level demonstration of HBC. There have also been previous studies [3, 10, 11, 37, 38, 43, 54], which focus on the design of custom HBC integrated circuits. Most of these designs also operate at high frequencies, making them prone to signal leakage out of the body.

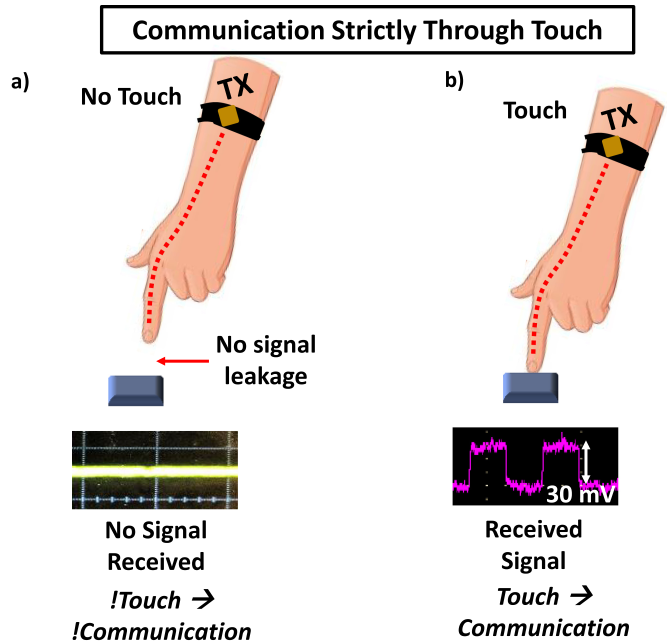

Fig. 4. (a) EQS-HBC enables signal confinement within body. So, there is no signal leakage out of the body. (b) This results in communication strictly during touch.

2.4 Open Problems

The previous demonstrations of HBC show information exchange when a path exists between the transmitter and the receiver. However most of them suffer from signal leakage, which results in the receiver triggering even when there is no direct physical contact with the receiver. [30] shows information getting transferred even when the transmitter is a few centimeters away from the receiver. The authors in [63] show that signal leaks into the adjacent floor tiles even when the person with the transmitter is standing on a separate floor tile. Other demonstrations also show communication when the device is not in direct contact with the body. This shows that there is significantly high signal leakage out of the body, resulting in communication between the devices even without direct touch. As a result, these demonstrations do not have the property of information exchange strictly during touch.

However, the goal of this article is to design systems such that a touch event is the necessary and sufficient condition for signal transmission (Figure 4). This can also be represented as

$$\text{Touch} \rightarrow \text{Communication} \tag{1}$$

$$!\text{Touch} \rightarrow !\text{Communication} \tag{2}$$

Each of the individual equations provides a necessary condition for communication. When combined together, these equations provide the necessary and sufficient condition for strictly touch–based communication. However, it does not differentiate between the touch of an intended device or a malicious attacker. An attacker can snoop the signal only if he can make contact with the person. Strictly touch–based communication reduces the possibility of signal leakage to an attacker significantly compared to other scenarios, where the signal is available even when the attacker is

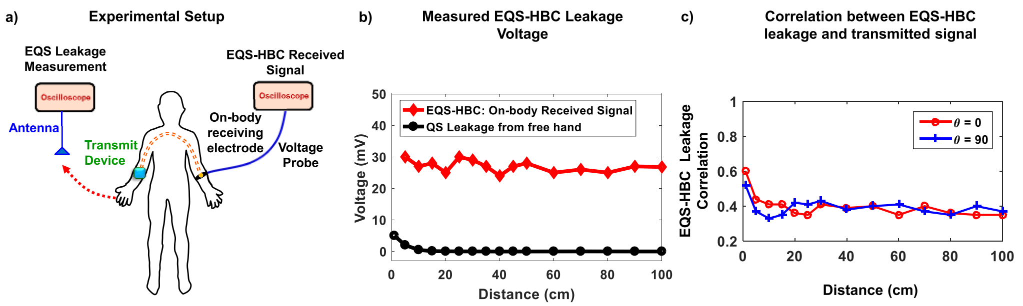

Fig. 5. Measurement of signal leakage into the air, as the receiver is moved away from the body. (a) Measurement setup showing leakage measurement and on-body signal transmission measurement. (b) Plot of measured voltage with distance away from body. (c) Correlation between the measured and transmitted voltage over distance at different angles. The correlation is <0.5 even for distances a few cm away from the body, highlighting the difficulty for an attacker to snoop an ongoing transmission [14].

away from the person. This can provide a security benefit compared to previous implementations of HBC.

3 FUNDAMENTAL TECHNIQUES

We design the *BodyWire-HCI* prototype following certain system level techniques and parameter choices to minimize signal leakage out of the body and ensure selectivity and security during HCIs. The key system level design techniques utilized to achieve this are: (a) EQS-HBC, (b) Capacitive receiver termination, and (c) Voltage mode transmission and reception. In this section, we discuss the effect of each of these techniques in achieving the goal of higher selectivity and security.

3.1 Electro-Quasistatic (EQS) HBC

In EQS-HBC, the signal transmission between the transmitter and the receiver occurs through electric fields, contained within the human body [15]. The signal propagation occurs primarily through the low impedance tissue layers underneath the skin. Propagation of electro-magnetic waves is not the primary mode of communication in this scenario. Hence, there is minimal signal leakage out of the body during ongoing signal transmission within the body. The low frequency operation of the HBC system enables electro-quasistatic operation and is the primary reason for the confinement of the transmitted signals within the body. Figure 5 shows the measured voltage at varying distances from the body when there is a signal transmission within the body at 1 MHz frequency. It can be seen that the amount of signal leakage in the air falls below 10 millivolts even 1 centimeter away from the human body, showing signal confinement primarily within the body. The signal received only a few centimeters away from the body also shows minimal correlation with the transmitted signal. Hence, it will be nearly impossible for an attacker to successfully decipher the ongoing data transmission even from a distance of a few centimeters away from the body. However, to achieve electro-quasistatic operation, it is important to operate at low frequencies to minimize signal radiation. Previous studies characterizing the human body [1, 2, 7, 31, 36, 39, 44, 47, 52] had shown high signal attenuation at low frequencies, making it an undesirable frequency band for HBC transmission. However, for our current system design, we use capacitive termination and voltage mode operation to reduce the human body channel loss at low frequencies and extend the bandwidth of the human body. This enables the use of the body as a wire-like communication channel, even in low frequencies and opens up the possibility of using it as a secure, selective communication channel.

This article develops a HCI device using EQS-HBC for a wearable form factor. This article further investigates the EQS-HBC channel under different conditions. The signal confinement property of EQS-HBC is evaluated through signal leakage measurements on multiple electrodes in close proximity to each other. The understanding developed from the channel characteristics and signal leakage measurements are utilized to show the first COTS component-based demonstration of EQS-HBC. Moreover, the signal confinement property of EQS-HBC is extended to selective, strictly touch–based communication to demonstrate applications towards computer human interaction. The selectivity property of *BodyWire-HCI* enables modalities which require *simultaneous multi-user multi-touch identification*, not possible through existing HBC or wireless communication techniques.

3.2 Capacitive Termination

The value and type of termination impedance of the human body channel at the receiver end is an important parameter in determining the operable frequency range of the HBC system. Resistive termination is the commonly used termination methodology in most previous studies. However, in our design, the termination at the receiver end is done through a high impedance capacitor. Because of the capacitive return path between the transmitter and the receiver, using a capacitive termination at the receiver end creates a loss response independent of frequency [38, 40, 41, 57–59]. This reduces low frequency loss and enables HBC at these frequencies. In our current demonstration, specific design techniques are followed such that the receiver's input impedance and hence the termination impedance seen by the channel is primarily capacitive. Also, the receiver is designed to minimize the input capacitance, which reduces the channel loss.

3.3 Voltage Mode Transmission and Reception

Previous HBC system designs primarily use signal power as the metric for communication between devices. However, power transmission requires low impedance termination at the receiver end, and therefore is not suitable for low frequency signal transmission through HBC. In our demonstrations we use voltage mode operation, where the transmitter sends out voltage through the system and the receiver is designed to maximize the received voltage. Voltage mode operation requires high impedance termination at the receiver end, enhancing the amount of signal received for low frequency HBC operation [41, 57]. Hence, design of voltage mode systems also help reduce the low frequency loss. This in turn enables EQS-HBC, providing signal confinement within the body.

4 HUMAN BODY COMMUNICATION CHARACTERIZATION

In order to reliably realize the goals of selective and secure EQS-HBC for a wide range of applications, *BodyWire-HCI* was designed after careful user experimentation to ensure system functionality independent of human factors and also provide security and selectivity. This requires characterizing the human body as a communication channel along with the signal leakage aspect of EQS-HBC. Channel characterization is done through an experiment on channel loss variation among different users. In addition, design parameters, such as electrode size, were also investigated to determine best practices for hardware design of EQS-HBC systems. In these experiments, signal of a particular frequency is applied at the transmitter end and the received signal is measured through an oscilloscope. The transmitter device is on the wrist of the user and the received voltage is measured on the other hand. The channel loss is calculated from the ratio of the received (V_{Rx}) and transmitted voltage (V_{Tx}) ($Loss = 20 \log_{10} \frac{V_{Rx}}{V_{Tx}}$). The selectivity and security properties are evaluated through signal leakage measurements at different positions away from the body. Since the signal leakage magnitude is very small, a spectrum analyzer, which provides more sensitivity

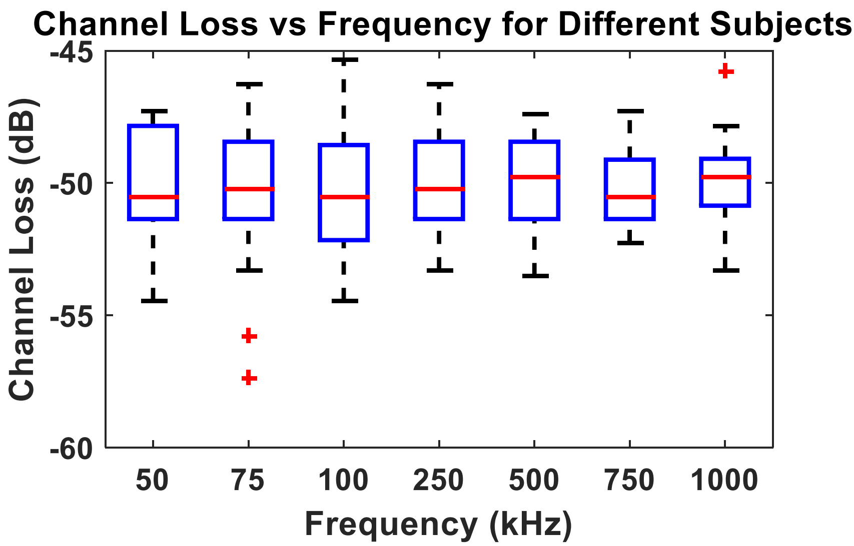

Fig. 6. Box and whisker plots of channel loss across different subjects with frequencies. The results show that the channel loss is almost independent of frequency and is primarily contained within -55 dB to -45 dB.

compared to oscilloscope, is used for measurements. The spectrum analyzer measures the power of the received signal (P_{Rx}). The noise floor (P_{noise}) of the spectrum analyzer determines the lowest signal that can be measured by the equipment. In a practical scenario, any signal under the noise floor cannot be recovered by a receiver. Hence, to establish the strength/quality of the received signal for leakage measurements we compare it with the noise floor and use Signal to Noise Ratio (SNR) as the measurement metric ($SNR = 10\log_{10}\frac{P_{Rx}}{P_{noise}}$). Sections 4 and 5 use these measurement setups to evaluate the channel and leakage characteristics of the EQS-HBC channel. The results of this evaluation are used to determine the implementation details of the *BodyWire-HCI* system, particularly the receiver device. The implementation details are discussed later in Section 7.

4.1 Loss Variation Across Subjects

Channel loss measurements were acquired during different times of the day for seven users over an extended period of time. Environmental interferences and variation in ground coupling on the human body (posture) were strictly controlled in order to measure channel loss variation. External interferences present in the laboratory environment and picked up by the body were eliminated through passive filtering to accurately measure the received signal amplitude. The results are presented in Figure 6 to show the range of intra-body channel loss for seven different subjects (four male and three female) across multiple days in the frequency range of 50 kHz to 1 MHz.

The channel loss ranges between −55 and −45 dB for all users while implementing EQS-HBC. Using the data from this characterization, *BodyWire-HCI* is designed with an input range capable of handling this dynamic signal from all users and is robust against channel loss fluctuations between different users, as well as the fluctuations arising from use during different times of the day.

4.2 Loss Variation with Transmitter/Receiver Electrode Size

Electrode size is a critical factor in the design of an HBC device as the total device form factor of a wearable HBC device is critically dependent on the electrode size. During the design of *BodyWire-HCI*, the effect of electrode area on channel loss was studied for both the transmitter and receiver

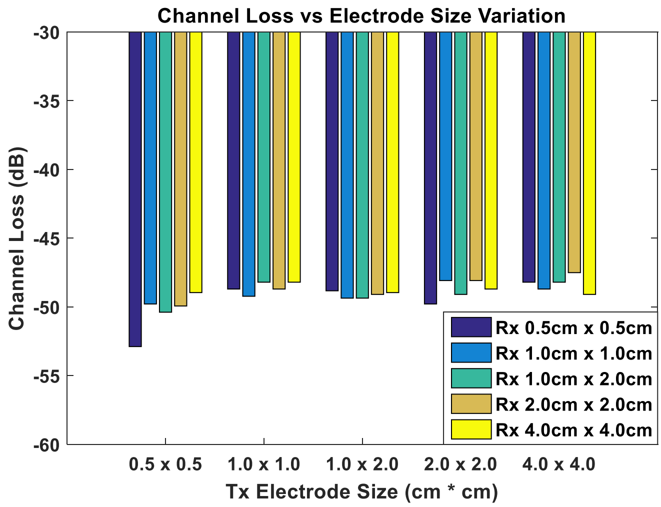

Fig. 7. Channel loss variation with transmitter/receiver signal electrode size. The channel loss is almost independent of the electrode sizes with slightly extra loss for the smallest eletrode size (0.5 × 0.5 cm).

side. Channel loss measurements were carried out with different combinations of transmitter and receiver electrode size. The loss showed little variation depending on electrode size from 0.5cm × 0.5 cm up to 4 × 4 cm. This is intuitive as the channel loss is dominated by the return path loss, dependent on the size of the floating ground electrode [48] and not strongly dependent on the variations in the forward path, of which the electrodes are a part of. The channel losses for all the combinations of electrode sizes are shown in the form of a bar graph in Figure 7.

5 DESIGN GOALS

5.1 Touch–Based Communication

One of the primary design goals of the *BodyWire-HCI* system is to show communication strictly during touch events. The transmitter and receiver should communicate only when there is a direct conductive path through the human body. This can only be achieved if there is sufficient difference in the amount of signal received between the cases of direct touch and leakage from an adjacent electrode. As a result, the receiver will be selectively sensitive to signals received directly through touch. For this, we have utilized signal transmission at frequencies of around 500 kHz. The low frequency operation enables EQS-HBC and results in minimal signal radiation out of the body. The measurements carried out in Figure 8 shows the viability of strictly touch–based communication. The experiments are carried out on two subjects (two male) and the results are the average of five different measurements over multiple days. In the experiments, electrodes of size 1 × 1 cm size are kept 3 mm away from each other. The user touches one of the electrodes and the received signal is measured through a spectrum analyzer at all of the electrodes. Figure 8 shows the variation in SNR of the received signal with frequency at all of the electrodes. It can be seen that the signal leakage to adjacent electrodes increases with signal transmission frequencies. The received signal at the touched electrode increases with frequency in this case due to the low input impedance (50 Ω) of the spectrum analyzer. However, at all the measured frequencies between 500 kHz and 20 MHz, we see a significant difference (>20 dB) in actual received signal and the leakage from adjacent electrodes. As a result, the receiver can be designed to be sensitive to received signal only when it is touched directly but insensitive to leakage from adjacent electrodes. This enables the selectivity

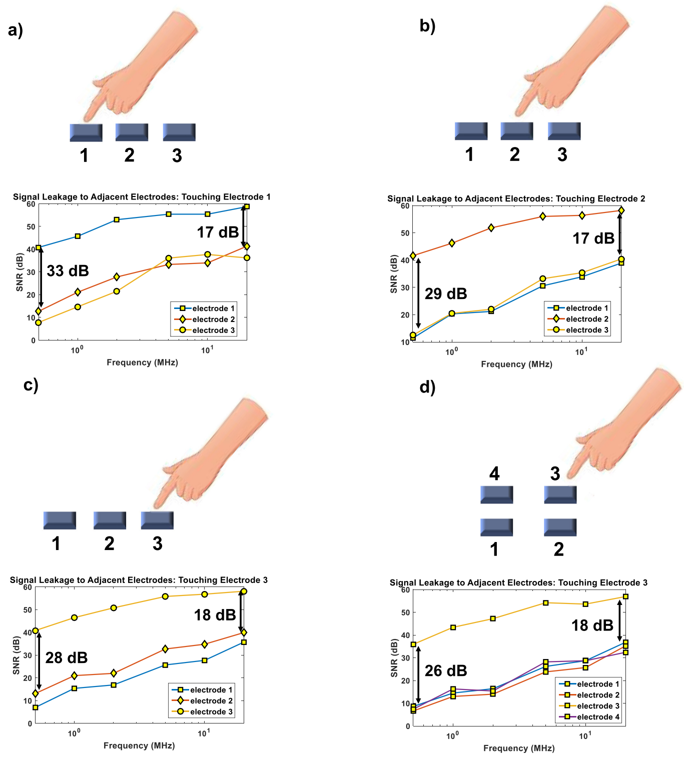

Fig. 8. Measurement of received SNR for different electrode configurations: User touching (a) electrode 1, (b) electrode 2, and (c) electrode 3, respectively, for a three electrode configuration. (d) User touching electrode 3 in a four electrode configuration. All measurements show more than 20dB degradation in SNR on adjacent electrodes compared to the electrode being touched enabling selectivity. The signal leakage to adjacent electrodes also significantly reduces at 500 kHz, compared to 20MHz, when measured using a spectrum analyzer with 50Ω input impedance.

of the touch events achievable through EQS-HBC in our current system design. Also it can be seen that the difference in SNR on the electrode being touched and the leakage to adjacent electrode gets larger as the frequency of operation reduces.

Furthermore, a characterization of hand position during transmission was conducted to ensure that *BodyWire-HCI* remains strictly touch based independent of the posture of the hand touching the electrode. A total of 24 participants were presented with an array of electrodes as well as the EQS- HBC system and asked to touch electrode 5 in the electrode array, as shown in Figure 9. The way in which the user's hand naturally selected the electrode could be characterized into three main hand postures as shown in Figure 9. Each hand posture elicits a distinct leakage pattern on the surrounding electrodes that are 3mm apart. Leakage measurements were conducted for each of the hand postures—leading to the SNR data shown in Figure 9. In addition, the most popular posture (posture 1) was tested with the user approaching the electrode from five different angles. Again, there was a distinct difference in leakage pattern as displayed in Figure 10. Although leakage varied due to hand position and angle, the SNR difference between the intended receive signal to the leakage never fell below 20 dB giving the ability for *BodyWire-HCI* to formulate heavily localized electrode arrays for data transmission or authentication.

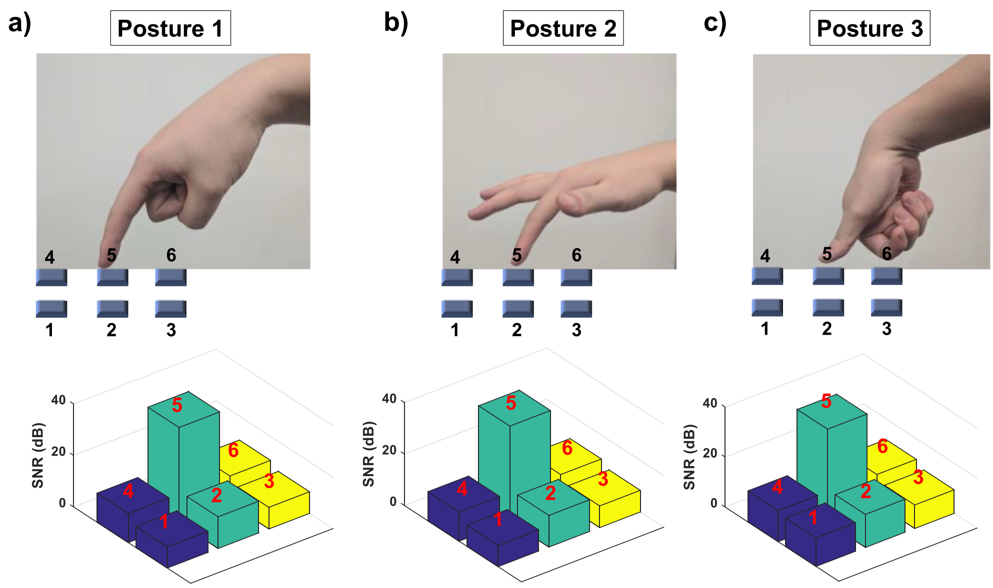

Fig. 9. The effect of posture of the touching hand on signal leakage to adjacent electrodes. Measurement results show that the signal leakage is almost independent of the hand posture. The SNR at the electrode being touched (electrode 5) is also significantly larger than the SNR at the adjacent electrodes.

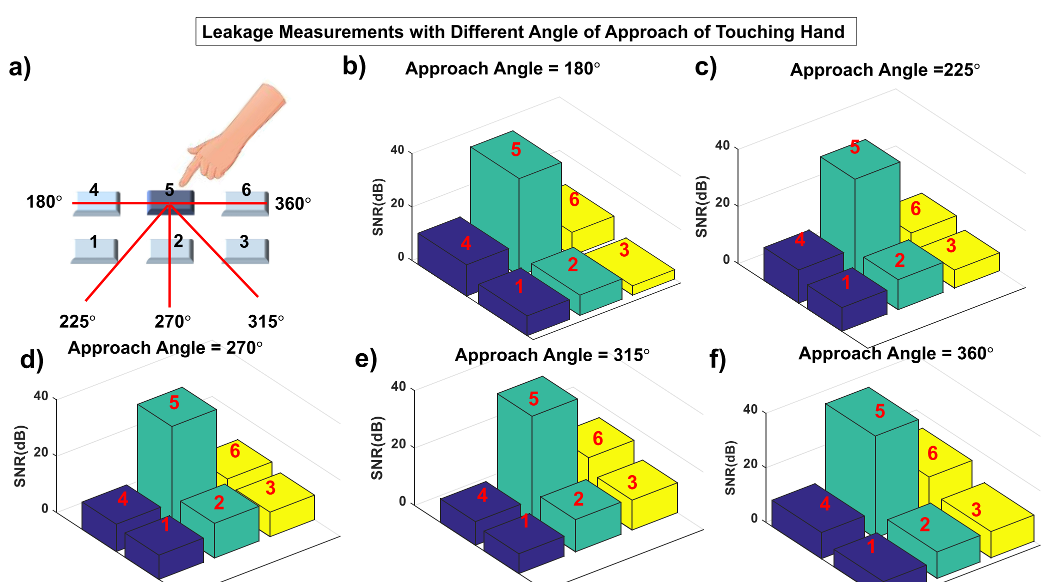

Fig. 10. (a) Characterization of leakage in surrounding electrodes as the user approaches the electrode array from the various angles with hand posture as in Posture 1. The SNR of the touched electrode and the leakage to the adjacent electrodes as the angle of approach is (b) 180°, (c) 225°, (d) 270°, (e) 315°, and (f) 360°.

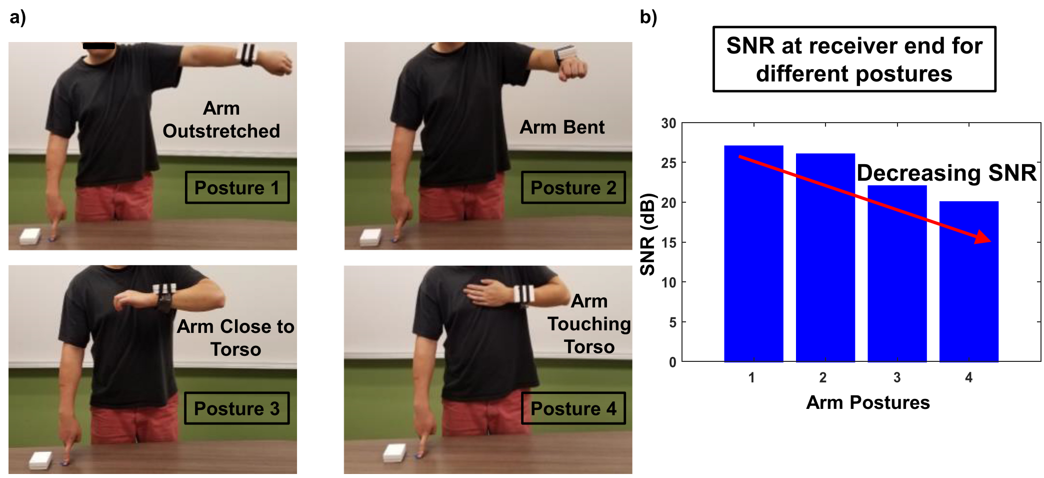

Fig. 11. The effect of transmitting arm posture on received signal strength. (a) The transmitting arm gradually moves closer to the torso from its outstretched position and (b) the received signal strength, hence the SNR, reduces as the arm moves closer to the torso.

5.2 Posture Independence

For signal transmission between a wrist worn/handheld device and a computer, the arm posture affects the amount of signal received at the receiver end. Specifically, the distance of the arm from the torso of the user affects the amplitude of the received voltage. Experiments in Figure 11 show four different postures of the arm with the transmitter and the corresponding received signal at the receiving electrode when the other hand is touching it. It can be seen that there is 7 dB difference in the amount of received signal depending on the posture of the arm. The maximum amount of signal is received for the posture with an outstretched arm. As the arm with the transmitter is brought closer to the torso, the received signal amplitude decreases. Touching the torso with the transmitting arm shows minimum received signal at the receiver end. The *BodyWire-HCI* system is required to be designed to operate across all these posture variations. The receiver is required to have sufficient sensitivity to operate during the posture with minimum received voltage but should not get saturated when the amount of received signal increases to maximum for a different posture.

5.3 Convenience

One of the primary goals of HBC is to enhance convenience during user interaction by combining communication with touch. The combination of communication and touch combines multiple user interaction steps into one single step, which enhances the ease of use. The *BodyWire-HCI* system is designed to provide secure communication during touch and enhance user convenience during HCI.

5.4 Wide Applicability

The *BodyWire-HCI* system serves as the communication backbone infrastructure for any application requiring transmission of information strictly through touch. The system is designed to take data from a transmitter device, transmit it through EQS-HBC, and decode it at the receiver end. The type of transmitter and receiver device does not affect the hardware/software of the

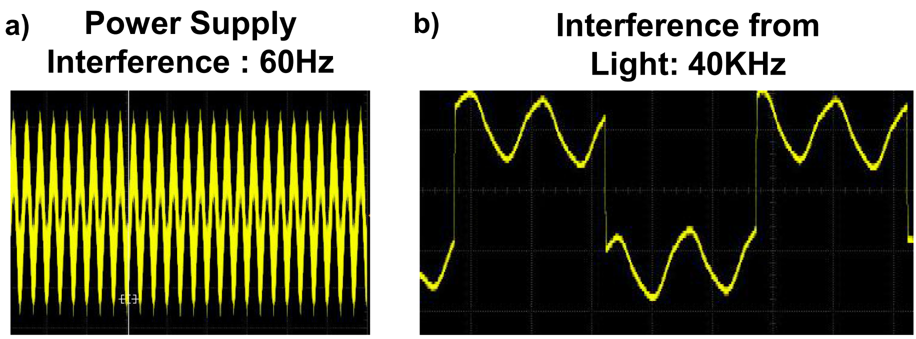

Fig. 12. Interferences picked up by the body during transmission in EQS-HBC. (a) 60 Hz mains power supply noise. (b) Additional 40 KHz interference present in the laboratory environment.

BodyWire-HCI system. This will allow wide applicability of the *BodyWire-HCI* system for different application scenarios such as data transfer and secure authentication.

5.5 Interference Tolerance

The human body picks up any interference present in the environment due to the human body antenna effect [11, 47]. This interference affects any ongoing HBC data transmission, resulting in bit errors. Since the frequency of operation of the *BodyWire-HCI* system is in the range of 100s of KHz, any environmental interference in this frequency range affects data transmission. Figure 12 shows two of the prominent source of interference present in the laboratory environment, as measured through an oscilloscope connected to the body. The 60 Hz noise (Figure 12(a)) originates from the supply mains within the building, an interference that will be present in an actual application scenario within any building. The interference around 40 KHz (Figure 12(b)) is due to the light sources present in the laboratory. The hardware of the *BodyWire-HCI* system is designed to filter out the different interferences present within the environment. The physical layer also needs to have error detection/correction mechanisms to tolerate bit errors happening due to any interference affecting transmission.

5.6 Form Factor

The *BodyWire-HCI* system is designed for applications involving HCI. Hence, one of the devices involved in the interaction will be a wearable or a handheld device. Therefore, both the transmitter and the receiver should be designed to have a wearable form factor. This puts a limit on the battery life and the processing power of the computing unit (microcontrollers) present on these devices.

6 DISCUSSION: SAFETY AND LIMITATION

6.1 Safety

HBC requires transmission of electrical signal through the human body. Hence safety limits of electrical signal transmission are one of the primary concerns of any HBC system. Every HBC-based system should be designed to adhere to the safety limits of current and radiation (Figure 13). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides guidelines for limits of human exposure to time varying electric, magnetic and electro-magnetic fields up to 300 GHz frequency. Since the *BodyWire-HCI* system operates in the frequency range of a few 100s of KHz, we are primarily focused on the low frequency range. The RMS current density through the body is the primary bottleneck at this frequency range. The 4Hz–1kHz frequency range has the most stringent current density requirement as the current at these frequencies has effect on nerve

a) **ICNIRP safety limits**

Frequency(f)	RMS Current Density (mA/m²)	Whole Body SAR (W/Kg)
<1Hz	8	-
1-4 Hz	8/f	-
4Hz – 1KHz	2	-
1-100 KHz	f/500	-
100KHz – 10MHz	f/500	0.08
100MHz – 10 GHz	-	0.08

b)

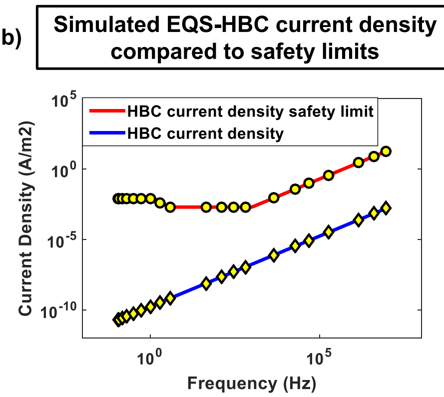

Fig. 13. (a) Safety limit table of current density and SAR provided by the ICNIRP guidelines. (b) Current density of EQS-HBC from simulated circuit models, showing >10000x lower current density compared to the safety limits.

stimulation. Figure 13(b) shows the safety requirement of current density for different frequencies. Simulating an EQS-HBC circuit model [33] shows that the current density in EQS-HBC is more than 10000x lower than the safety limits imposed by the guidelines [45]. This is primarily due to the high impedance provided by the return path capacitance at the low frequency of operation, limiting the overall current through the system. A detailed study about the safety of HBC can be found in [45].

6.2 Limitations

The *BodyWire-HCI* system enables strictly touch–based communication through the underlying hardware design. However, there is no way for the system to differentiate between the touch of an intended receiver and an unintended malicious attacker. An attacker can touch the user and receive the transmitted signal and there is no mechanism in place to stop that from happening since the transmitter does not depend on any feedback from the receiver during transmission. If we look into previous HBC implementations or other technologies such as Bluetooth, it is possible for an attacker to be in close proximity and still snoop the signal. Hence the possibility to attack from close physical proximity can be thwarted through *BodyWire-HCI*, significantly reducing the chance of an attack. To summarize, although *BodyWire-HCI* does not protect the signal from touch-based attacks it nullifies any chance of nearby snooping.

7 SYSTEM LEVEL IMPLEMENTATION

The evaluation of the channel and leakage characteristics in Sections 4 and 5 is used to determine the design requirements of the *BodyWire-HCI* system, such as receiver sensitivity and maximum operating data rate for reliable operation. The complete *BodyWire-HCI* transceiver is implemented using Commercial Off-The-Shelf components, as shown in Figure 14(a). The receiver consists of an Analog Front End (AFE) designed on a custom Printed Circuit Board (PCB) for signal processing and a Digital Processing Unit (DPU) to run the software and interface with the external world. The AFE primarily consists of filters and amplifiers to process the received signal. The transmitted signal gets attenuated and is affected by environmental interference at the receiver end. Hence, appropriate analog signal processing needs to be performed to recover the received bits from the noisy, attenuated signal, before it can be utilized by the DPU. The amplifiers are designed from off the shelf Operational Amplifier IC (LM 324 series). The filters are designed from passive

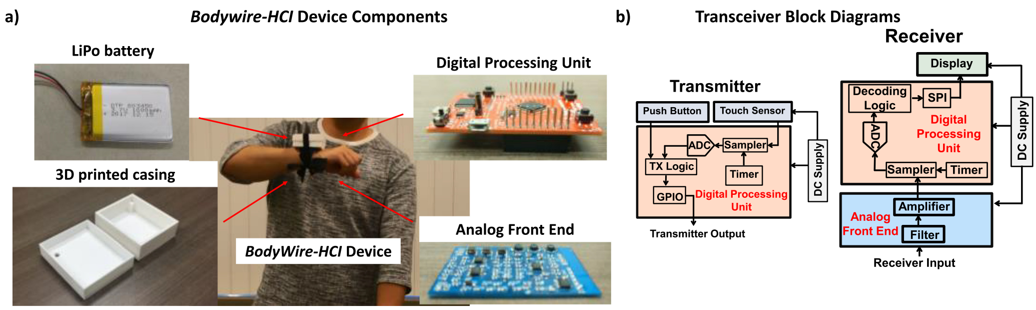

Fig. 14. (a) BodyWireHCI device components: PCB of the analog front-end, TM4C123G microcontroller acting as the Digital Processing Unit, Lithium Poly Battery used as power source, and 3D printed casing for packaging the device. (b) Block diagram of the transmitter and receiver showing the basic building blocks and how they are interconnected.

resistances and capacitances. The DPU is implemented on a Texas Instruments TM4C123G microcontroller, which has a 32 bit, 80 MHz, ARM Cortex M4 processor. The board consists of 32 KB SRAM and 56 KB flash memory. Two 12 bit, 2 MSPS ADCs are used to sample the signal coming out of the AFE and these act as an interface between the AFE and the DPU. The 32 bit Timer internal to the microcontroller is used to provide precise timing necessary for ADC sampling operation. The DPU performs basic error correction on the received bits and decodes the data from its packetized form. The DPU also acts as an interface to the touchscreen display unit through the Serial Peripheral Interface. A BOOSTXL-K350QVG-S1 QVGA touchscreen display is used for detecting external touch input and displaying images or text. The complete block diagram of the receiver board is shown in Figure 14(b).

The transmitter also has a TM4C123G microcontroller unit as its DPU. The transmitter packetizes the data payload and transmits it through one of the General Purpose Input Output pin present in the microcontroller. The transmitter can also receive external input through touch screen display (BOOSTXL-K350QVG-S1) or push buttons present on the microcontroller board. Both the transmitter and receiver are powered through rechargeable Li-ion batteries to reduce power supply noise and comply with the wearable form factor. The data rate of transmission achievable in the prototype *BodyWire-HCI* system is 8 Kbps. The transmitter block diagram is also shown in Figure 14(b).

BodyWire-HCI uses a half-duplex channel through the body for communication. The transmitter and receiver use Time Division Multiplexing to transmit/receive data at alternate time intervals. It is possible to use Frequency Division Multiplexing to use the body as a duplex channel but has not been implemented in the current version. The synchronization between transmitter, receiver, and error detection is achieved through packet-based protocol. There are the following three different types of packets: (a) Preamble Packet: calibrates the receiver for decoding; (b) Header Packet: determines transmission size; and (c) Data Packet: Contains the transmitted data (64–1024 bit data in one packet). Error Correction is implemented to recover transmission errors. The maximum transmission length without calibration is limited by the clock frequency drift between the transmitter and receiver device.

8 APPLICATIONS

We show three example demonstrations of the *BodyWire-HCI* system and illustrate how it can be used for strictly touch–based communication. The first application demonstrates the selectivity and the strict touch requirement of communication through HBC, where the data intended for a

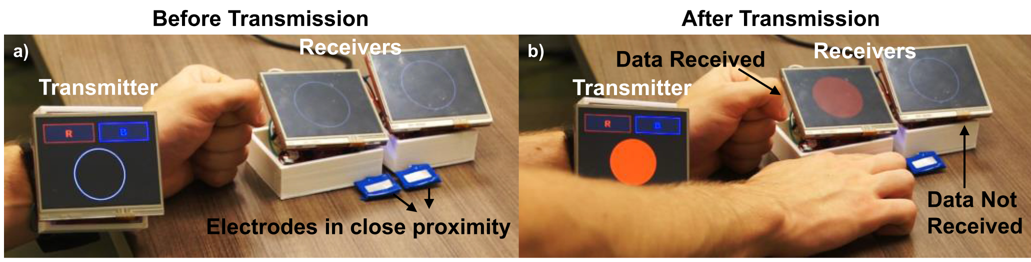

Fig. 15. Selective information transmission from a transmitter to a receiver: (a) Two receivers kept in close proximity to each other; and (b) Data transmitted to the receiver, whose electrode is touched by the user. The adjacent receiver does not receive the signal. Demo: https://www.youtube.com/watch?v=Uwrig2XQIH8.

particular receiver is not picked up by an adjacent receiver in close proximity. The second application shows transfer of information from a wrist-watch to a computer through the touch of an electrode, highlighting the convenience and entertainment potential. Lastly, we demonstrate the envisioned application of secure authentication through touch by unlocking a computer when a person wearing the appropriate key touches an electrode connected to the computer—highlighting an application where security is enhanced.

8.1 Selectivity: Data Transmission with Multiple Receivers

Selectivity is one of the key advantages of signal confinement within the body, achieved by *BodyWire-HCI*. The selectivity aspect of *BodyWire-HCI* is the focus of this current demonstration. In this scenario there are two receivers, which are kept in close proximity to each other. The transmitter transmits a code corresponding to the color chosen by the user on the touchscreen display. The data only gets transmitted to the receiver whose electrode is touched by the user (Figure 15). Although the electrode of the other receiver is in close proximity, it does not receive the signal (Figure 15(b)), showing selectivity provided by the *BodyWire-HCI* prototype. The signal confinement property of EQS-HBC makes selective information transmission possible, as shown through this demonstration. This selectivity property can be utilized for applications requiring precise location tracking and localization.

8.2 Data Transfer: Wearable to Computer Data Transfer

In this demonstration, we utilize the *BodyWire-HCI* framework to transfer information from a wearable device such as a smart-watch to a computer (Figure 16). A *BodyWire-HCI* receiver is connected to the computer, which uses serial USB to communicate with the receiving computer. When the user touches the electrode connected with the receiver, it forms a communication channel between the devices. The code corresponding to the image being displayed in the wearable gets transferred to the *BodyWire-HCI* receiver through EQS-HBC, which is subsequently transferred to the receiving computer through USB serial communication. The receiving computer displays the image corresponding to the code it receives on its display. This demonstration shows information exchange between a wearable transmitter and a computer. This can be extended to image transmission also but that requires higher data rates than 8kbps supported through the *BodyWire-HCI* prototype. The receiver device in this demonstration is implemented as a separate device connected to the computer through USB for the ease of implementation. However, it can always be integrated within the computer as a separate module with only the electrode acting as the external interface.

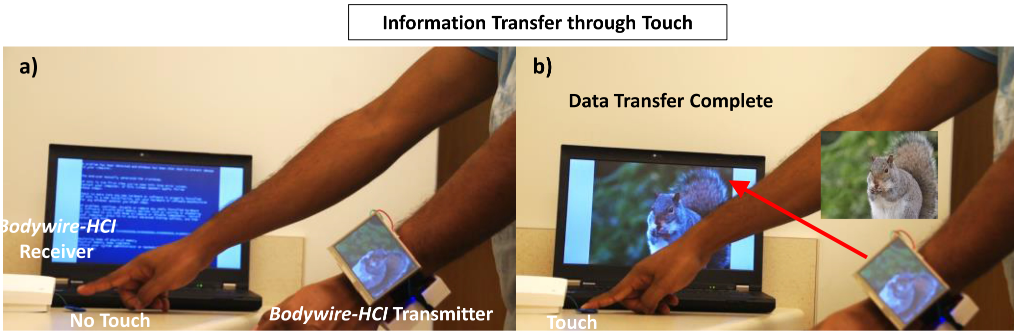

Fig. 16. Information transmission from a wearable device to a computer through touch. (a) User about to touch the electrode and (b) information transfer during touch of electrode resulting in image displayed in the computer.

This example illustrates the possible usage of *BodyWire-HCI* framework for entertainment purposes. Transferring data from one device to another just through touch provides a very natural and intuitive way of information exchange and enhances user convenience significantly. This demonstration can also be utilized for other usage scenarios such as downloading map information from computer to a smart-watch or using a body worn wearable as an intermediate device for data transfer between two computers.

8.3 Secure Authentication: Unlocking Computers

This demonstration of the *BodyWire-HCI* system shows a mock up demonstration of unlocking of a computer screen with the touch of an electrode connected to a HBC receiver, as seen in Figure 17(a)–(d). The computer unlocks only when the user with the correct key touches the electrode connected to the computer, through the HBC receiver. To demonstrate the unlocking process, the image transitions from the lock screen to the unlock screen only when the correct code is received from at the receiver connected to the computer. This is analogous to unlocking a computer only when a correct code is received from a wearable device, acting as an additional factor in a multi factor authentication scenario. It can also be seen from our experiments that the computer does not unlock when the fingertip of the user is very close (<1cm) to the receiver electrode but not touching it. This shows that there is very little signal leakage out of the body, demonstrating the additional physical layer security provided by EQS-HBC compared to radio communication. Hence, utilizing EQS-HBC is advantageous for applications like secure authentication as shown here.

This demonstration can also be seen as part of a two factor authentication system, where the unique key of the transmitter acts as a substitute to password. This can also be used for two factor authentication systems where the user has to use both his/her biometric identification (like fingerprint) and a passcode for authentication. This requires two separate steps of scanning fingerprint and entering the passcode. However, by doing communication through touch it is possible to perform two-factor authentication through fingerprint matching and also authenticating through the key sent by the transmitter. This can potentially enhance the convenience of such applications by reducing the number of steps performed by the user.

Through EQS-HBC, it is possible to utilize the human body as a physical communication channel, where the signal is primarily confined within the channel itself and there is minimal radiation out of the body. This enables additional physical layer security which can be utilized to create secure channels during pairing of devices, such as a streaming device and a TV. Traditionally, in

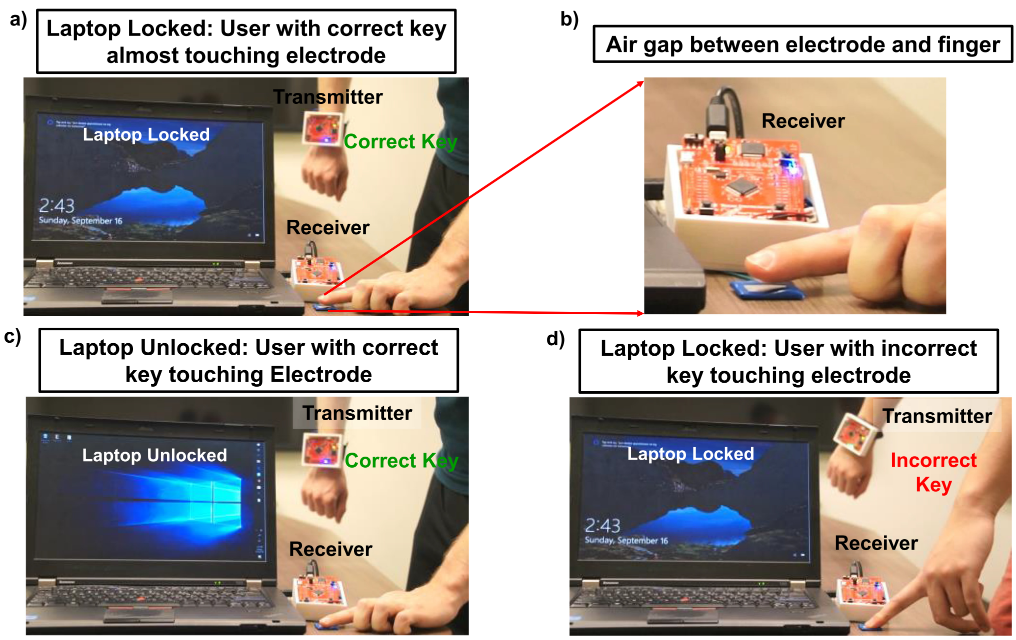

Fig. 17. Demonstration showing secure authentication of a computer through the key transmitted by a body worn device. (a) The computer is locked and does not get unlocked even when the user with correct key is in close proximity to the electrode. (b) Zoomed in diagram showing air gap between the finger and electrode. (c) Computer gets unlocked when the user with the correct key is touching the electrode. (d) Computer does not unlock when the user with the incorrect key touches the electrode.

wireless protocols such as Bluetooth, such pairing process begins by key exchange over non-secure air medium, making them vulnerable to malicious attacks. This demonstration shows the possibility of key exchange through EQS-HBC, which can be utilized for establishing secure channels for wireless communication.

9 CONCLUSION

Touch acts as a natural way of interaction between humans and computing resources present in the environment. Coupling communication with touch will enhance its effect significantly opening up new interaction modalities in HCIs. In this article, we demonstrate *BodyWire-HCI*, which uses EQS-HBC to minimize signal leakage out of the body and hence enable communication strictly during touch, previously not achievable through wireless radio wave communication or other HBC-based systems. The low frequency operation of EQS-HBC helps it reduce signal leakage out of the body significantly, enabling communication strictly through touch. Design techniques, such as capacitive termination and voltage mode transmission/reception have been used to minimize loss through the human body at low frequencies to enable EQS-HBC. The system has been designed to tolerate variation of signal strength among different users as well as for a user due to posture variation, time of day, and so on. It is also designed to be tolerant to interferences present at low frequencies. The *BodyWire-HCI* system has been used to show data transmission selectively and strictly during touch events and demonstrate applications such as transfer of an image from a wearable to a computer. *BodyWire-HCI* also shows promise for applications such as secure authentication of a computer through a body worn key. As computers increasingly become ubiquitous, systems coupling communication and touch will provide new modalities to interact with them. *BodyWire-HCI* provides such a platform for communication strictly during touch. We hope this will stimulate future research on new HCI modalities which benefits from the coupling of communication and touch.

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