Body-Resonance Human Body Powering

Samyadip Sarkar, Lingke Ding, Shreyas Sen
School of Electrical and Computer Engineering, Purdue University, USA
{sarkar46, ding359, shreyas}@purdue.edu

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***Abstract*— The growing demand for the perpetual operation of body-connected devices and distributed sensor nodes, along with an exponential reduction in the size of computing units, has highlighted the need for novel wireless powering solutions for wearable devices. Over the past two decades, the use of the human body as an energy-efficient alternative to radio wave-based techniques for wireless communication, particularly in the Electro-Quasistatics (EQS) region, and more recently, the concept of body-coupled power transfer has gained considerable attention. Moreover, revealing the advantages of the Body Resonance (BR) regime over EQS, recent studies demonstrated the potential for designing power-efficient body-coupled communication systems for Body Area Network devices. However, a comparison of the wirelessly transferred power through the human body between the EQS and BR regimes has not been presented in the literature. In this paper, we present a comparative analysis of the variation in received power between EQS and BR. Highlighting the benefits of wirelessly charging portables/wearables by transferring power through the human body while remaining below the safety limit, we analyze a Machine-to-Wearable scenario that can provide higher on-body voltage and consist of a floor-based, ground-connected power transmitter and a portable receiver in BR frequencies. The results show that the BR regime improves the received power (∼ 100 μW over > 1 m) by ∼200X compared to the EQS scenario and has the potential to wirelessly charge low-medium power physiological sensors, fitness trackers, etc.**

***Keywords*— Body Resonance (BR) Regime, Human Body Powering (HBP), Machine-to-Wearable (M2W) Measurements.**

I. Introduction

Technological advances have significantly reduced the size of computing units, leading to the development of innovative wearable sensors and devices distributed around the human body. Over the past two decades, wearable devices have transformed the once science-fiction vision of a connected lifestyle into a reality in various fields, such as fitness tracking, defense, healthcare, and entertainment. This progress has generated considerable interest in wirelessly powering these devices to achieve continuous battery-free operation while maintaining seamless connectivity with the human body. Various energy harvesting methods have been explored, including piezoelectric, thermoelectric, photovoltaic, and radio frequency (RF) technologies. While these methods offer promising powering solutions, they encounter challenges in Non-line-of-sight (NLOS) scenarios and experience significantly reduced efficiency in transferring power wirelessly over longer distances, especially for miniaturized wearables. In HBC, devices that are ground-connected are often termed as "machine" and devices that are ground-floated are termed as "wearable".

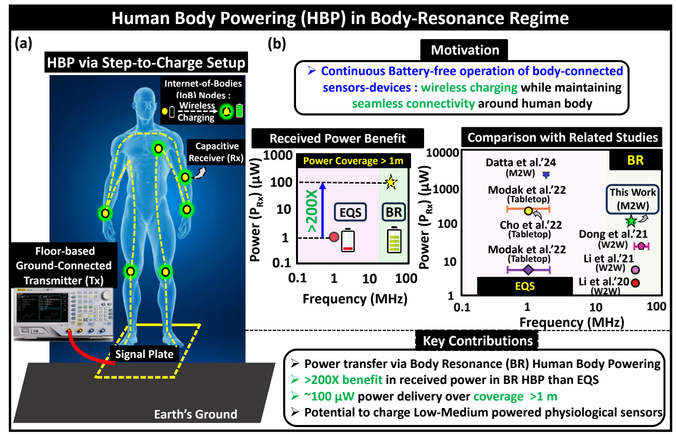

Fig. 1. Human Body Powering (HBP) in the body-resonance (BR) frequency regime: (a) Wireless powering solution via Step-to-Charge setup [1] in Body Resonance frequency regime is presented. (b) Specifically, improvement in received power over EQS is achieved across a wireless power transfer channel with coverage exceeding 1 meter.

Devices that experience an unrealistically higher amount of return path capacitance (C_{ret}) by bringing them close to the environmental ground are often termed "table top". Previous studies on body-coupled communication have unveiled opportunities to leverage the electrically conductive properties of the human body for information exchange between connected devices. This approach has demonstrated energy-efficient and physically secure data transmission around the body using capacitive Electro-Quasistatic Human Body Communication (EQS HBC) [2], [3], [4]. However, existing capacitive power transfer system designs indicate that the power received over long channels remaining $\leq$ 20 μW, as the dominant return path (C_{ret} < 1pF) in the communication channel leads to higher transmission losses (∼60-70 dB) in the EQS regime. Furthermore, tabletop setups used to measure wireless power transfer, as shown in some studies [5], [6], increase the capacitance of the return path by interacting with nearby objects, making them less representative of realistic scenarios. Body-coupled power transfer has shown potential for wireless power transfer in wearable to wearable scenarios[7]. Recently, Body-Resonance HBC (operating in the near-intermediate field i.e., wavelength (λ) < 10 m) has been shown as a favorable option for power-efficient, high-speed body-centric connectivity in a wearable-to-wearable scenario, outperforming EQS HBC [8]. Its ability to provide higher on-body voltage and greater channel gain (∼40-50 dB) encourages exploration of wireless powering through the human body within the Body Resonance frequency regime. To address the challenges of limited power delivery to wearables with existing wireless charging methods in non-line-of-sight situations over longer channels, this paper proposes a wireless powering solution for wearable devices, illustrated in Fig. 1. This solution utilizes a floor-based power transmitter setup, resembling a "Step-to-Charge" system [1] but operating within the Body Resonance framework. We demonstrate that by capitalizing on the resonance phenomena of the human body—without introducing any resonant tuning at the transmitting and receiving ends—it is possible to deliver hundreds of microwatts of power to body-connected devices.

II. Body Channel Characteristic in EQS vs BR

Understanding the fundamentals of capacitive HBC from existing studies [9], [10], [2], [11], [4] suggests that in the electro-quasistatic regime (EQS) (frequency $\leq$ 30 MHz), the human body channel can be viewed as a lossy wire and its electrically distributed nature can be lumped as a single node in the biophysical model, having constant body-potential (V_{Body}) throughout. With the human body constituting the forward path, the channel transmission loss experiences dominance of the high impedance from the parasitic capacitive couplings (i.e., return-path capacitances) from the floating ground of the wearable devices to the earth's ground. Consequently, for wireless power transfer among body-connected devices, there is a need for inductors (L) with a high quality factor (Q) to achieve resonant tuning at the communicating devices. This tuning helps cancel the effects of C_{ret}, ultimately maximizing the output voltage (V_{Rx}) across the load (R_L) and enhancing power transfer efficiency ($\eta = \frac{P_{Rx}}{P_{Tx}} \times 100\%$). In contrast, in Body-Resonance (BR) regime (f > 30 MHz), the body potential (V_{Body}) gets a boost from the resonance phenomenon of the human body and starts to experience a frequency and location-dependent gradient from the distributed transmission line-like behavior of the body channel.

III. Simulation Setup

To validate the previously discussed theoretical concepts, we conducted numerical electromagnetic simulations using a Finite Element Method (FEM)-based software tool: High-Frequency Structure Simulator (HFSS) from ANSYS. To improve simulation speed while minimizing computational complexity, we utilized a simplified cross-cylindrical model of the human body that incorporates the tissue properties of skin and muscle [12]. The accuracy of this simplified model was verified [13] through comparisons with a more detailed and complex human body model - VHP Female v2.2 from Neva Electromagnetics [14]. The system setup, featuring a ground-connected transmitter and a floating-ground wearable-sized receiver for power transfer to body-worn devices, is illustrated in Fig. 2 (a), which presents the structural parameters of the model. The comparison of electric field (E-field) distributions in the EQS and BR regimes, as shown in Fig. 2 (b, c), illustrates the benefits of using HBP in BR.

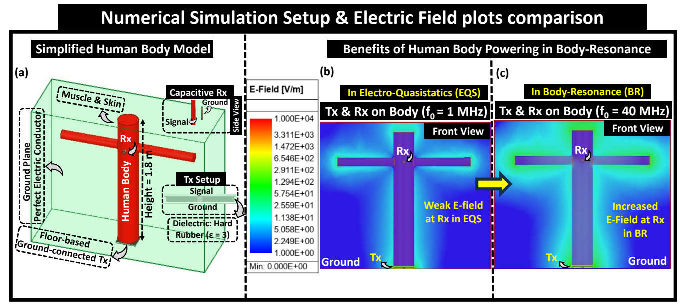

Fig. 2. Simulation Setup: (a) The model used for numerical simulations in Ansys HFSS, with its structural parameters. Comparison of E-Field plots: (b) In Electro-Quasistatics (EQS): Reduced field strength at the receiver (Rx) resulting in lower on-body received power (c) In Body-Resonance (BR): Strong field strength at Rx, leading to higher on-body received power.

Specifically, it demonstrates an increase in E-field strength around the human body within the BR frequency range, further validated through experimental verifications discussed in the subsequent section.

IV. Simulation Results

The variation in the received power in the body (P_{Rx}) with the load resistance (R_L) is presented in Fig. 3. As we travel from EQS to the BR regime, owing to a significant increase in the on-body voltage, an improvement in the received power is observed.

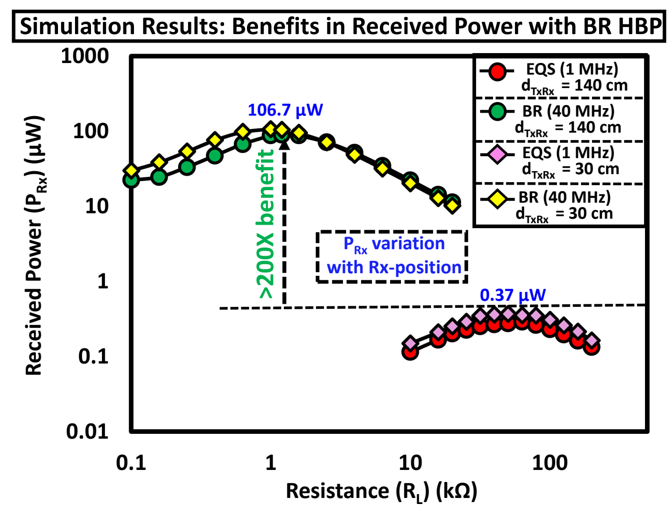

Fig. 3. Simulation Results: Comparative analysis of human body powering between EQS and BR frequency regime with a ground-connected Tx and wearable Rx at neck (Tx to Rx distance = 140 cm)

This improvement comes from the resonator-like behavior of the human body [15], [8] shown in a wearable-wearable scenario, which can be effectively utilized for wireless powering. By tuning the operating frequency of the ground-connected transmitter to align with the resonant peak frequency of the human body channel, appearing between ~30-40 MHz for a machine-wearable scenario, the received power across a load resistor is optimized. This variation in received power with Rx-position can be attributed to the electrically distributed nature of the human body as a powering channel.

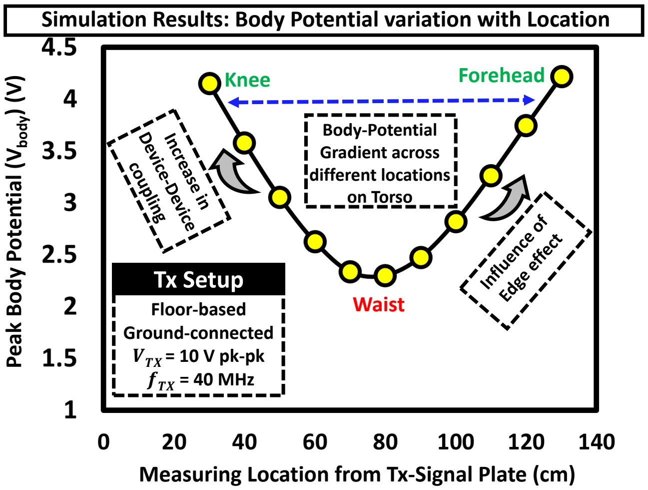

Fig. 4. Simulation Results: Variation in Body potential with change in measuring location from the signal plate of the floor-based ground-connected transmitter, operating at a frequency of 40 MHz.

In addition, an increase in P$_{Rx}$ is observed at a reduced distance (d$_{TxRx}$) between the transmitter and receiver that can be attributed to increased coupling between devices. Moreover, the variation in received power with location can be explained by the change in the on-body potential with distance from the Tx signal plate, captured in Fig. 4. At the two ends of the model (i.e. near the feet and head), an increase in body potential is observed from the increased E-field strength as illustrated previously in Fig. 2 (c) owing to the proximity to the signal plate near the feet and from the edge effect at the neck that results in higher E-field strength in the vicinity of the terminal body locations with reduced radius of curvature.

V. Experimental Setup

This section presents the experimental setup for wireless power transfer through the human body. The power transmitter, the wearable receiver, and the overall system schematic are illustrated in Fig. 5. The measurements were performed in a standard laboratory environment following the guidelines and regulations issued by the Institute Review Board (IRB). With its floor-based signal plate, emulated by a sheet of aluminum foil, and its ground plate connected to the earth's ground, the wall-powered transmitter (a function generator from Rigol DG4202, set to transmit a sinusoidal signal of 10 V peak-to-peak across a frequency from 1 MHz to 70 MHz), illustrated in Fig. 5 (b). The ground-connected transmitter setup, namely Step-to-Charge in EQS, as proposed by Datta et al.[1], can offer higher on-body voltage for a certain transmitted voltage compared to a wearable transmitter setup. To wirelessly transfer power to body-worn devices, the subject needs to stand on the floor-based signal plate with no other objects present in the vicinity of it to avoid undesirable couplings from the environment. During experiments, the subject holds the portable receiver setup, which has a decisive

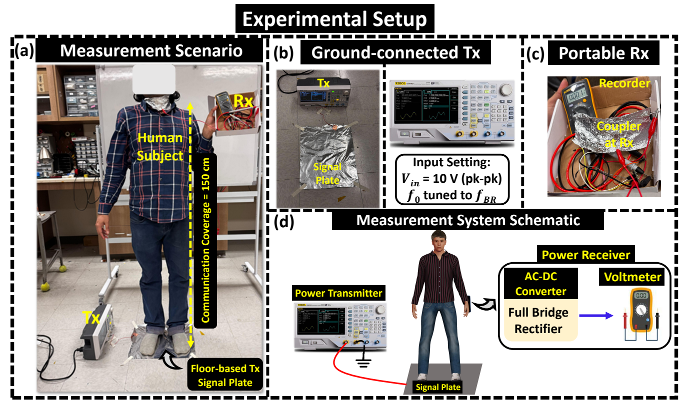

Fig. 5. Experimental Setup: (a) Measurement Location: Standard Laboratory Environment & Subject's body posture during measurement scenario, (b) Ground-connected Transmitter (Tx) Setup: Floor-based signal plate inspired from "Step-to-Charge" (c) Portable Receiver (Rx) Setup: AC-DC converter (full bridge rectifier) with digital multimeter as voltmeter, (d) Measurement system schematic

influence in accurately emulating a real-world scenario, shown in Fig. 5 (a), as this approach allows us to take into account the realistic contribution of the return path capacitance of the receiver. In contrast, measurements taken with a capacitive receiver on a tabletop setup can result in overly optimistic estimates of path loss values as this leads to a higher return path capacitance due to strong ground coupling. Now, to efficiently pick up the received power at different locations from the human body, an aluminum foil is used as a coupler at the receiver-end and connected to a rectifier network in full-bridge configuration, made from commercial SMD Schottky diodes (SMS7630-005LF) from Skyworks Solutions Inc. while keeping one input floating, is connected at the input to the receiver being a multimeter measuring the DC of the on-body voltage, presented in Fig. 5 (c). The received RMS power (P_{Rx}) is calculated from the measured DC voltage across a load resistor (i.e., $P_{Rx} = \frac{V_{Rx}^2}{R_L}$).

VI. Experimental Results

To confirm the trends captured via numerical simulations, the experimental result for the variation in the received power at different Rx positions with the change in load resistance (R$_L$) at EQS and BR frequencies is presented in Fig. 6. The BR HBP demonstrates its capability of transferring $>\sim$100 μW received power over an on-body powering link spanning >1 m. Additionally, the position of the receiver critically influences the on-body received voltage, shown in Fig. 7 and hence, amount of power received toward maximizing power transfer efficiency, which remains concurrent with the findings of the simulation scenario. Moreover, the required load resistance to maximize received power in EQS remains higher compared to BR regime owing to a lowering in the impedance of the powering channel in BR. This amount of power received can facilitate wireless powering to a variety of devices ranging from low power (e.g., ECG) to medium power (SPO$_2$) physiological sensors, digital watch, smart trackers, etc. facilitating augmented living.

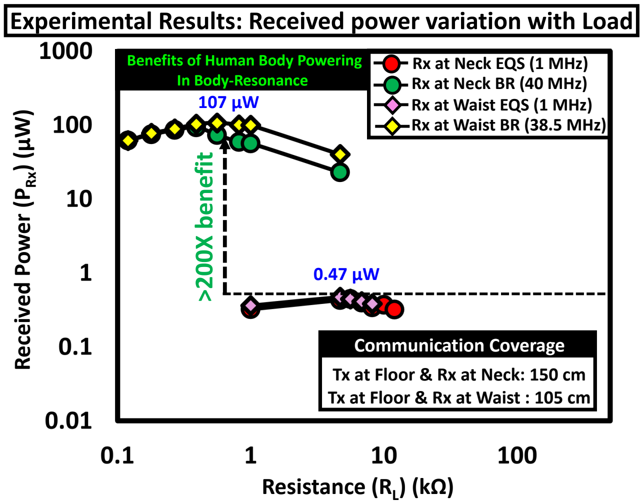

Fig. 6. Experimental Results: Received power variation with load: Utilizing the resonance of the human body >100 μW received power is achieved over a coverage exceeding 1 m.

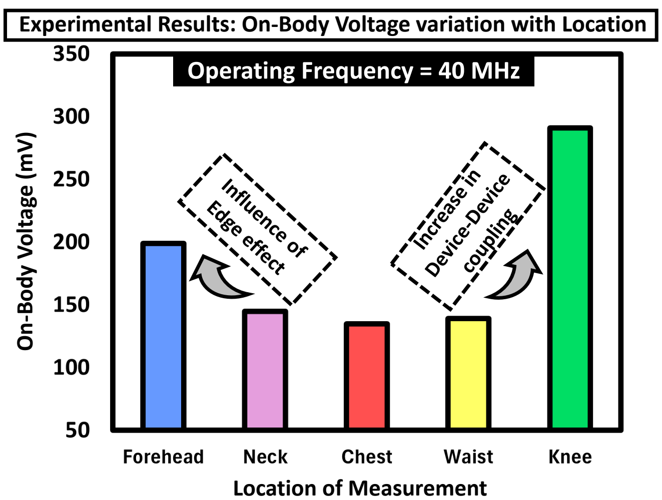

Fig. 7. Variation in On-Body received voltage at different locations: existing voltage gradient captures the electrically distributed behavior of the powering link.

VII. Conclusion

In summary, we present the benefits of wirelessly transferring power through the human body within the body-resonance (BR) frequency range, specifically in a Machine-to-Wearable scenario to various body-worn sensors and devices. Our findings indicate that, in a power transfer mode in BR, we can achieve **>100 μW received power**, even over a communication channel with **coverage exceeding 1 m**, utilizing **body-resonance human body powering (BR HBP)**. In addition, the amount of power received varies depending on the operating frequency and location of the receiver on the body. This is due to the electrically distributed nature of the human body in the BR regime, resulting in variations in the received voltage at different locations. The received power can be further increased via different circuit optimization techniques, motivating potential avenues for future research.

Acknowledgement

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