Bioacoustics-Based Human-Body-Mediated Communication

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An acoustics-based method can utilize the human body as a communication channel to propagate information across different devices. The proposed system can propagate acoustic signals under 20 kHz within or between human bodies and even between the human body and the environment.

In the next generation of computing, we can expect a wave of wearable devices that will influence many aspects of our lives. These wearables will come in different form factors of fully interactive systems (such as smartwatches and head-mounted displays like Google Glass) and as a plethora of wearable sensors that are attached to the human body to monitor activities and internal physiological status (such as heart rate). It is likely that many people will be wearing a variety of devices in addition to carrying smartphones within the next few years.

Given the anticipated mass adoption of wearables, natural and convenient communication between devices has never been more important. Each device requires frequent information exchange with other devices and the service provider. Most mobile and wearable devices currently use wireless communication technologies such as Bluetooth and Wi-Fi to transmit and receive data. However, these technologies are not optimized for wearables for two reasons.

First, wireless communication technologies do not completely solve some of the new challenges introduced by wearable technology. For instance, because these devices are worn, they constantly change locations with the user. Therefore, wearables frequently need to connect with new devices in the environment to exchange information. The current solution requires tedious setup procedures before two devices can communicate with each

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other. Most procedures even require the user's input. The user experience would certainly be greatly improved if a wearable could be innately aware of which other devices the user wants to communicate with.

Second, current communication solutions do not take advantage of wearables. Compared with traditional computing devices (such as a laptop), wearables are directly attached to the human skin. This provides a unique opportunity to capture signals from the human body.

We propose using the body itself as the physical transport mechanism for interdevice communication by transmitting acoustic signals. By attaching a wearable to the body, the system can automatically complete the authentication process. Also, we introduce an inherent security protection to the link between devices: if the devices are connected to the same body, then they can communicate; otherwise, no such transmission occurs.

Human-body-mediated communication can motivate novel and natural interactions. For instance, handshaking is a popular ritual, usually accompanied by an oral introduction. With the proposed method, information such as a business card could be automatically exchanged during a handshake. Our method can also be applied to communications between users and the environment. Simply by touching relevant objects, a user could transmit personal data to them to provide authentication, and the environment could in turn send necessary data back. Other benefits of a human-body-mediated communication channel might include power or cost savings.

The idea of using the human body as a medium to transfer information has already been demonstrated with electrical coupling[1,2] and magnetic coupling[3] to the body. However, no prior study has investigated the propagation of acoustic signals under 20 kHz through the body. (See the sidebar for related work in this area.) Compared with some RF methods, generating low-frequency acoustic signals might be more practical. We designed and implemented a system that demonstrates the feasibility of propagating acoustic signals under 20 kHz within the body, across human bodies, and between the body and an object in the environment. We then demonstrated via an eight-participant study how the propagation varies among different people. Experiments show that the proposed method can detect touch contact with 100 percent accuracy. We also built a system to transmit text information via the body, with both customized hardware and off-the-shelf smartwatches.

INTRABODY ACOUSTIC SIGNALS UNDER 20 KHZ COULD BE SUPPORTED BY SENSORS AND ACTUATORS ON MANY CURRENT COMMERCIAL DEVICES.

TRANSMITTING ACOUSTIC SIGNALS THROUGH THE BODY

The propagation of acoustic signals occurs differently through air, solid, and liquid objects—that is, the speed of propagation varies between media. The human body consists of a heterogeneous mixture of materials including bone (solid), water (liquid), and muscle (mixed).

Research has shown that bone is a good conductor for transmitting acoustic signals. However, most efforts using bone conduction to transmit acoustic signals have been limited to short distances (several centimeters), such as with bone-conductive headphones. It is still unclear how acoustic signals can be propagated through a relatively long distance involving different parts of the body. Characterizing the propagation of acoustic signals through the body would introduce opportunities for personal area networks and natural human–computer interaction. Our effort focuses on signals under 20 kHz, which can potentially be supported by sensors and actuators on many current commercial devices.

We demonstrate our method using the Sony Smartwatch 3 to propagate information across two human bodies via a handshake and from the body to a table. Specifically, to propagate acoustic signals through the body, our system consists of two subsystems: one for generating and coupling the acoustic signals to the body, and the other for capturing the transmitted signals. The most challenging part is to find sensors that can appropriately couple to the skin while being resistant to

RELATED WORK IN HUMAN-BODY-MEDIATED COMMUNICATION

As wearable computers became a research topic in the 1990s, the risk of eavesdropping on wireless communications became a concern.[1] Researchers thus started investigating how to communicate information among computing devices near the human body by passing an electrical current through the body.[2–4] Since those initial pioneering efforts, more work has been done to explore the characteristics of transmitting an electrical signal through the body[5–8] and its potential applications.[9] In addition, recent research has demonstrated the possibility of using magnetic resonance for data transfer in body area networks.[10]

All of the previous work focused on propagating electrical or magnetic signals (MHz frequencies) through the human body. The human body is also an active medium for transmitting acoustic signals. Researchers have investigated transmitting sound through a cadaver[11] and using sound to transmit information between smartphones[12,13] or recognize gestures.[14–16] OsteoConduct used sound to transmit information within the same body with a very low bit rate (5 bits/s).[17] And ViBand demonstrated a data transmission rate up to 165 bits/s between a wristwatch and a vibration motor.[18] However, it is still unknown how the acoustic signal would transmit across a longer distance or from the body to other objects with relatively higher data rates.

In contrast to this existing body of work, our research demonstrates the possibility of intra-body signal transmission using acoustic signals under 20 kHz from the wrist to different locations on the body, between two bodies, and between the body and other objects via touch contact.

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environmental noise (such as electromagnetic [EM] noise). For instance, we experimented with a piezoelectric-film sensor as the receiver and determined that it was too sensitive to EM noise, which made it difficult to characterize acoustic signals.

We decided to use a bone transducer (B81, RadioEar) as the sender and an ultra-low noise accelerometer (356A32, PCB Piezotronics) as the receiver. This bone transducer provides the appropriate coupling to the body, especially when the actuator is positioned over bone. Compared with other typical acoustical sensors (such as piezoelectric film sensors), the accelerometer is electrically shielded and mechanically tuned to accurately detect small vibrations and should thus be more resistant to other noise while attached to the body. Moreover, compared with electret-based or microelectromechanical system (MEMS)–based microphones, the accelerometer is a contact microphone that only picks up direct vibrations of the medium upon which it is mounted (for example, the skin) versus airborne vibrations (that is, ambient noise). Excluding noise helps us to characterize the propagation in the experiments.

EXPERIMENTAL SETUP

To understand acoustic signal propagation through the body across different persons, we collected data in a lab-based environment from eight participants (five females and three males), with an average age of 27 and a body mass index (BMI) of 17 to 24.2 (average 21.35). All subjects provided written informed consent, and our experimental protocol was approved by the Georgia Institute of Technology Institutional Review Board. A researcher attached the sensors tightly to each participant's body using an armband. The experiments were designed to characterize how acoustic signals can be propagated through the body, between two human bodies, and between the body and the environment, in particular via small actuators

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and sensors that could be integrated into wearable technology.

Figure 1a shows the experimental apparatus. The experiment was conducted using a dynamic signal analyzer (SR785, Stanford Research Systems). For each experiment, the dynamic signal analyzer swept a sine-wave signal between 250 Hz and 20 kHz (spaced logarithmically). The signal was fed to the bone transducer and transmitted into the body. The signal received by the accelerometer was fed into an amplifier (482C, PCB Electronics), and then the output from the amplifier was fed into the input of the dynamic signal analyzer. The signal analyzer then computed the transfer function between the sine wave sourced to the bone transducer (the input) and the signal received by the accelerometer (the output) for the range of swept frequencies. We recorded the transfer function calculated by the signal analyzer for further analysis.

To measure the frequency response of the combined accelerometer and bone transducer, we taped the bone transducer and accelerometer together and then swept a sine wave from 250 Hz to 20 kHz with an amplitude of 30 mV, as Figure 1b shows. The system generates the highest amplitude around 1 kHz.

The signal voltages to the transducer were all set at 1 V, except when the accelerometer was placed on the forehead and right wrist. We set the output signals at 5 V in those two positions because the signal attenuates more at the longer propagation distances.

WITHIN-BODY COMMUNICATION

Many wearables that could be enhanced by enabling intrabody acoustical communication are worn on the wrist or arm, such as smartwatches and armbands. Accordingly, the question of how strongly acoustic signals propagating through the arm are attenuated for multiple frequencies of excitation is of great interest to the wearable computing community.

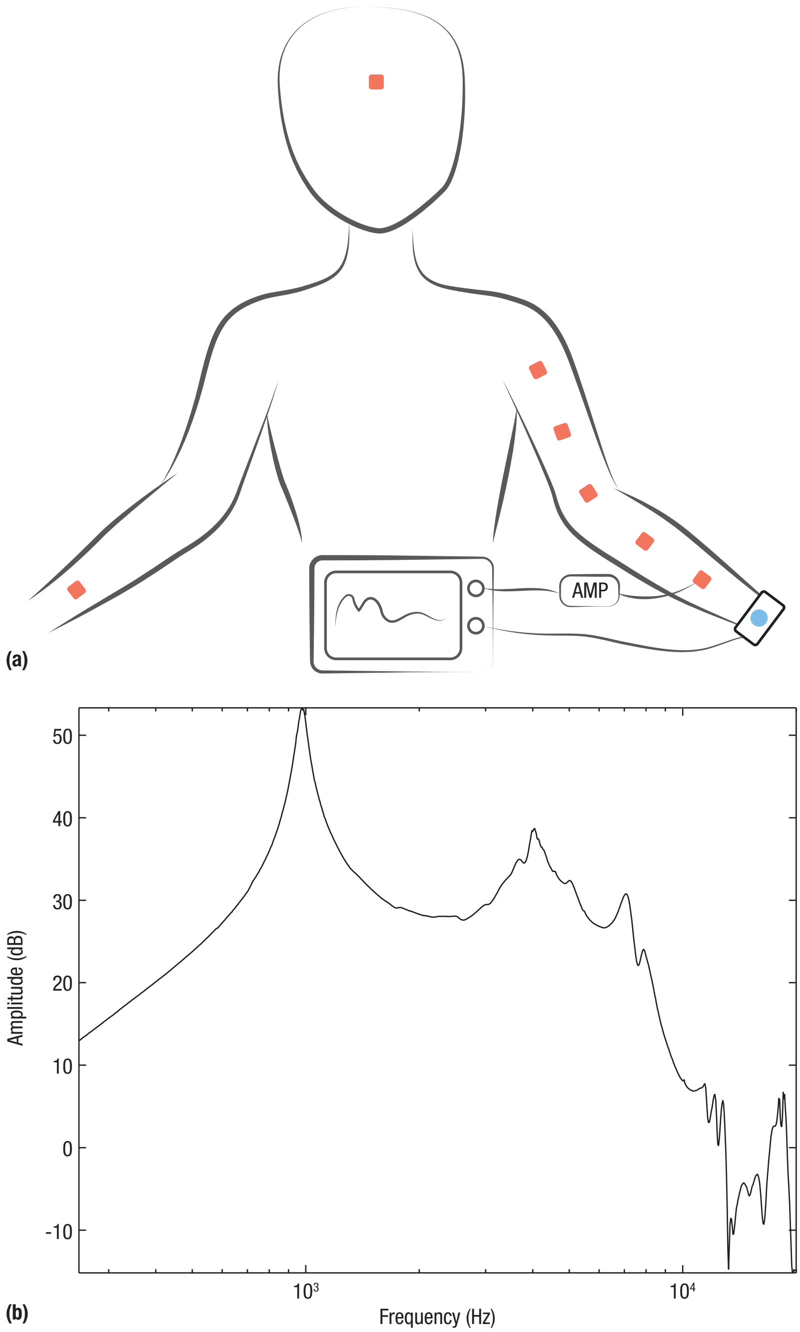

FIGURE 1. Experimental setup. (a) The experimental apparatus shows the sensor placement on the body (red dots), with the bone conduction transducer placed on the radial bone at the wrist and driven by a function generator. (b) For this work, the transducers were suspended in free space and coupled to each other rigidly. We taped the bone transducer and accelerometer together and then swept a sine wave from 250 Hz to 20 kHz with an amplitude of 30 mV.

To investigate this research question, we put the receiver (accelerometer) at several locations away from the bone transducer, which was on the left wrist: 7.6, 15.2, 22.9, 30.5, and 38.1 cm. Figure 2a shows the magnitude response measured by the accelerometer at each position, averaged across all eight participants. The dot on each line indicates the frequency at which the maximum magnitude is reached. We also report the noise floor when the bone transducer was operating at 1 V as the red dashed line. The noise floor was calculated by the signal analyzer, while we disconnected the bone transducer to avoid any coupling and connected the internal source and the accelerometer output to the first and second channel, respectively, in the analyzer.

Figure 2a shows that the amplitude of the frequency responses in all settings is much higher than the amplitude of the noise floor across the whole frequency range. In other words, the receiver attached to the arm received signals generated from the bone transducer on the left wrist.

We can also see that the amplitudes vary substantially at different frequencies in each setting. There are two major factors that potentially influence the received signal strength. One is sensor performance: ideally, the transducer and accelerometer should have a flat frequency response when directly combined (taped together). Unfortunately, this is rarely the case in practice. As Figure 1b shows, the frequency-response curve peaks around 1 and 7 kHz. Peaks can also be observed in similar positions from all the frequency-response curves in Figure 2a. We label the peak for each line with dots. The peak frequencies are 1,004, 987, 953, 1,049, and 1,054 Hz for the distances of 7.6, 15.2, 22.9, 30.5, and 38.1 cm, respectively.

The second factor is that signal attenuation varies for different frequencies of acoustic energy traveling through the body. For this reason, Figure 2a noticeably differs from Figure 1b. For instance, the curve from 250 Hz to 1 kHz is much flatter in Figure 2a than in Figure 1b. This result might indicate that the acoustic signal attenuates less under 1 kHz.

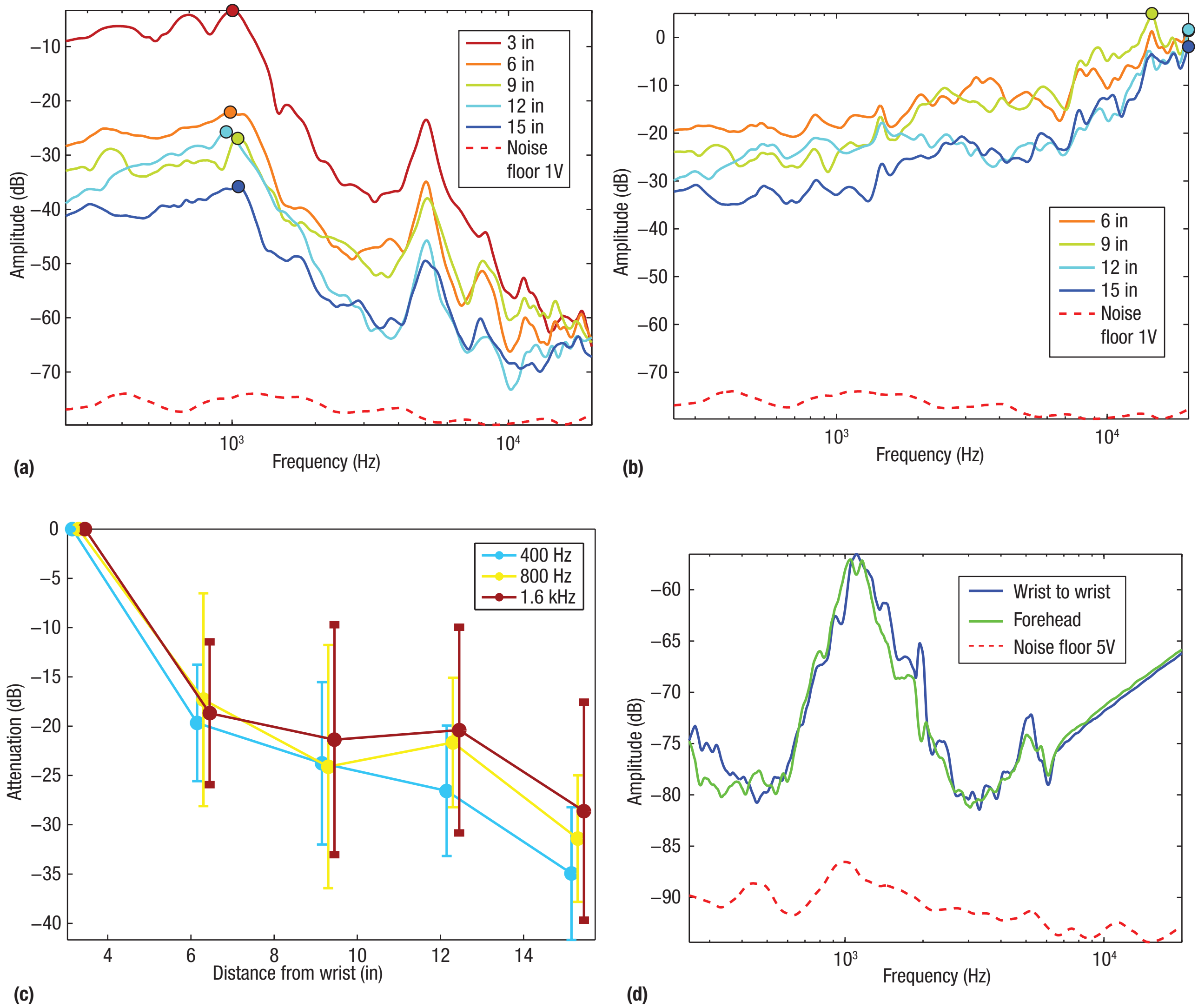

FIGURE 2. Frequency response on the same body: (a) frequency response at different positions on the arm, (b) path loss across the arm, (c) signal attenuation at different frequencies, and (d) frequency response from the left wrist to the right wrist and forehead. The dot on each line indicates the maximum magnitude frequency reached.

To further investigate the path loss of the acoustic signal along the arm at different frequencies, we extracted Figure 2b by subtracting the frequency response when the receiver was at 7.6 cm from the frequency response when the receiver was at 15.2, 22.9, 30.5, and 38.1 cm, respectively. Figure 2b reflects the signal's pass loss at further distances compared with when it was at 7.6 cm. Practically, it has a rather flat frequency response under 10 kHz.

In theory, the longer the propagation distance, the more attenuation should be observed in the received signals. Figure 2c plots signal attenuation along the arm across all eight participants at each location at 400 Hz, 1 kHz, and 1.6 kHz. We took the received signal measured at 7.6 cm from the wrist as a reference (0 dB) in the figure. The attenuation at other locations was calculated in decibels. In general, attenuation increased as the receiver was moved away from the wrist. However, when the distance from the receiver to the transducer increased from 30.5 to 38.1 cm, the average amplitude of the received signal increased instead of decreased. Interestingly, 30.5 cm from the wrist is approximately where the elbow joint is located.

We attribute the high intersubject variance in the signal strength to the different propagation path and coupling mechanism when the sensor is placed around the elbow joint. The sensor is coupled more to the bone when placed around the elbow joint, whereas it is coupled mostly to the tissue and muscle when attached to the forearm and upper arm. These results suggest the impedance of different body parts for propagating acoustic signals might vary at different frequencies, as we might expect. More experiments are required to draw further conclusions.

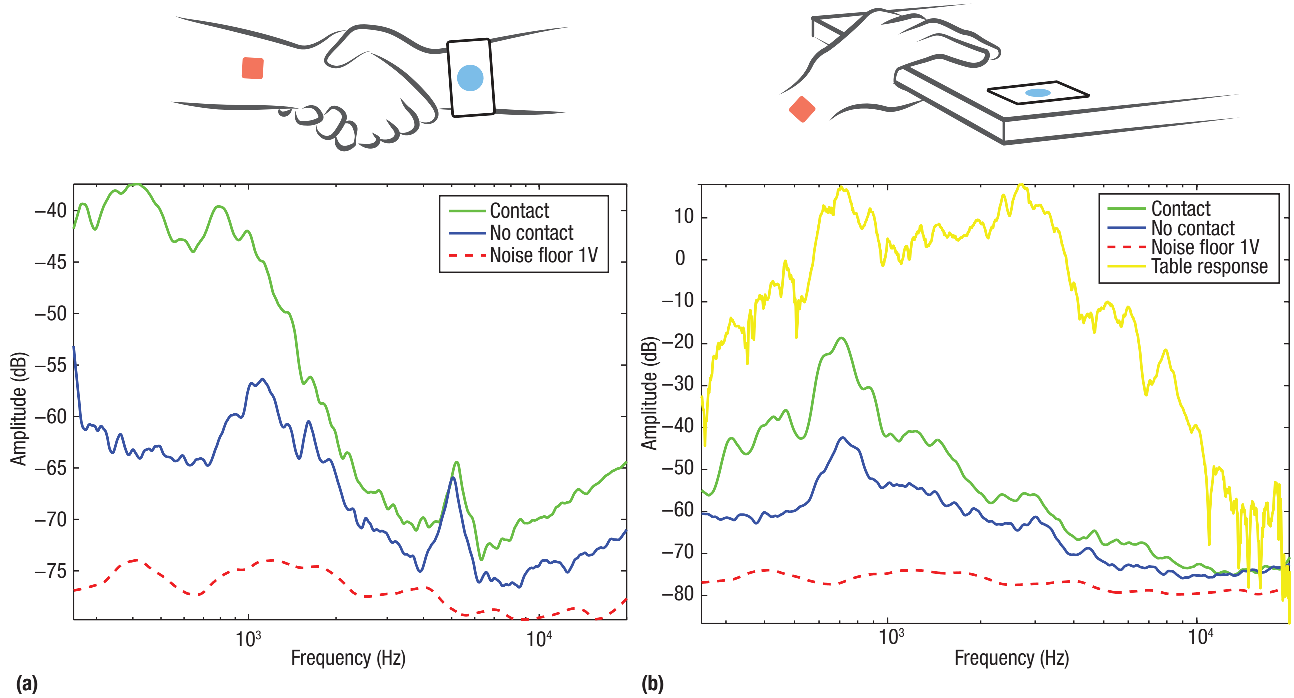

FIGURE 3. Frequency response curves: (a) handshaking and (b) table-touching scenarios.

In addition to the arm, wearables can be worn at other body locations that have longer propagation distances and more complicated paths. For instance, Google Glass sits on the head, which can be more than 50 cm away from the wrist. To understand how the signal can be propagated to further locations, we repeated the previous experiment but attached the accelerometer to the center of the forehead and right wrist, while keeping the transducer at the left wrist. The average frequency responses in Figure 2d serve as a proof of concept. Again, the amplitude of received signals are apparently higher than the noise floor, which means the system received the signal. The frequency responses peaked at 1,045 and 1,106 Hz when the receiver was on the forehead and right wrist, respectively.

COMMUNICATION ACROSS HUMAN BODIES

We also investigated how the acoustic signal would propagate between two persons during a handshake. We attached the bone transducer on the left wrist of one participant and put the accelerometer on the other participant's left wrist. Similar to the previous experiments, we recorded the frequency response from 250 to 20 kHz. This experiment was repeated twice. For the first trial, we asked the participants to hold hands tightly. For the second trial, we asked the participants to keep the same posture but not touch the other person's hand, staying about a centimeter away from the other participant. Because the only difference between the two experiments was whether the participants' hands were touching, we were able to estimate how much acoustic energy was propagated through the contact between two hands by comparing the frequency response of the two trials.

Figure 3a shows the frequency-response curves. When the hands were held together, the frequency response peaked at 410 Hz (–37.4 dB), although we can also observe another peak around 800 Hz, which is closer to the peak of the system's frequency response. Because the system does not generate maximum power at 410 Hz, the peak at 410 Hz indicates the signal might suffer from less path loss around 410 Hz. In contrast, the system generates the most energy at 1 kHz but does not receive the highest energy at 1 kHz. One possible explanation for the inconsistency in the peak frequencies is that the signal with a lower frequency has a longer wavelength, which makes it easier to pass through obstacles and suffer from less energy loss while the signals are traveling across the two hands.

COMMUNICATION BETWEEN THE BODY AND OTHER OBJECTS

In addition to intrabody and across-bodies communication, we are also interested in how a signal can propagate between the body and other objects in the environment. We designed an experiment to simulate the scenario where a user can receive information from the environment by touching an object—a wooden table, in our experiment. We attached the bone transducer to the table and the accelerometer to the participant's left wrist. Each participant was asked to hold the table's edge, which was 50.8 cm away from the transducer.

Similar to the handshaking experiment, we repeated the table-touching experiment twice. The only difference between the two trials was whether the hands touched the table. Figure 3b shows the average results. Not surprisingly, the amplitude was much higher than the noise floor. However, when the hand was touching the table, the frequency response only had a single peak around 700 Hz, not the 1 kHz at which the system outputs the most energy.

We attribute the difference to two factors: the table's frequency response, and path loss due to coupling between the hand and table. To measure the table's frequency response, we attached the accelerometer to the position where the participants touched the table and recorded the response (see Figure 3b). We observed two peaks around 700 Hz and 2.7 kHz. The frequency of the first peak is consistent with the response when the hand touched the table, but the amplitude decreased significantly when the frequency was larger than 700 Hz. This result indicates there might be more path loss when the table is coupled to the hand at the higher frequency. In addition, the result is consistent with the finding in the handshaking experiment that the lower frequency might result in less path loss when the acoustic signal propagates off the body.

INFLUENCE OF AIR COUPLING

Because the bone transducer was not completely isolated from the air, the system possibly received energy from air coupling. To examine how much energy was actually received from this source, we compared the frequency responses in the table-touch experiments.

We averaged the amplitudes from the touch and nontouch scenarios and found the captured signal's amplitude was at least 20 dB higher when touch contact occurred. However, Figure 3b shows that the accelerometer can still pick up the signal with a strength up to –40 dB. We believe that the bone transducer is so powerful that it essentially turned the whole table into a huge speaker, which amplified the energy coupled to the air. Therefore, to apply this technology in the future, it will be necessary to eliminate air coupling.

DETECTING THE PRESENCE OF TOUCH CONTACT

One potential advantage of a body area network compared with wireless networks is that it is more secure because information is transmitted only when a device is attached to the user's body. If there is coupling between the transducer and air, however, it is still possible to eavesdrop on the information transmission without touching the user's body. Specifically, if the capturing device is close enough to the source, it can receive enough energy from air coupling to restore the information. To reduce this risk, touch contact will be necessary before initializing any information communication.

Based on the previous experimental results, the signal's amplitude declined significantly when touch contact was not initialized. Therefore, it is possible to recognize touch versus nontouch contact by simply comparing the amplitude to a threshold. However, the amplitude varies from person to person, which requires the threshold to be adjusted each time. Failing to do so appropriately would introduce the risk of information leakage.

To address this concern, we explored the possibility of detecting touch contact by matching the frequency-response curves rather than by comparing the strength of the received signals. Figure 3 shows that the touch and nontouch frequency-response curves visually differ, especially under 1 kHz. Based on this observation, we conducted another experiment.

First, we normalized the response curve to reduce the influence of different amplitudes between different people. We extracted the delta curve from the original response by calculating the difference between the current frequency and the previous one under 1 kHz (318 positions in total). We calculated the delta curves for the frequency responses of each participant and the average response for all eight participants in the table-touching and handshaking scenarios. Second, to determine whether there was touch contact, we calculated the Pearson correlation values between the to-be-determined delta curve and the average delta

TO APPLY THIS TECHNOLOGY IN THE FUTURE, IT WILL BE NECESSARY TO ELIMINATE AIR COUPLING.

curves of both the touch and nontouch scenarios. We classified the current curve to the class that presents a higher correlation. We applied this method to the data we collected in both the handshaking and table-touching experiments with 100 percent accuracy from the 32 frequency-response curves of the eight participants.

This experiment showed it is possible to detect the presence of touch contact, but more work is required to apply it in real-world scenarios. For instance, we used a transfer function between the sender and receiver that requires information from both sides. In reality, the sender might not have information about the received signal, unless the receiver sends the information back. Such a system would require each device to contain both a receiver and a sender, which we plan to explore in the future.

TRANSMITTING TEXT THROUGH THE BODY

Using frequency-shift keying (FSK) as the encoding method, we built a system to transmit text information encoded in acoustic signals through the body, between two bodies, and between the body and a wooden table. For this experiment, we slightly modified the hardware from the earlier experiments. On the receiver side, we used a contact microphone (Knowles BU-23173-000) to record the data. We connected the microphone to a customized preamplifier (see Figure 4) designed for low noise amplification and signal filtering. Signals from the contact microphone are filtered with a second-order low-pass filter with a cutoff frequency of 8 MHz to remove any RF interference. At this stage, a high-pass filter with a cutoff frequency of 0.16 Hz is cascaded to remove DC offset before amplification. Following this, the signal passes through a gain stage of 20 dB. The final front-end stage is a sixth-order Sallen–Key Butterworth low-pass filter with a cutoff of 20 kHz. The output of the preamplifier is connected to an audio interface (Fireface 800).

An iMac desktop computer connected data from the audio interface. On the sender side, we used the same bone transducer to send acoustic signals as in the previous experiments. The only difference was that we connected the bone transducer to a MacBook Pro sound card, which output the encoded acoustic signals. During the experiment, the input text was first translated to ASCII code, which was then encoded to acoustic signals using FSK. The lower and higher frequencies were set to 1,575 and 3,150 Hz, respectively.

OUR SYSTEM CAN TRANSMIT DATA WITH A BAUD RATE OF UP TO 105 BITS/S AS FAR AS 38.1 CM AWAY ON A PERSON'S ARM.

As in the previous experiments, we placed the bone transducer on the wrist and placed the contact microphone at a distance of 7.6, 22.9, or 38.1 cm on the participant's arm. In each position, we sent five characters at different baud rates (5, 35, 70, and 105 bits/s). We saved the data and then passed it through a band-pass filter before FSK decoding.

We successfully decoded the text for all the settings. These results show that our system can transmit data with a baud rate of up to 105 bits/s as far as 38.1 cm away on a person's arm. Such a data transmission rate can be used to transmit a short message, such as a name. We plan to test the text transmission system with more subjects and more locations in the future.

NOISE INFLUENCE

Transmitting using a frequency with high environmental noise might affect the signal within the body. Thus, we conducted another experiment to evaluate the influence of ambient noise on acoustic signal propagation through the body. Similar to the previous experiments, we placed the bone transducer on the participant's left wrist and attached the accelerometer about 7 cm away. In the first trial, we recorded the frequency response from 250 to 20 kHz without playing any ambient noise. In the second trial, we played 1 kHz noise at 90 dB through a speaker, which was 58.4 cm away from the accelerometer. The amplitudes recorded at 1 kHz for the two rounds of experiments were –5.0 and –4.6 dB, respectively. There was an increment of 0.3 dB when the environmental noise was present.

Body movement can introduce noise as well because the receiver could scratch the skin while the user is in motion. Carefully choosing the position and carrier frequency can reduce the influence of the scratching sound. Nevertheless, movement artifacts corrupting signal transmission are a limitation of the current system. Future work will focus on developing methods that mitigate these artifacts, either via sensor fusion (such as by combining the acoustic data with simultaneously obtained accelerometer recordings) or by gating the signal transmission to occur only when motion levels are low.

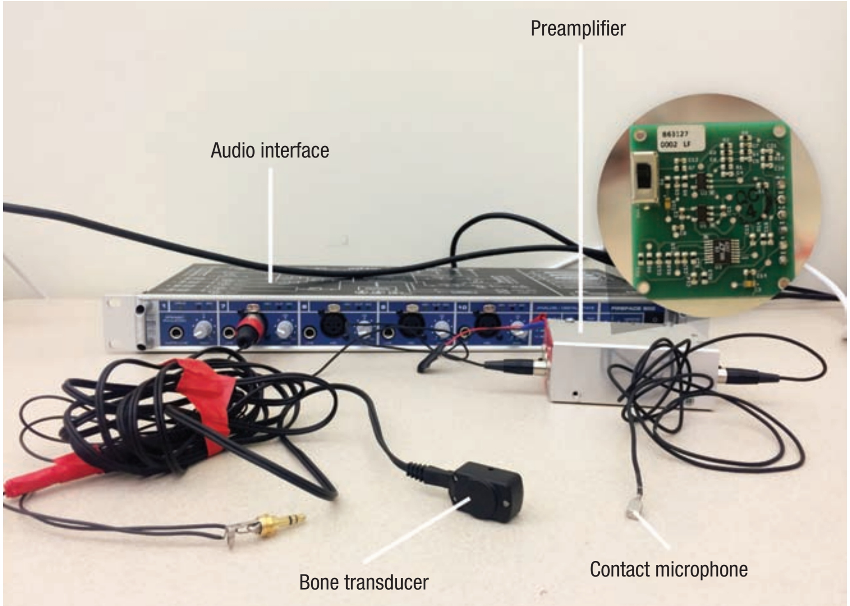

FIGURE 4. System setup for the data-transmission experiment. The microphone is connected to a customized preamplifier designed for low noise amplification and signal filtering.

SIGNAL TRANSMISSION WITH OFF-THE-SHELF DEVICES

One advantage of transmitting acoustic signals under 20 kHz is that most mobile devices (such as smartwatches) already possess sensors (including accelerometers and gyros) to capture and transmit (via vibration motors) such acoustic signals. Therefore, we used a Sony SmartWatch 3 with a 200-Hz vibration motor as the transducer to transmit encoded acoustic signals from the wrist to the table. We observed a clear pattern for the received signal. We also successfully received information by using the watch's microphone as the receiver in the handshaking experiment. (See the web extra video at youtu.be/6Vo3gm5oJnM for a real-time demonstration.) The received pattern was visually apparent. Although this experiment is preliminary, it demonstrates the feasibility of applying the proposed technique using off-the-shelf devices.

POTENTIAL APPLICATIONS

A host of potential applications could be enhanced by our proposed technology. As we explained earlier, wireless communication requires tedious setup procedures before information transmission can occur. By using the body as a communication medium, a device can only communicate when it is on the body. This technique would optimize the user experience when setting up cross-device communication because the setup procedure could be automatically completed the moment the device is attached to the body. Also, it potentially reduces the risk of exposing information to a public medium.

Being able to transmit information from a wearable to the environment by physical contact would also introduce a more natural user experience for different applications. User authentication is one such example. For instance, rather than inputting a password or using a card with a built-in chip to open a door, a user would only need to hold the door handle to complete the authentication process; the identification information would flow from the wrist-mounted device to the door handle.

Our method could also be used to retrieve information from the environment using touch interactions. For instance, when visiting museums, users could obtain more information about certain exhibits and have such information displayed on their wearables, such as a smartwatch or head-mounted display. Instead of having to read labels and descriptions adjacent to an object while standing amongst a crowd or needing to scan a QR code with a camera, the information about the exhibit could flow to a wearable from the encoded object when the user simply touches it.

Future work will address additional challenges in bioacoustics-based human-body-mediated communication. The experiments we describe here only explored attaching sensors to a limited set of locations (mostly on the upper body) while the participants maintained a static posture. However, the sensor's position and the tightness between the sensor and the skin might change the transfer function. This is a limitation of our current system, which might not work well when the user is involved in high-intensity activities.

Furthermore, we currently do not isolate the bone transducer from air coupling, such that it was audible when the system was operated

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at the audible range with 5 V input. Although the participants did not report any discomfort when the signal passed through their bodies, the user can feel the vibration when the transducer is operating at lower frequencies (such as 250 Hz).

In the future, we plan to investigate the influence of sensor positions, the tightness of the coupling between the sensor/actuator and the body, and the frequency on the system's efficiency as well as explore the relevant user experience. We also plan to build more demo applications and quantify the error rates during data transmission for various body types under different scenarios. ■

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