ShaZam: Charge-Free Wearable Devices via Intra-Body Power Transfer from Everyday Objects

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In this work, we investigate a wireless power transfer technology that can unobtrusively charge wearable devices while users interact with everyday objects, such as an office desk, laptop, or car. We design and develop our solution, ShaZam, that exploits the human body as a medium to transfer Radio Frequency (RF) energy-carrier signals from minimally-instrumented daily objects to wearable devices. We focus on establishing the technical groundwork of the proposed technology by incorporating the capacitive coupling mechanism, in which the forward signal path is established through the human body, and the return path is established via capacitive coupling to the surrounding environment. To showcase the feasibility of our technology, we investigate three different use scenarios—i.e., interacting with a keyboard on a desk, a laptop, and the steering wheel of a car—to transfer power to a wrist-worn device. Using data obtained from ten healthy individuals within a setting where uncontrolled electromagnetic interference was relatively low, we demonstrate that we can transfer approximately $0.5\text{ mW} - 1\text{ mW}$ of DC power to the wrist-worn device. We also investigate several critical environmental and design parameters that could affect the power transfer and offer design guidelines that optimize performance. Our initial results suggest the potential for a new design paradigm towards completely charge-free wearable devices.

CCS Concepts: • **Hardware** → **Power and energy**; • **Computer systems organization** → Embedded and cyber-physical systems; • **Human-centered computing** → Ubiquitous and mobile computing;

Additional Key Words and Phrases: Intra-body power transfer, capacitive power transfer, wireless power transfer, energy harvester, batteryless device, wearable device

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1 INTRODUCTION

The unprecedented advancements in semiconductor and material sciences have stimulated the development and growth of ultra-low power wearable devices in the consumer market and research communities, allowing opportunities for users to continuously monitor important health-related physiological parameters. Recent surveys have reported that self-tracking is becoming more ubiquitous, and roughly 20% of Americans own a wearable device for self-tracking purposes [31, 58]. However, these devices often pose critical constraints in usability and functionality due to their use of an on-device battery as the primary power source [61]. First, users are required to charge the devices periodically, which has been identified as one of the major reasons (i.e., inconvenience and cumbersomeness) for discontinuing the use of wearable devices [9, 20, 27]. Second, periodic charging of wearable devices hampers the continuous monitoring of users' fitness or health conditions. For example, it has been shown that most users use their bedtime to charge their wearable devices [41, 50], which prohibits them from monitoring their sleep patterns. Last but not least, owing to the proliferation of wearable devices, charging equipment (e.g., plug-in charging bricks) has been identified as one of the rapidly growing electronic waste streams [28], which is a matter of concern for wearables' overall environmental footprint.

To counteract the above-mentioned complications associated with the management of on-device batteries, wireless power transmission technologies that can charge wearable devices in a completely unobtrusive and seamless manner have become an emerging topic of research over the past decade [46, 50]. For example, prior studies have investigated an approach to inductively transfer power, where the receiving coil is mounted on the body-worn devices, and the transmitting coil is embedded within everyday objects (e.g., under an office desk) [40, 85]. Although inductive power transfer has the potential to charge wearable devices without user interventions, it suffers from substantially reduced power transmission efficiency when the coils are misaligned and only supports reasonable power transfer at extremely short distances (e.g., $< 2\text{ cm}$). To tackle these issues, researchers have instrumented daily objects (e.g., an office desk with a movable coil underneath) [40, 85] or the surrounding environment with equipment that can wirelessly transfer energy from a variety of sources, such as Radio Frequency (RF) signals [16, 29, 63, 74, 76], laser [39], and electromagnetic fields [67, 89]. However, these solutions require large and costly infrastructure and/or need to transmit a significant amount of power to support reasonable power harvesting at the wearable devices, which conflict with the vision of ubiquitously available and scalable charging support. Researchers have also demonstrated their attempts to power up wearable devices from readily available, ambient energy sources, including thermal energy [48], bio-mechanical energy from limb movements [49, 51, 73], friction between human skin and smart fabric [47], and sweat [15, 22, 77, 78]. Nevertheless, those solutions require continuously available power sources (thermal gradient, human movements, or sweat) and support only a relatively small amount of power harvesting, even when the power source is fully available.

In this paper, we investigate an emerging topic of research, called Intra-Body Power Transfer (IBPT), that exploits the human body as a medium to transfer power in order to wirelessly and unobtrusively charge wearable devices while users interact with everyday objects. More specifically, objects that users interact with for relatively long periods of time on a daily basis—such as the office desk, chair, car, or bed—could be instrumented with compact, inexpensive electronic components that can infuse RF energy into the human body, which is then received and rectified by wearable devices at different body parts. While the concept of IBPT was first introduced in the late 1990s [60, 79], it has recently gained interest in the research communities to demonstrate the feasibility of the concept [71, 80], owing to the advancements in power harvesting and related MEMS technologies. However, unfortunately, the systematic understanding of important design factors and rigorous evaluation of the technologies in human subjects largely remain under-explored.

Fig. 1. Ubiquitous charging of a wrist-worn device (e.g., a smartwatch or fitness tracker) from interacting with everyday objects, such as (a) an office desk, (b) a laptop, and (c) the steering wheel of a car

We design and develop our solution, ShaZam¹, aiming to establish the technological foundation of the proposed interaction-driven IBPT technology. This study primarily contributes to enhancing our systematic understanding of important design factors, specifically for the envisioned application of IBPT to unobtrusively and seamlessly charge wearable devices while interacting with everyday objects. The major technical challenge associated with IBPT is to secure the forward and return paths of the power circuit over the human body, a chunk of conductive materials that does not explicitly define the two isolated signal paths. ShaZam employs the capacitive coupling architecture, in which an RF signal is injected into the body tissue via a dry (copper) electrode to construct the forward electrical path, while the return path is established via the inherent natural capacitance between a pair of metal (copper) electrode floating in the air and the surrounding environment. As a motivating example, in this work, we consider charging a wrist-worn device (e.g., a smartwatch or fitness tracker) while interacting with three different objects: a keyboard on the office desk, palm rest on a laptop, and the steering wheel of a car, as shown in Fig. 1.

2 BACKGROUND

2.1 Overview of Intra-Body Power Transfer

IBPT is a technique that leverages the body tissue to transfer power between two devices that are placed on or near the body [71]. The primary technical challenge for IBPT is to secure the forward and return paths of the energy-carrier signal on the human body channel, which could be considered as a single conductive medium that does not distinctly define two isolated signal paths. Inspired by the field of Intra-Body Communication (IBC)—a wireless communication technology over the human body channel between two battery-powered, on-body devices [23, 35, 55, 92]—there exist two potential solutions to the problem [69, 71, 88]: 1) the *capacitive coupling* method that leverages the quasi-static near-field capacitive coupling to establish the signal return path while using the human body as the forward path and 2) the *galvanic coupling* method that considers the human body as a lossy conductive medium.

¹ShaZam is a fictitious comic-book character with a superpower that can wirelessly transfer power, for example, to charge electronics [2].

Fig. 2. (a) A conceptual illustration of the capacitive coupling method, where the skin electrodes of the power transmitter and receiver establish capacitive coupling to the human body, and the two ground electrodes establish another capacitive coupling to the environment. (b) Application of the conceptual illustration to the office desk use scenario.

In the capacitive coupling method, both the power transmitter and receiver will have 1) an electrode (termed as the *skin electrode* hereafter) that establishes capacitive coupling to the human body and 2) a metal plate (termed as the *ground electrode* hereafter) that floats in the air to establish another capacitive coupling to the environment (including the parasitic coupling between the two ground electrodes) [18, 56, 69], as shown in Fig. 2. In this configuration, the time-varying electric field around the human body can be approximated as a uniform phase field, which induces the current to flow—hence, transfer power—through the human body tissue.

ShaZam adapts the capacitive coupling architecture because it offers evident advantages for the considered use scenarios, in which we aim to seamlessly charge the on-device battery of wearable devices while the user ubiquitously interacts with daily objects. Capacitive coupling can transfer a greater amount of energy compared to galvanic coupling. In galvanic coupling, the power transmitter uses two skin electrodes to infuse the carrier signal into the human tissue, where one of the electrodes acts as a signal electrode and the other as a ground electrode. Consequently, most power transfer occurs between the two electrodes of the power transmitter rather than through the human body towards the receiver [69]. However, one notable weakness of capacitive coupling is that its power transfer performance could be susceptible to ambient electromagnetic (EM) noise [70, 87]—e.g., FM radio signals in outdoor settings that operate at a similar signal frequency as the carrier signal [68]—because the return path is established via capacitive coupling to the environment. Fortunately, the spectral density of most RF noise sources are often insignificant and thus have minimal impacts on signal propagation between two capacitively-coupled devices [68, 87]. More importantly, in this paper, we consider use scenarios where the power transmitters are embedded in daily objects that the user may frequently interact with for a long period of time, such as a keyboard on the office desk, the palm rest of a laptop, and the steering wheel of a car, as shown in Fig. 1. Hence, the user's nearby environment does not change dynamically and remains relatively static, making the system less vulnerable to ambient EM noise. Moreover, capacitive coupling supports reliable power transfer against subtle motion artifacts or the presence of obstructing materials (e.g., clothing) because the coupling between the human body and skin electrode could still be established even with a reasonable physical separation (e.g., $< 3\text{ mm}$). Capacitive coupling could also substantially simplify the human-machine interface design because it requires the user to make contact with only one electrode (i.e., the skin electrode) in order to

enable the power transfer. Galvanic coupling, on the other hand, requires the user to make firm contact with two electrodes simultaneously, which significantly complicates the interface design.

2.2 Human Safety Regulations

Time-varying EM fields (EMF) may potentially degenerate nerve tissue or cause microwave heating of tissue [38, 71, 81]. Studies have reported that perceivable nerve and muscle stimulation are likely to occur at frequencies below 100 KHz, which is not a concern for the proposed system that operates in the High Frequency (HF) range (3 - 30 MHz). However, in the HF range, the incident EMF wave induces electric displacement current (i.e., temporal change of the electric field in the space) through human tissue [13, 38]. The lossy part of the dielectric material will generate heat due to the displacement current flow inside the medium, which may result in a thermal injury of tissue [13, 38]. According to the human safety guidelines outlined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Federal Communications Commission (FCC), four dosimetric quantities should be considered for the chosen operating frequency (i.e., 13.56 MHz) which include the specific energy absorption rate (SAR), power density per contact area, contact current intensity, and current density per contact area [38, 53, 54].

2.2.1 Specific Energy Absorption Rate. : SAR is the rate at which EM energy is absorbed by a 10 g of the body tissue of cubic geometry [64]. The unit of SAR is W/kg , and it is correlated with the induced electric field and conductivity at a point inside the EM boundary [38, 64]. Hence, this parameter needs to be accounted for wearable applications that are likely to be placed at different epidermal locations of the human body. SAR is only effective in frequencies greater than 100 KHz, and a higher value may lead to whole body or local tissue heating [38, 64]. For the general public, the ICNIRP limits the upper bound of the whole-body SAR to $0.08 W/kg$, and the localized SAR for the peripheral limbs (e.g. hand) to $4 W/kg$ [54].

2.2.2 Power Density per Contact Area. : Power density (measured in W/m^2) refers to the amount of power flowing through per unit area of a cross-section of a body part. The maximum permissible power density contributed by the EMF for the operating frequency f in the range of 1–30 MHz can be computed by $1800/f^2$ [38]. Power density above these limits could result in tissue heating in the contact area.

2.2.3 Contact Current Intensity. : Contact current (measured in mA) is the amount of induced current on the human tissue due to the potential difference between the electrode and skin [38]. Excessive contact current might result in burning sensation and tissue ulcer. The ICNIRP recommends contact current to be limited to $16.7 mA$ at 100-110 MHz [54].

2.2.4 Current Density per Contact Area. : Current density (measured in mA/m^2) is the displacement current per unit area at a cross-section of the body channel. High current density may yield adverse effects on the nervous system. According to the ICNIRP, the current density should be limited by $f/500mA/m^2$ at 1 KHz-10 MHz [54]. However, for $f > 10 MHz$ on which our system operates, the health risks associated with current density are negligible, and the SAR plays a more critical role [71].

2.2.5 Potential Complications for Implanted Medical Devices. : Another concern for RF exposure is EM interference with active/passive medical implants, such as cardiac pacemakers, implantable defibrillators, neurostimulators, infusion pump, and stent. According to plane wave approximation [13], RF energy impinging on conductive objects within the propagation medium (e.g., metal enclosure of implants in the body) yields a scattered field, which may result in heating and elevated SAR near the vicinity of the objects. However, the possibility of such

Fig. 3. Schematic representations of the hardware design for the (a) power transmitter and (b) power receiver.

damages requires a field with extremely high intensity. Therefore, the proposed system, which only emits power in the order of a few dBm , poses minimal risks for medical implants. Nevertheless, the Center for Devices and Radiological Health at the US Food and Drug Administration (FDA) recommends a minimum distance of 15 cm between mobile devices emitting active EM fields and medical implants [4].

3 DESIGN AND IMPLEMENTATION OF SHAZAM

In this section, we provide a detailed engineering design of the power transmitter and receiver. Then, we discuss important design criteria (i.e., the size and placement of the electrodes and the frequency of the carrier signal) and an approach to search for an optimal configuration that could maximize power transfer and its reliability. Finally, based on the identified optimal configuration, we discuss the hardware implementation of the system. The detailed schematic circuit diagrams of our hardware are provided in the Supplementary Materials.

3.1 Hardware Design of the Power Transmitter and the Receiver

3.1.1 Power Transmitter: Fig. 3a provides a schematic illustration of the power transmitter. A Direct Digital Synthesis IC (AD9910; Analog Devices, USA) generates the RF power carrier signal, whose power is further amplified using an RF amplifier (ZX60-43-S+; Mini-Circuits, USA). The amplified RF signal is then injected into human tissue after conditioning via an impedance matching network (see Section 3.5 for details).

3.1.2 Power Receiver: Fig. 3b provides a schematic illustration of the power receiver. The signal received at the skin electrode is fed into an impedance matching network. The output of the matching circuit is then doubled and rectified using a two-stage Dickson topology charge pump in order to support the minimum input voltage requirement (i.e., 600 mV) of the battery manager (BQ25570 by Texas Instruments, USA). This battery manager contains an integrated boost mode regulator to further increase the rectified DC voltage level in order to charge a battery.

3.2 Important Design Configurations

Given the above-mentioned architecture for the power transmitter and receiver, the primary design components of ShaZam include 1) the size and placement of the skin and ground electrodes and 2) the carrier signal frequency. The electrode design of the wearable power receiver allows only limited configurations because the design is primarily determined by the wearable form factor. For example, for the smartwatch form factor, the skin electrode

Fig. 4. (a) The FEM model for the office desk application consisted of a wooden desk, dry copper electrodes, and a multi-layered human hand (i.e., skin, muscle, and bone). We investigate three different sizes and placements of the ground electrode of the power transmitter: (b) $1 \times 1 \text{ cm}^2$, (c) $5 \times 5 \text{ cm}^2$, and (d) $10 \times 10 \text{ cm}^2$

should be placed under the watch straps, and the ground electrode should be placed under the screen. A similar design constraint should be applied to other form factors, such as a patch-like sensor on the chest [45] or a ring-like sensor on the finger [44].

The power transmitter electrode design, on the other hand, provides some level of flexibility subject to the physical constraints imposed by specific use cases. The skin electrode should be carefully placed on the daily objects to support frequent, long-term physical contact with the body part where the wearable sensors are placed. For example, in the office desk application, the skin electrode should be placed in front of the keyboard such that the wrist could make firm contact while typing, as shown in Fig. 1a. In contrast, the ground electrode offers almost an infinite number of configurations for its size and placement. Hence, configurable parameters simplify to 1) the size and placement of the transmitter ground electrode and the 2) carrier signal frequency. In the following two subsections, we introduce our methods to identify the optimal solutions to these two configurable parameters.

3.3 Investigating The Optimal Electrode Configuration

Without loss of generality, we use the office desk application to demonstrate our method to identify an optimal electrode configuration. Because 1) the search space is almost infinitely large and 2) it is impractical to empirically search for an optimal solution via experiments, we computationally model the physical characteristics of the components involved in power transfer (i.e., the human hand and electrodes of the transmitter and the receiver) and search for an optimal ground electrode configuration that can maximize signal propagation. In this work, we use a commercially available 3D electromagnetic simulator (HFSS, ANSYS, USA) that employs the Finite Element Method (FEM) for modeling. This tool has been similarly used to model the propagation characteristics of the human body channel for communication purposes [55, 93].

Fig. 4 shows the FEM model that consists of a wooden desk, dry copper electrodes, and multi-layered human hand (i.e., skin, muscle, and bone). The electrical properties of different human tissue components (i.e., conductivity and permittivity) were determined based on the values outlined by the Federal Communications Commission (FCC) [21]. The sizes of both the skin and ground electrodes of the power receiver on the wrist were set to $2.5 \times 3.5 \text{ cm}^2$ in order to comply with the smartwatch form factor (e.g., roughly equivalent to the screen size of Apple Watch Series 2). The dimension of the skin electrode of the power transmitter was set to $15 \times 15 \text{ cm}^2$

Fig. 5. The simulated Maximum Available Gain (MAG) plot for the considered frequency range from 10 MHz to 100 MHz.

Fig. 6. The measured S_{11} parameters of the power transmitter (a) before and (b) after the impedance matching.

in order to support a reasonable contact area for the human hand and wrist while typing on a keyboard. We carefully selected three different sizes and placements of the ground electrode of the power transmitter: $1 \times 1 \text{ cm}^2$, $5 \times 5 \text{ cm}^2$, and $10 \times 10 \text{ cm}^2$, where its center was placed 23 cm away from the center of the skin electrode, as shown in Fig. 4. The choice of the ground electrode configuration was driven by our initial simulation results that the capacitive coupling strength of the return path decreases substantially when the ground electrode is placed beyond 23 cm from the skin electrode. The maximum size of the ground electrode (i.e., $10 \times 10 \text{ cm}^2$) was determined to maintain a reasonable distance from the skin electrode in order to avoid shorting the circuit, as shown in Fig. 4d. The other two ground electrode sizes (i.e., $1 \times 1 \text{ cm}^2$ and $5 \times 5 \text{ cm}^2$) were chosen arbitrarily under the constraint of this maximum size.

We investigated the Maximum Available Gain (MAG) [55] as the evaluation metric for the three ground electrode configurations between 10 MHz and 100 MHz. This frequency range was chosen because 1) the capacitive coupling to the environment has been shown to become relatively weak in frequencies lower than 10 MHz [10, 14, 18, 71, 80] and 2) the human body starts to behave as a dipole antenna and dissipate energy in the air at frequencies greater than 100 MHz [10, 11, 56]. Fig. 5 shows the MAG responses within this frequency range for the three different ground electrode configurations, which supports that a larger transmitter ground electrode yields greater MAG due to stronger capacitive coupling to the environment and to the ground electrode of the receiver.

3.4 Investigating The Optimal Operating Frequency

Once the optimal configuration of the ground electrode of the transmitter is determined for the maximal capacitive return path, we conducted a preliminary experiment to find the optimal operating frequency by investigating the static and dynamic characteristics of the forward body path while incorporating more realistic factors into account. We analyzed two-port S-parameters (i.e., S_{11} and S_{22}) of our system using a bench-top Vector Network Analyzer (VNA; E5071C, Keysight Technologies, USA). The two-port network consisted of 1) the power transmitter coupled to the environment and human skin, 2) the human body channel, and 3) the receiver coupled to the environment and human skin. One volunteer subject participated and placed the hand naturally on the keyboard, as shown in Fig. 1a, except that the signal generator was removed, and the transmitter and receiver skin electrodes were respectively connected to Ports 1 and 2 of the VNA.

Both the S_{11} and S_{22} parameters showed flat responses within the considered frequency range between 10 MHz and 100 MHz, implying that there exist no specific operating frequencies that can minimize the signal reflectivity at both ends of the channel, mainly due to the simple, square-shaped electrode design. Therefore, we decided to operate our power carrier signal at 13.56 MHz based on 1) a number of prior studies that have reported maximal signal propagation at this frequency [75, 80], 2) our simulation results in Fig. 5 corroborating that lower frequencies (e.g., 5 – 20 MHz) could yield higher power transfer, and 3) potential benefits to leverage available existing electronic components for RFID systems that operate on the same frequency.

3.5 Further Increasing Power Transfer Efficiency: Impedance Matching Network Design

With the identified electrode configurations and operating frequency, we design impedance matching networks to strengthen the signal propagation through the human body channel and improve the transmission gain. The matching network design is primarily driven by the configurations of the transmitter and receiver electrodes (i.e., material, size, and placement) but minimally impacted by the inter-subject variability in the body channel characteristics because electrodes' fields are concentrated between the skin and ground electrodes for each device. In other words, although matching networks need to be designed specifically to different applications, they could generalize across different users.

We first measured the input and output impedances of the power transmitter and receiver electrodes. The input impedance of the transmitter electrodes was measured while the electrodes were coupled to the environment and to the body channel of a volunteer subject under the same experimental setup in Section 3.4. We confirmed that the output impedance of the RF source (i.e., the RF amplifier of the power transmitter) was 50 Ω , but it was different from the measured input impedance of the harvester module of the receiver. Therefore, it was necessary to design a matching circuit. In the harvester, the charge pump contains non-linear diodes whose impedance varies across different power levels. We performed a harmonic analysis and identified that the diode used in our prototype (HSM285C, Avago Technologies, USA) requires a minimum power of -10 dBm in order to support the cold start current needed for the battery manager. Therefore, the input impedance of the harvester was obtained at the operating frequency of 13.56 MHz and the minimum power of -10 dBm. Furthermore, the preferred quality factor of the matching network was set to 1 to exploit the bandwidth/gain trade-off, which ensures that the electrode's available power can be captured by the harvester that has a varying input impedance. The aforementioned impedance measurements for the office desk and laptop applications were obtained in a laboratory setting using a bench-top VNA (E5071C, Keysight Technologies, USA). Those for the car application were obtained from a vehicle that was parked in an outdoor parking lot using a portable VNA (N9912A, Keysight Technologies, USA).

Based on the measured impedances, we created a total of six matching networks for each application using three different matching methods (i.e., L, T, and π -type) and two different topologies (i.e., Low and High Pass Filters). Then, we empirically chose the optimal matching by investigating the S_{11} parameter, which is an indicator of the maximal power transfer rate of the system. Fig. 6 shows the S_{11} response of the power transmitter of the desk application before and after incorporating the matching network. We applied this procedure identically to the four electrode pairs used in this study (i.e., the transmitter electrodes of the three driving applications and the receiver electrodes). Fig. 7 shows the matching networks designed for these four electrode pairs.

3.6 Hardware Design of the Power Transmitter and the Receiver

Fig. 8 shows our implementation of the power receiver on a custom-design circuit board. We used a 470 μ F capacitor as the energy buffer instead of a lithium-ion battery because 1) the energy stored in a battery cannot be accurately measured using its voltage level, and 2) the battery capacity is considerably large (usually in tens or hundreds of mWh) with respect to the charging rate supported by the proposed power transfer technique (i.e., a

Fig. 7. Designs of the optimal matching networks for (a) power receiver and for the power transmitter in the (b) office desk, (c) laptop, and (d) car applications.

Fig. 8. Implementation of (a) our custom-designed power transmitter and (b) the 3D-printed enclosure with skin and ground electrodes.

few hundred μW). Fig. 9a shows our implementation of the power transmitter and placements of the electrodes for the office desk, laptop, and car applications.

4 EXPERIMENTAL SETUP

The three use scenarios considered in this work (i.e., office desk, laptop, and car) were chosen not only to demonstrate ShaZam's versatility for different applications but also because they offer unique technical conditions to investigate critical factors affecting the strength of capacitively-coupled IBPT. We use the office desk as the benchmark experiment—for its reliable forward/return path coupling and superior power transfer compared to the laptop and car applications—and investigate the impacts of different gestures, motion artifacts, and environmental factors in a longitudinal manner. The laptop application was chosen to investigate an electrode configuration where the power transmitter electrodes need to be placed close to each other due to limited footprints. Note that we identified two optimal ground electrode configurations for the laptop application: a large square ground electrode on the back of the screen panel (Fig. 9c) and a thin rectangular (dipole) electrode on the frontal panel (Fig. 9d). In the car application, the metal frame of the car serves as the ground electrode, as shown in Fig. 1c. Hence, we chose this application to investigate the effect of a large ground electrode encapsulating the user and the system, which we hypothesize attenuates external noise and thus supports stronger power transfer. It is noteworthy that the experiments for the office desk and laptop applications were performed in a different location (i.e., a different building) from where the impedance values of the electrodes were measured. In other words, the matching networks were not specifically tuned to the environments for these two experiments. The car application, on the other hand, used the same vehicle for both the impedance measurement and experimentation.

4.1 Human Experiments

Ten healthy volunteers (31.3 ± 6.63 years, mean $\pm$ standard deviation; 1 females and 9 males) were recruited from the University of Massachusetts Amherst. The recruitment criteria required participants to be healthy and aged

Fig. 9. The implementation of (a) our custom-designed power transmitter and optimal electrode configuration(s) for (b) the office desk application, (c,d) laptop application, and (e) car application.

Fig. 10. A study participant performing (a-c) three different experiments for the desk application, (d) the laptop application, and (e) the car application.

between 18 and 45 years old. Two sets of experiments were conducted over a three-month period: the baseline experiments in October/November 2020 and the follow-up experiments in January/February 2021.

4.1.1 Baseline Experiments: When participants arrive at the research laboratory (termed as Location #1, hereafter), they were asked to put the wrist-worn power receiver on their non-dominant wrist. For the benchmark office desk application, we conducted three different experiments using the optimal ground electrode configuration that we identified in Section 3. The transmitter's skin and ground electrodes were covered with a thin paper insulator to avoid accidental shorting of the transmitter circuit with the hand and to minimize potential skin-to-metal allergic reactions. First, participants were asked to type on a keyboard (WK117, Dell, USA) on a wooden desk

(with metal legs) as they would do in real-world settings for four minutes in order to investigate the amount of power transfer that could be achieved during naturalistic interactions (see Fig. 10a). Then, we asked participants to place their hand vertically (i.e., semi-pronation) for four minutes, as shown in Fig. 10c, in order to evaluate the effect of different postures on the power transfer performance. Last, we placed a 3 mm-thick insulating material (i.e., a stack of paper) between the skin electrode and hand during typing, as shown in Fig. 10b, in order to evaluate the effects of the reduced electrode-to-body coupling strength from motion artifacts; we hypothesized that we could transfer some amount of energy but at a reduced rate. In the laptop application, participants were again asked to naturally type on the keyboard for four minutes, as shown in Fig. 10d, under two optimal electrode configurations (i.e., Fig. 9c and d). For the car application, subjects were asked to sit on a car that was parked in an outdoor parking lot and place their non-dominant hand on the steering wheel for four minutes, as shown in Fig. 10e. After the experiments, participants reported their height and weight information to compute the Body Mass Index (BMI) as a rough estimate of their body composition characteristics (e.g., fat distributions) and investigate potential correlations to the power transfer performance.

4.1.2 Follow-up Experiments: Nine of the ten subjects came back to the laboratory setting approximately three months after the baseline experiments. The follow-up experiments focused on the benchmark office desk application to investigate important environmental factors that may affect the establishment of capacitive coupling and thus power transfer. First, the ambient temperature in the Western Massachusetts, where the experiments were performed, differed quite substantially between baseline (October/November) and follow-up (January/February). The average high and low temperatures in October/November are 13 °C and 2 °C, and those in January/February are 3 °C and -7 °C, which also significantly impact the indoor climate (e.g., temperature and humidity). We also examined the power transfer performance by making some important changes in the immediate surrounding environments of the user in order to demonstrate the reliability and generalizability of the system for real-world deployment. For example, we tested the system on two desks with different panel materials (e.g., non-conductive wood vs. conductive metal) that can significantly influence capacitive coupling between the skin and ground electrodes of the power transmitter.

Participants were first asked to repeat the three experiments associated with the office desk application—i.e., natural typing, semi-pronation, and 3 mm insulation—in Location #1, as shown in Fig. 10f-h. Then, participants repeated the natural typing experiment on a desk with the metal panel in Location #1, as shown in Fig. 10i. We hypothesized that the increased parasitic coupling between the skin and ground electrodes of the transmitter would result in inferior power output. Finally, participants repeated the natural typing experiment again in another location within the same building (i.e., Location #2) on a desk with a wooden panel (Fig. 10k). After the completion of the experiments, participants filled out Likert-scale survey questions on the usability of ShaZam and potential safety concerns about acting as an electrical medium to transfer power. The questions were “Q1: Did you find the electrodes interfering with your natural interactions with the object?”, “Q2: Did you have any fear or safety concerns about acting as a medium to transfer electric signals prior to participating in the experiments?”, and “Q3: Did you have any fear or safety concerns about acting as a medium to transfer electric signals after participating in the experiments?” Participants also self-reported their height and weight information again at follow-up visits for the BMI. We also recorded the temperature, humidity, and background EM noise level prior to each experiment. The EM noise was measured using an E-field sensing probe (EM-6992, Electro-Metrics, USA) and a bench-top oscilloscope (MSOX4104A, Keysights, USA) centered at 13.56 MHz with a 1 MHz bandwidth. The experimental procedures were approved by the Internal Review Board of the University of Massachusetts Amherst (#1444), and all participants provided signed informed consent that described the benefits and risks associated with the experiments.

Fig. 11. (a) Custom-designed embedded system that measured the power transfer rate by monitoring voltage across the capacitor during charging and discharging cycles. (b) Experimental data collected from one of the study participants using our assessment tool.

4.2 Data Acquisition System

We used an independently-powered, custom-designed embedded system to measure the power transfer rate, which is shown in Fig. 11a. This device continuously monitors and records the DC voltage across the energy storage capacitor on the power receiver. When the voltage of the capacitor reaches an upper hysteresis threshold of 3.8 V, it discharges the energy stored in the capacitor to ground through a shunt resistor using a transistor until the capacitor voltage reaches a lower hysteresis threshold value of 3.1 V. This process is repeated across a number of charge/discharge cycles during the four-minute experiment duration. The voltage data is sampled at roughly 30 Hz and stored in an SD card. Fig. 11b shows sample voltage data that we collected from one of the study participants. To compute the power transfer rate, we measured the power for each charge/discharge cycle (indexed i) using the following equation:

$$P_i = \frac{E}{T_i} = \frac{\frac{1}{2}C(V_u^2 - V_\ell^2)}{T_i},$$

where $C = 470 \mu F$, T_i represent the duration of the i^{th} cycle, and V_u and V_ℓ represent the upper and lower hysteresis values, respectively. Then, the average and standard deviation of the values of P_i for all i were computed for each experiment and each subject.

5 FINDINGS

In this section, we report our experimental findings on the feasibility of charge-free wearable sensors via interaction-based IBPT and discuss critical factors that could impact power transfer. The amount of power that we used in our experiments strictly complied with the safety regulations that we discussed in Section 2.2. The power that we injected into the human body channel was measured 2.04 mW, which is far less than the allowed localized SAR for the upper-limb (i.e., 8 W). The contact current computed using the measured impedance values was approximately 3 mA, which was also substantially lower than the allowed contact current for the upper-limb (i.e., 16.7 mA). In addition, the power and current density per approximated contact area (i.e., 26.25 cm²) was computed as 0.11 mA/cm², which is far less than the FCC-recommended value of 271.2 mA/cm². At the end of this section, we report on participants' concerns about the safety and perceived usability of the proposed system.

5.1 Baseline Experiments: Power Transfer Performance for the Three Applications

Fig. 12 shows the DC power received at the wrist-worn device for the office desk (i.e., natural typing), laptop (i.e., a rectangular ground electrode on the frontal panel), and car applications of the baseline experiments. These results show that 1) the inter-subject variability for each application is reasonably low (see Section 5.4 for more details) and 2) the amount of power transfer may vary significantly depending on how the system is configured subject to the constraints imposed by daily objects. The mean and standard deviation of the power transferred

Fig. 12. (a) The average and standard deviation of DC power measured at the wrist-worn device for the office desk, laptop, and car applications. (b) Measured power in the three different experiments for the desktop application: using the keyboard in a natural manner, placing a 3 mm insulation material between the human hand and transmitter skin electrode, and placing the hand in a semi-pronation posture. (c) Measured power for the two different configurations of the transmitter ground electrode in the laptop application. Asterisk indicates $p < 0.01$.

across the ten participants were $993.2 \pm 126.5 \mu W$ for the office desk application, $177.4 \pm 117.1 \mu W$ for the laptop application, and $688.6 \pm 119.8 \mu W$ for the car application.

The office desk application supported the largest average power transfer among the three applications, followed by the car and the laptop applications. First, we believe that the office desk application was able to transfer a larger amount of power compared to the car application because the ground electrode of the power transmitter in the desk application was more proximate to the ground electrode of the receiver on the wrist, creating stronger parasitic capacitive coupling between them. On the other hand, in the car application, the distance between the ground electrodes of the receiver and the transmitter (i.e., the metal frame of the car) was much larger. Prior research also supports that the coupling capacitance strength is inversely proportional to the separation distance between two conductive electrodes [10–12, 87]. Interestingly, the laptop application, where the distance between the two ground electrodes was comparable to that of the desk application, showed the lowest power transfer rate. This result was counter-intuitive because the simulation results from our FEM-based modeling supported a similar MAG for the desk and laptop applications. It appears that there are conductive materials under the front panel of the laptop (e.g., ground traces on the circuit board), which may have provided an additional local transmission path between the skin and ground electrodes of the transmitter, causing the majority of the electrical current to flow between the two electrodes instead of flowing through the body channel as intended. These results have two critical design implications for ShaZam: 1) a reasonably short distance between the transmitter and receiver ground electrodes needs to be maintained in order to support strong parasitic coupling between them, whereas 2) the parasitic coupling between the skin and ground electrodes of the transmitter needs to be minimized in order to drive the electrical current into the human body channel.

5.2 Baseline Experiments: Impact of Motion Artifacts and Electrode Configuration on Power Transfer

We explored the impacts of motion artifacts by 1) placing a 3 mm insulating material between the hand and skin electrode (i.e., continuously lifting the hand 3 mm above the electrode) and 2) vertically placing the hand (i.e., semi-pronation) on the skin electrode. Fig. 12b compares the power transfer between the natural typing vs. these two experiments. When the hand was physically disengaged from the electrode by 3 mm, the average power transfer rate degraded from $993.2 \pm 126.5 \mu W$ to $725.6 \pm 171.5 \mu W$. Although the degradation in power transfer was statistically significant (paired t -test, $p < 0.01$), the amount of received power was still reasonable to support an ultra-low sensing system. This result implies that ShaZam is robust in the face of moderate motion artifacts during daily interactions. Furthermore, this offers an important design implication that the skin electrode (as well as the ground electrode) could be embedded within an object's structure beneath the surface, without a need

Fig. 13. (a) Received average DC power in the three different experiments for the desktop application (i.e., natural keyboard, 3 mm insulation, and semi-pronation gesture) at baseline (blue) and follow-up (red). (b) The comparison of the received average DC power on two desks with different materials (wooden vs. metal panels) in different locations. Note that we were not able to transfer sufficient energy to the receiver to charge up the energy storage capacitor on the metal desk. Asterisk indicates $p < 0.01$.

for establishing direct physical contact with the skin. This could significantly improve the aesthetics and avoid potential health issues (e.g., avoiding allergic reactions to metals like copper).

Fig. 12b also shows that ShaZam could transfer slightly more power when participants placed their hand vertically ($1029.0 \pm 152.9 \mu W$) compared to the hand posture during natural typing ($993.2 \pm 126.5 \mu W$), although the difference was not statistically significant (paired t -test, $p = 0.33$). We believe there are two factors contributing to this result: 1) the coupling to the skin electrode was established with a larger area of the hand while in the vertical orientation and 2) the distance between the ground electrodes of the transmitter and receiver slightly decreased, as shown in Fig. 10c. Similarly, Fig. 12c shows that the placement of the transmitter ground electrode closer to the receiver ground electrode could slightly increase the power transfer rate for the laptop application. When the transmitter ground electrode was placed on the edge of the frontal panel (Fig. 9d), we were able to transfer $177.4 \pm 117.1 \mu W$ of power. When the electrode was placed on the back of the screen panel (Fig. 9c), $135.3 \pm 67.92 \mu W$ of power was transferred. However, the difference was not statistically significant (paired t -test, $p = 0.26$), which is corroborated by our FEM simulation results that showed similar MAGs between the two configurations.

5.3 Follow-up Experiments: Impact of Changes in the Surrounding Environments on Power Transfer

The measured temperature at follow-up was $25.3 \pm 0.2 ^\circ C$ at Location #1 and $25.8 \pm 0.4 ^\circ C$ at Location #2. The measured humidity was $14.6 \pm 0.92\%$ at Location #1 and $15.4 \pm 0.92\%$ at Location #2. Finally, the EM noise around the operating frequency (i.e., 13.56 MHz) in the two locations were quite low: $-81.4 \pm 0.5 dBm$ at Location #1 and $-81.3 \pm 0.5 dBm$ at Location #2. Fig. 13a compares the three experiments associated with the benchmark office desk application (i.e., natural typing, 3 mm insulation, and semi-pronation posture) at baseline vs. follow-up. Power transfer at follow-up showed an approximately 50% reduction in all experiments, which were statistically significant. The average power transfer during natural typing at follow-up was $476.4 \pm 133.7 \mu W$ vs. $993.2 \pm 126.5 \mu W$ at baseline (paired t -test, $p < 0.01$), $318.0 \pm 146.6 \mu W$ for the 3 mm insulation at follow-up vs. $725.6 \pm 171.5 \mu W$ at baseline (paired t -test, $p < 0.01$), and $488.5 \pm 155.8 \mu W$ for the semi-pronation posture at follow-up vs. 1029.0 ± 152.9 at baseline (paired t -test, $p < 0.01$). Interestingly, similar to the baseline experiments, statistically significant differences were observed between natural typing vs. 3 mm insulation (paired t -test,

$p < 0.01$) and semi-pronation posture vs. 3 mm insulation (paired t -test, $p < 0.01$), but no difference between natural typing vs. semi-pronation posture (paired t -test, $p = 0.31$).

Seasonal changes could explain the reduction in power transfer since they impact the ability to establish effective forward and return paths. First, the return path is established via capacitive coupling between the ground electrodes of the transmitter and receiver over the air. The strength of the coupling could be influenced by the concentration of gaseous molecules (particularly, water molecules or humidity) within the air. For example, a prior study has shown that the capacitance between two parallel conductive plates is proportional to the permittivity of the dielectric medium (in our application, the air) between the plates [52]. Therefore, higher humidity could yield stronger capacitive coupling between the two ground plates [8, 33]. Second, seasonal changes could also influence the forward path. Because the forward path is comprised of 1) capacitive coupling between skin electrodes and human skin and 2) the conductive human body channel, both the capacitance (or reactance) and conductivity (or resistance) of the human body channel could influence the power transfer in the forward path [52]. The humidity in the surrounding environment could change the moisture level (or the intra-cellular fluid level) in the epidermal layer of the skin, which consequently affects the forward path capacitance [19]. Similarly, the number of water molecules on the epidermal (as well as sub-epidermal) layers could regulate the reactance of the forward path [37]. Hence, the current through the body channel could increase at higher humidity. However, a more systematic investigation of the impacts of temperature and humidity on IBPT remains important future work.

Fig. 13b compares the measured power at the receiver when subjects were naturally typing on a wooden desk in Location #1 (left), a metal desk in Location #1 (center), and a wooden desk in Location #2 (right). There was no statistically significant difference in power transfer at two different rooms when office desks with wooden panels were used (t -test, $p = 0.078$). It is important to note that, although it was not specifically controlled, there was a reasonable amount of conductive materials in the surrounding environments of the two locations (e.g., metal desk legs, monitors, keyboards, and desktop computers). On the other hand, when the desk with metal panel was used in the experiment, we were not able to transfer sufficient energy to charge up the storage capacitor at the receiver to the upper hysteresis threshold of 3.8 V. This is because there exists only a small impedance difference between the skin and ground electrodes of the transmitter due to the increased capacitance via coupling through the metal panel. Hence, only a fraction of the energy (e.g., almost 10 %) could be generated. For example, the peak-to-peak voltage of the RF signal measured at the two transmitter electrodes on the wooden desk was 1.91 V, whereas that on the metal desk was only 180 mV. This result offers a critical design implication that the placements of the skin and ground electrodes of the transmitter need to be done to avoid capacitive coupling via surrounding environments.

5.4 Intra- and Inter-Subject Variability

5.4.1 Intra-Subject Variability: Fig. 14a-c shows the average and standard deviation of the received DC power for each participant across the charging/discharging cycles when they were naturally typing on a keyboard in the office desk setup. Particularly, Fig. 14a shows the results obtained from a wooden desk in Location #1 at baseline, Fig. 14b from a wooden desk in Location #1 at follow-up, and Fig. 14c from a wooden desk in Location #2 at follow-up. These results support reliable intra-subject variability in all experiments. Some participants (e.g., Subjects 5 and 6 in Fig. 14a, Subjects 2 and 9 in Fig. 14b, and Subject 9 in Fig. 14c) showed a relatively larger intra-subject variation due to a small number of outlier data points (i.e., charging/discharging cycles). The variability in these subjects became comparable to other subjects once we removed the outlier data points.

5.4.2 Inter-Subject Variability: On the other hand, Fig. 14a-c show significant inter-subject variability across all applications. We believe the key contributing factor for this inter-subject variability is impedance mismatch across different individuals due to 1) variations in the contact area between the hand and the transmitter skin

Fig. 14. Received DC power per subject for the benchmark office desk application (i.e., natural typing) (a) on a wooden desk in Location #1 at baseline, (b) on a wooden desk in Location #1 at follow-up, and (c) on a wooden desk in Location #2 at follow-up. Scatter plots between the received DC power and BMI for all subjects (e) on a wooden desk in Location #1 at baseline, (f) on a wooden desk in Location #1 at follow-up, and (g) on a wooden desk in Location #2 at follow-up.

electrode, 2) variations in gestures and postures that resulted in different 3D orientations of the receiver electrodes, and 3) variations in the body channel properties of permittivity and conductivity. Particularly, we investigated the impacts of the variations in the body channel properties by comparing the average power received from the participants to their BMI. Fig. 14d-f show scatter plots between power transfer and BMI for the three different benchmark experiments, all of which showed inverse correlations: $\rho = -0.68$ for the wooden desk in Location #1 at baseline, $\rho = -0.57$ for the wooden desk in Location #1 at follow-up, and $\rho = -0.81$ for the wooden desk in Location #2 at follow-up.

We believe these strong inverse correlations were caused by increased impedance of the human tissue in participants with higher BMI. For instance, prior research reports that individuals with higher BMI have larger bio-impedance [17, 26, 57]. Since the phase of the time-varying electric field at tens of MHz becomes uniform throughout the human body channel [11] and the body can be reasonably modeled using a lumped RC network [52], the power should be inversely proportional to the impedance of the RC load of the network. Therefore, we believe the inter-subject variability is mainly driven by the bio-impedance variation [69] because the matching networks used in this work were not personalized to each individual.

5.5 System Usability and Participants' Concerns on Safety

Fig. 15 summarizes participants' self-reports on the three questions that we asked on the system usability and their safety concerns about acting as a power transfer medium. Participants reported that our system (i.e., electrodes embedded in everyday objects) is minimally invasive. Participants were not concerned about safety as they were informed that the amount of power infused into their body complies with the safety regulations and poses minimal health risks during the review of the IRB-approved consent. The severity level of their safety concerns

Fig. 15. A graphical summary of participants' self-reports on the three questions: Q1: “Did you find the electrodes interfering with your natural interactions with the object?”, Q2: “Did you have any fear or safety concerns about acting as a medium to transfer electric signals prior to participating in the experiments?”, and Q3: “Did you have any fear or safety concerns about acting as a medium to transfer electric signals after participating in the experiments?”

slightly decreased after participating in the experiments, but it was not statistically significant (paired t -test, $p = 0.35$).

6 LIMITATIONS AND FUTURE WORK

This study has a number of limitations worth discussing. In this study, we focus on establishing the technical foundations for the proposed concept of wireless and unobtrusive charging of wearable devices via interaction-based IBPT, and successfully demonstrate that we could transfer a maximum power of roughly $0.5\text{ mW} - 1\text{ mW}$ when the users naturally interact with daily objects. However, the real-world deployment and longitudinal evaluation of ShaZam, as well as how the system configuration (e.g., choice of daily objects to instrument and electrode designs) could be personalized, remain as important future work. Second, we observed a number of environmental (e.g., seasonal) factors and electrode characteristics that can regulate the coupling capacitance between the electrodes, hence significantly influencing the power transfer rate. Although we observed significant changes in power transfer across different seasons, we anticipate a future study that could investigate if the amount of time interacting with daily objects would still yield sufficient energy to support a variety of ultra-low power sensing applications. Third, our experiments were conducted in environments where EM interference is relatively small. The expected primary source of interference would be near-field RFID, which also operates at 13.56 MHz . However, near-field RFID uses inductively coupled links over short distances, which implies that there should be minimal interactions between the two systems. Last, our results reported some degree of inter-subject variability in power transfer for all use scenarios. Further investigation of a solution to minimize such inter-subject variability is an important topic of future study, where one possible solution could be the introduction of a closed-loop wide-band impedance matching network recently introduced by Abdelhamid *et al.* [7].

7 RELATED WORK

In recent years, considerable attention has been paid to alternate methods of keeping energy-constrained devices reliably powered. This challenge is of particular relevance to wearable devices since their battery capacity needs to be maximized to improve their operational lifetime while their form-factor must be minimized to maintain user comfort for long-term wear. Current commercially-available wrist-worn wearables, such as the Fitbit [3] or Apple Watch [5], rely on the tried-and-true use of a rechargeable battery and depend on the user to recharge the battery to maintain operation on long time scales. While this approach towards energy management is well-suited for some consumer-grade devices, the wearable eventually needs to be removed for charging, which

limits the sensing applications that they can potentially support. To close this gap, researchers have proposed a host of new techniques that could seamlessly deliver energy over time to a wearable device containing a small battery while imposing no additional burden to the user. These techniques span the boundary between hardware and software, including programming languages and software run-times, and have helped spawn a number of research communities focused on topics like intermittent computing. Most relevant to ShaZam are the modes of energy transfer themselves, which we highlight in this section.

7.1 Environmental Energy Harvesting

One widely used approach towards keeping energy-constrained devices powered is making use of energy harvested from the device's surroundings. There are two primary categories of energy harvesting to consider: 1) energy harvested from the environment and 2) energy harvested from the human body. The former exploits energy sources that are naturally or readily available in the environment. For example, photovoltaic cells on wearable devices can be used to harvest photons from artificial light sources or from the sun [24, 32, 62]. In the latter, harvesting energy from the body exploits the relationship between a human and their environment. The human body actively regulates its core temperature, so thermal harvesting can be used to capture energy from the temperature gradient that exists between the skin and surrounding environment [36, 82]. As humans move through their environment, the kinetic energy can be harvested from their joint motions and individual footsteps that are tuned to the overall resonant frequency of motion [22, 72, 91]. There has also been interest in harvesting chemical potential energy from glucose in the bloodstream, allowing a wearable device to be powered as a side effect of normal eating activities [42].

While all these approaches offer partial solutions towards keeping wearable devices powered, they fall short in terms of either consistency of power delivery or in the raw magnitude of transferable power. Solar panels on wearable devices can be easily occluded by garments or body pose, typical piezoelectric power generators can harvest energy on the order of hundreds of microwatts but only when substantial cyclic stress is applied, and thermoelectric generators can extract $40 \mu\text{W}/\text{cm}^3$ from a heat gradient of 10°C [1] but only in ideal conditions. We view our concept of ShaZam as complementary to these other forms of ambient energy harvesting and can offer an additional charging modality that is available whenever the user interacts with instrumented daily objects and is independent from specific user motions or environmental conditions.

7.2 Wireless Power Transfer

Another approach to power wearable devices is the use of wireless power transfer schemes that transmit energy through dielectric mediums, including free space, human-built infrastructure, or tissue mediums such as the human body. Research in wireless power transfer roughly maps to two categories of work: 1) power transfer between pairs of antennas using radios and 2) instrumented infrastructure that creates electric or magnetic fields that allow pairs of devices to establish coupling.

In antenna-based systems, devices are either designed around intermittent operation [66], periodic power transfer between a dedicated transmitter/receiver pair [6, 63], or harvesting from ambient wave sources such as television or broadcast radio [59, 76]. While these systems enable one to minimize or eliminate the battery of a low-power device, the transmitter typically needs to use a large, high gain antenna integrated with a costly transmitter in order to ensure that enough power could reach the receiver for successful operation. Furthermore, the receiver's antenna also needs to be sized according to the wavelength of the transmitted signal, which imposes another form-factor constraint, especially at lower frequencies. Furthermore, the transmitter in such systems typically operates at a high power output, often at the maximum value specified by a regulatory body (i.e., 30 dBm in the US for the unlicensed ISM band) or at much higher levels for broadcast systems, such as television or FM radio. These transfer mechanisms are inherently energy inefficient because they are accounting for free-space

path loss or the amount of power dissipated into the propagation medium. Furthermore, there are significant safety concerns regarding high power RF signals in close proximity to human tissue. The working principle of IBPT is to minimize the size of the transmitter and losses to the medium by directly coupling the transmitter and receiver through human tissue with significantly constrained transmission power.

In field-based techniques, prior work has looked at both capacitive [89] and inductive modes of transfer [67] that create an electric or magnetic field within a large room that allows devices to obtain power through field coupling. While more energy efficient than antenna-based systems, these approaches require substantial modification to infrastructure to ensure that the field ubiquitously covers the desired area (i.e., walls embedded with room-size plates of a capacitor [89]). Furthermore, the field strength near structural elements poses safety concerns. To operate over these large areas, the electric field near the capacitive plates can be high enough to warm up human tissues. Related to these techniques are more targeted systems that create fields constrained to much smaller volumes: e.g., IBPT that transfer power via capacitively coupled human body channel [33, 71, 80]. While existing studies have demonstrated the feasibility of IBPT, systematic understanding of important design factors and rigorous evaluation in human subjects have not yet been thoroughly investigated. Most of these IBPT systems, including ours, make use of technologies inspired by IBC, where data are exchanged over the body channel [23, 35, 55, 92]. However, these studies focus primarily on reliable, efficient data communication over the human body by, for example, minimizing the power of the carrier signal. While our hardware shares some similarities, the goal of our research is fundamentally different in that we aim to maximize the overall power transfer rate irrespective of quality of the transmitted signal (e.g., data communication performance).

Although capacitive power transfer has the potential to decrease the overall form-factor of the system (i.e., small electrodes vs. large antennas), the energy transfer rate is fundamentally limited by safety considerations (see Section 2.2). To address these safety concerns, other systems have used magnetic field coupling that is fundamentally safe for human tissue [29, 40, 65, 74, 85]. Magnetically coupled systems can achieve higher energy transfer efficiency over distance but require the coils to be electronically steered in MIMO-like configurations [40] or physically aligned using motors [85]. The fundamental challenge in using these techniques is the physical form-factor. Inductors are much more difficult to miniaturize than capacitors since they rely on physically wound coils rather than plates separated by a dielectric material. In our study, we make use of relatively smaller electrodes and capacitors but opportunistically exploit time periods where the transmitter and receiver electrodes are in close proximity to one another and are coupled through human tissue.

7.3 Interaction-based Power Transfer

Other work has looked specifically at the idea of exploiting human-object interactions for opportunistic power transfer. This area of research differs from prior efforts in wireless power transfer in terms of the amount of transferred power, as well as the distance over which the power transfer takes place. The main focus is on the intersection of technology and human behavior. Near-field RFID on mobile phones has been used to enable ubiquitous displays [25] and wearable rings [34] that obtain the power needed for operation during one-time or periodic interactions. Other work has explored the use of energy-optimized wrist-worn RFID readers to detect interactions with passive tags [43]. Another wrist-worn interaction detection system uses a far-field RFID reader to energize tagged objects over short ranges [30]; in this work, the authors view body capacitance as a challenge since it may interfere with the tuning of the reader's antenna. Near-field RFID uses magnetic coupling to achieve power transfer directly from devices to devices and avoids capacitive effects of the body, while far-field RFID systems need to mitigate the impact of body capacitance on antenna tuning. In contrast, ShaZam embraces the capacitance of the human body and uses it as its primary mode of power transfer. Furthermore, while interaction-based power transfer could solve one of the problems of wired charging systems, it also needs additional infrastructure in the form of a specific garment [83, 84, 86, 90]. Nevertheless, ShaZam does not require

the users to wear additional equipment (other than the wearable device to charge) to facilitate power transfer, but instead relies on modifications of existing daily objects. Finally, more recent work has looked at harvesting the kinetic energy of the interactions themselves [24]. This approach towards harvesting is based on interaction, but framed differently that the device is being powered by the human-generated motion during interactions and places the human directly in the charging loop. Our goal, on the other hand, is to enable interaction-based harvesting that is completely transparent to the user.

8 CONCLUSION

In this work, we introduce a unique power transfer technology that can wirelessly and unobtrusively charge wearable devices while interacting with daily objects equipped with compact, inexpensive electronics. We focus on establishing the technical groundwork for the proposed technology based on IBPT that leverages the human body as a medium to transfer power to wearable devices. To address this goal, we investigated three different use scenarios (i.e., interacting with a keyboard on a desk, a laptop, and the steering wheel of a car) to transfer power to a wrist-worn device (e.g., a smartwatch or fitness tracker) and demonstrated that we can transfer roughly $0.5\text{ mW} - 1\text{ mW}$ of DC power to charge the battery. We also investigated important design factors that could affect the power transfer rate and suggested design implications for optimizing the performance. Our demonstration of the feasibility of ShaZam offers significant implications for health monitoring technologies. With the evident trend of wearable electronics becoming more power-efficient over time, we believe the proposed technology herein could open up a new pathway towards completely charge-free wearable devices.

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