Noor Mohammed, Rui Wang, Robert W. Jackson, Yeonsik Noh, Jeremy Gummeson* and Sunghoon (Ivan) Lee*
University of Massachusetts Amherst, Amherst, MA, USA *Co-corresponding authors.

Editors: Nicholas D. Lane and Xia Zhou

Photo, istockphoto.com

CHARGING WEARABLE DEVICES THROUGH NATURAL INTERACTIONS WITH INSTRUMENTED EVERYDAY OBJECTS

Excerpted from "ShaZam: Charge-Free Wearable Devices via Intra-Body Power Transfer from Everyday Objects," from *Proceedings of the ACM on IMWUT* with permission. https://dl.acm.org/doi/abs/10.1145/3463505 ©ACM 2021

Recent advancements in semiconductor technologies have stimulated the growth of ultra-low power wearable devices. However, these devices often pose critical constraints in usability and functionality because of the on-device battery as the primary power source [1]. For example, periodic charging of wearable devices hampers the continuous monitoring of users' fitness or health conditions [2], and batteries and charging equipment have been identified as one of the most rapidly growing electronic waste streams [3].

To counteract the above-mentioned complications associated with the management of on-device batteries, wireless power transmission technologies capable of charging wearable devices in a completely unobtrusive and seamless manner have become an emerging topic of research over the past decade [4]. Researchers have instrumented daily objects or the surrounding environment with equipment that can wirelessly transfer energy from a variety of sources, such as Radio Frequency (RF) signals, laser, and electromagnetic fields [5]. 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.

In this paper, we investigate an emerging topic of research, called Intra-Body Power Transfer (IBPT), that exploits the human body as a power transfer medium to charge wearable devices while users interact wirelessly and unobtrusively 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 transfer RF energy along the human body, which is then received and rectified by wearable devices at different body parts. We design and develop our prototype system, aiming to establish the technological foundation of the proposed interaction-driven IBPT technology. The major technical challenge associated with IBPT is securing the forward and return paths of the closed-loop circuit over the human body that does not explicitly define the two distinct signal paths. Our system employs a capacitive coupling architecture, in which an RF signal is coupled to body tissue via a dry (copper) electrode to establish the forward electrical path, while the return path is established via the inherent natural capacitance between a pair of metal (copper) electrodes 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.

DESIGN AND IMPLEMENTATION

The primary design components of our system include 1) a skin-coupled power transmitter (Fig. 2), and a skin-coupled power receiver (Fig. 3). The power transmitter (Fig. 2a) includes an active RF generator coupled with transmitting electrodes. The major components of the RF generator include a Direct Digital Synthesizer (AD9910; Analog Devices) that generates the RF signal and an RF amplifier (ZX60-43-S+; Mini-Circuits) to amplify the power to a sufficient level following human safety regulations outlined by the FCC. The amplified RF signal is then coupled to human tissue via an impedance matching network to ensure maximum power transfer to the skin-coupled transmitting electrode.

Power transmitter electrode designs for the three everyday objects (i.e., Fig. 2b-d) provide 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 more flexible configurations for its size and placement.

Fig. 3a shows our implementation of the power receiver. The signal received at the skin electrode (Fig. 3b) 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). This battery manager contains an integrated booster to further increase the rectified DC voltage level to charge a battery.

EXPERIMENTAL DESIGN

Ten healthy volunteers (31.3 ± 6.63 years, mean ± standard deviation; 1 female and 9 males) were recruited from the University of Massachusetts Amherst. The recruitment criteria required participants to be healthy and aged between 18 and 45 years old. 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.

When participants arrived at the research laboratory, they were asked to place the wrist-worn power receiver on their non-dominant wrist. For the benchmark office desk application, 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

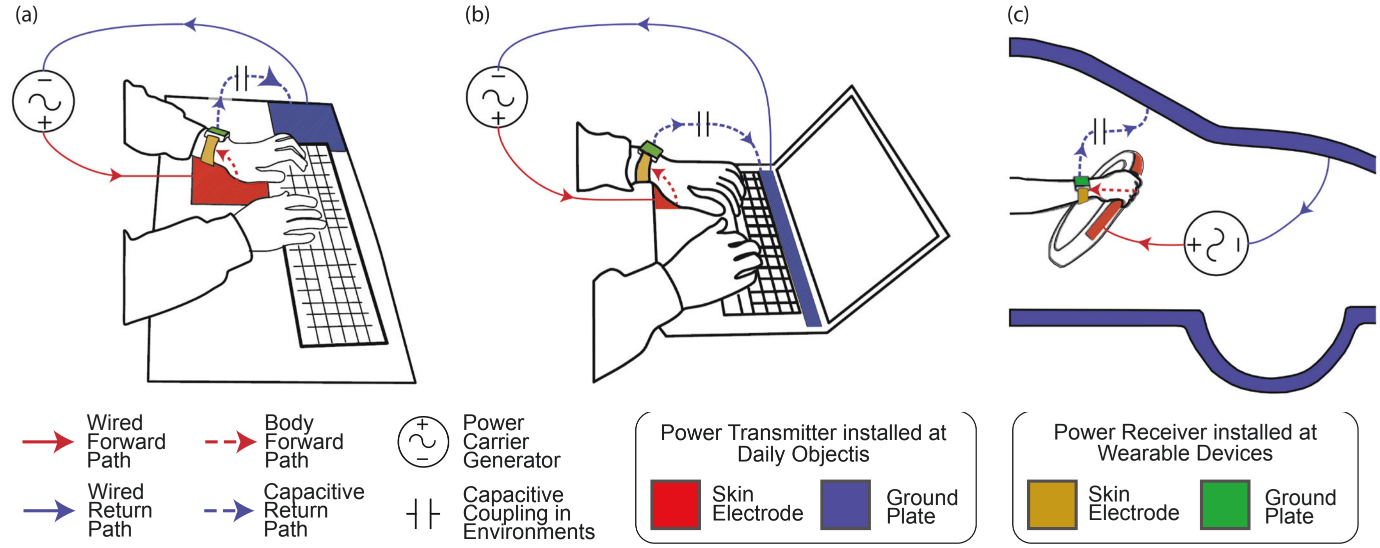


FIGURE 1. Ubiquitous charging of a wrist-worn device (e.g., a smartwatch or fitness tracker) from interacting with everyday objects, such as (a) an office desk, (b) a laptop, and (c) the steering wheel of a car.

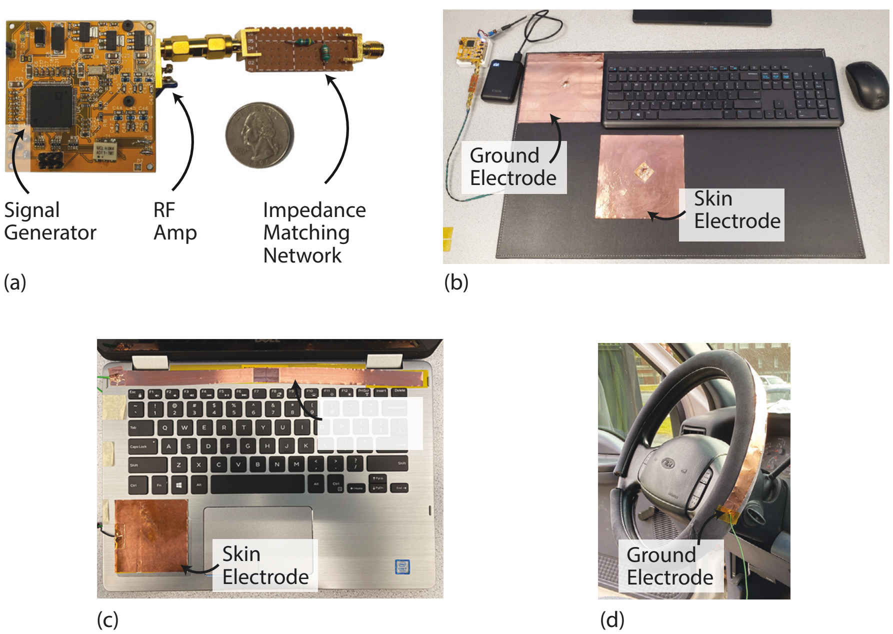


FIGURE 2. Implementation of (a) our custom-designed power transmitter and electrode configurations for (b) the office desk, (c) laptop, and (d) car applications.

of power transfer that could be achieved during natural interactions (see Fig. 4a). Then, we asked participants to place their hand vertically (i.e., semi-pronation) for four minutes, as shown in Fig. 4b, in order to evaluate the effect of different postures on the power transfer performance. Lastly, 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. 4c, 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. 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. Participants were asked to naturally type on the laptop keyboard for four minutes, as shown in Fig. 4d. The car application could investigate the effect of a large ground electrode encapsulating the user and the system because the metal frame of the car serves as the ground electrode, as shown in Fig. 1c. We hypothesized that the larger ground electrode would attenuate external noise and thus support stronger power transfer. Subjects were asked to sit in the driver's seat of 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 Figure 4e.

RESULTS

Figure 5a shows the DC power received at the wrist-worn device for the office desk (natural typing; 933.2 ± 126.5 uW), laptop (117.4 ± 117.1 uW), and car applications (688.6 ± 119.8 uW). These results show that 1) the inter-subject variability for each application is reasonably low, 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. Interestingly, the laptop application showed the lowest power transfer rate due to the conductive materials under the front panel of the laptop, creating an additional local transmission path. Furthermore, the car application did not show greater power transfer than the desktop application due to the increased distance between the transmitter ground electrode to the receiver ground electrode (i.e., car frame).

Figure 5b summarizes the impacts of gesture and motion artifacts on power transfer. The results show that our system could transfer slightly more power when participants placed their hand vertically (1029.0 ± 152.9 uW) compared to the hand posture during natural typing (993.2 ± 126.5 uW), although the difference was statistically insignificant (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. 4b. When the hand was physically disengaged from the electrode by 3 *mm*, the average power transfer rate degraded to 725.6 ± 171.5 uW. 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.

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. Our demonstration of the feasibility of interaction-based IBPT offers significant implications for health monitoring technologies. With the evident trend of wearable electronics becoming more power-efficient over time, we believe that the proposed technology herein could open a new pathway towards completely charge-free wearable devices. ■

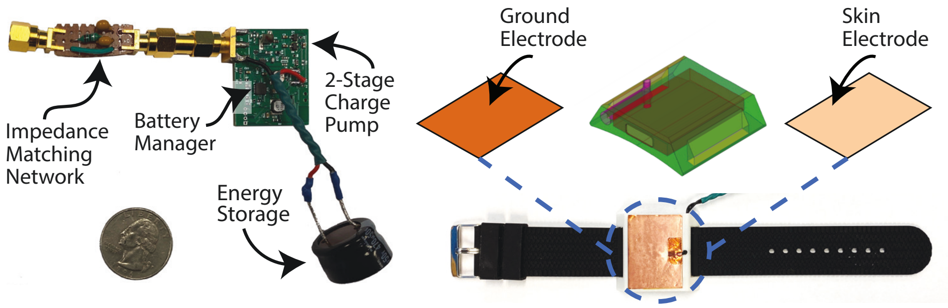


FIGURE 3. Implementation of (a) our custom-designed power receiver and (b) the 3D-printed skin and ground electrodes.

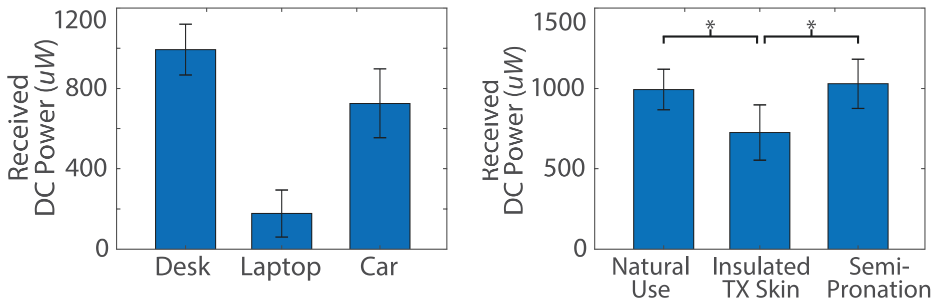
WE INVESTIGATE AN EMERGING TOPIC OF RESEARCH, INTRA-BODY POWER TRANSFER (IBPT), THAT EXPLOITS THE HUMAN BODY AS A POWER TRANSFER MEDIUM TO CHARGE WEARABLE DEVICES WHILE USERS INTERACT WIRELESSLY AND UNOBTRUSIVELY WITH EVERYDAY OBJECTS

Acknowledgments

This work was partly supported by the University of Massachusetts Amherst Armstrong Fund for Science and the NSF Computer and Network Systems Program under Grant No. 2107133.

(a) (b) (c)

FIGURE 4. A study participant performing (a-c) three different experiments for the desk application, (d) the laptop application, and (e) the car application.



(a) (b)

FIGURE 5. (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.

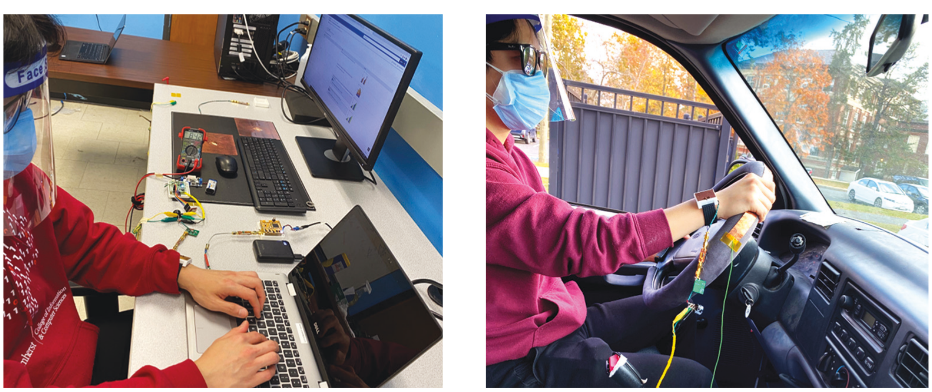
Noor Mohammed is a Ph.D. student in Electrical and Computer Engineering at the University of Massachusetts, Amherst. His research interests include wearable sensor design, bioinstrumentation, novel microwave sensing, RF electronics, and computational electro-magnetics. He received his M.Sc. in Biomedical Engineering from Wichita State University.

Rui Wang is an associate professor in the College of Information and Computer Sciences at the University of Massachusetts, Amherst. His research interests include computer graphics, computer vision, and embedded systems. He received a Ph.D. in Computer Science from the University of Virginia.

Robert W. Jackson is a professor of Electrical and Computer Engineering at the University of Massachusetts, Amherst. His interests include electromagnetic modeling of high frequency integrated circuits, novel circuit structures, and packages for microwave and millimeter-wave integrated circuits. He received a Ph.D. in Electrical and Computer Engineering from Northeastern University. He is a Fellow of the IEEE.

Yeonsik Noh is an assistant professor in the College of Nursing and the Department of Electrcial and Computer Engineering at the University of Massachusetts, Amherst. His research interests include wearable sensor design, biosignal processing, and evidence-based personalized healthcare model. He received a PhD in Biomedical Engineering from Yonsei University in South Korea.

Jeremy Gumesson is an assistant professor of Electrical and Computer Engineering at the University of Massachusetts, Amherst. His current research focuses on developing novel sensing, communication, and energy management techniques that enable closed-loop sensing systems that optimize our resources, health, and wireless environment. He received a Ph.D. in Computer Systems Engineering from the University of Massachusetts, Amherst.



(d) (e)

Sunghoon (Ivan) Lee is an assistant professor in the College of Information and Computer Sciences at the University of Massachusetts, Amherst. His research interests include wear-able sensor design and human-centered health informatics. He received a Ph.D. in Computer Science from the University of California, Los Angeles.

REFERENCES

[1] Arjun Puri, Ben Kim, Olivier Nguyen, Paul Stolee, James Tung, and Joon Lee. 2017. User acceptance of wrist-worn activity trackers among community-dwelling older adults: Mixed method study. *JMIR mHealth and uHealth*, 5, 11, e173.

[2] Hayeon Jeong, Heepyung Kim, Rihun Kim, Uichin Lee, and Yong Jeong. 2017. Smartwatch wearing behavior analysis: A longitudinal study. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 1, 3 (2017), 1–31.

[3] European Commission. 2019. Impact Assessment Study on Common Chargers of Portable Devices. Technical Report.

[4] Rishi Shukla, Neev Kiran, Rui Wang, Jeremy Gummeson, and Sunghoon Ivan Lee. 2019. SkinnyPower: Enabling batteryless wearable sensors via intra-body power transfer. *Proceedings of Conference on Embedded Networked Sensor Systems (SenSys'19)*, 68–82.

[5] Noor Mohammed, Rui Wang, Robert W. Jackson, Yeonsik Noh, Jeremy Gummeson, and Sunghoon Ivan Lee. 2021. ShaZam: Charge-free wearable devices via intra-body power transfer from everyday objects. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 5, 2, 1-25.