IBID: Intra-Body Identification Using Capacitive Backscatter

Noor Mohammed
Electrical and Computer Engineering
University of Massachusetts Amherst
MA, USA
noormohammed@umass.edu

Robert W. Jackson
Electrical and Computer Engineering
University of Massachusetts Amherst
MA, USA
jackson@ecs.umass.edu

Sunghoon Ivan Lee
College of Information & Computer Science
University of Massachusetts Amherst
MA, USA
silee@cs.umass.edu

Jeremy Gummeson
Electrical and Computer Engineering
University of Massachusetts Amherst
MA, USA
jgummeso@umass.edu

2024 IEEE International Conference on RFID Technology and Applications (RFID-TA) | 979-8-3315-4022-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/RFID-TA64374.2024.10965181

***Abstract*—This study presents a novel intra-body identification (IBID) technology that uses capacitive backscatter for data transmission. The primary goal of IBID is to facilitate transmission of arbitrary data (e.g., IDs) between a battery-powered interrogator and a batteryless tag through physical interactions . Unlike traditional RFID, which relies on electromagnetic fields in the air for backscatter, IBID uniquely utilizes the finite conductivity of human skin and air-coupled capacitance to enable backscatter communication. In this study, we explore a configuration where the interrogator is worn on the body, and the tags are affixed to everyday objects for human activity monitoring. Specifically, we investigate capacitive backscatter performance when acquiring IDs from two object models: a cylindrical handle and a rectangular switch panel. Preliminary results demonstrate the successful implementation of intra-body capacitive backscatter and the system's ability to interrogate binary IDs. However, variations in the tag electrode dimensions result in fluctuating path gain, even over short distances, causing distortion in demodulated bits. To address this, we designed and implemented a proof-of-concept tag circuit on a PCB that transmits bursts of 16-bit binary values within one capacitor charge cycle and an interrogator that reliably demodulates and decodes an 8-bit binary ID.**

***Index Terms*—Intra-body Identification (IBID), capacitive power transfer, backscattering, wireless communication.**

I. Introduction

Radio frequency communication through the human body is a groundbreaking concept that is crucial in enabling a functional body sensor network. Most prior research has mainly focused on sensors that use active power sources (i.e. batteries) to enable communication between the devices. However, keeping a network of devices continuously powered without interrupting sensing tasks remains challenging — the frequent recharging or replacement of batteries has led to the demand for batteryless body sensor networks that can support both wireless power and communication.

Prior work has investigated using the human body as a medium for wireless power transfer to support battery-free body sensors through Capacitive Intra-Body Power Transfer (C-IBPT) using an on or off-body RF power source [1]–[3]. In a typical C-IBPT setup, the human body and air capacitance allow displacement current flow by establishing a current loop within localized, skin-coupled electrodes by leveraging low frequency (tens of MHz) radio waves.

This work is supported in part by the NSF under Grant No. 016419-00001 and NIH under Grant No. R01HD114147.

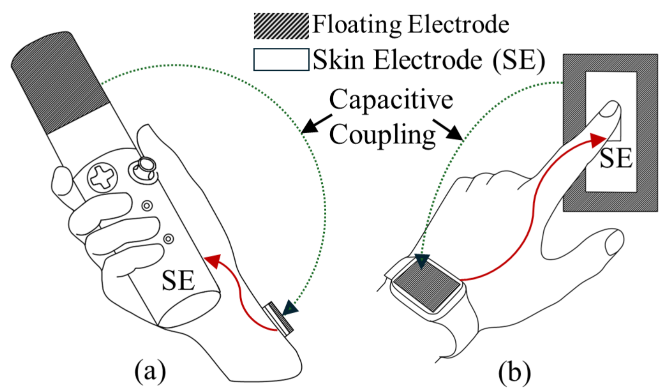

Fig. 1. (a) Cylindrical remote controller and (b) light switch, both of which are instrumented for IBID applications.

Previously, communication through the human body has been implemented in simplex mode or half duplex mode, leveraging the unilateral path loss between two battery-powered active devices [4]–[6]. Since backscatter communicaion results in double path loss, significant challenges remain in realizing fully batteryless body sensor networks that support both power transfer and communication.

In this work, we investigate a new intra-body identification (IBID) technology that combines the key technical features of C-IBPT and RF backscatter [7]. Similar to C-IBPT [1], IBID takes advantage of skin conductivity and air coupling capacitance to form the communication loop between a pair of skin-coupled electrodes. Additionally, the backscatter communication takes place between a batteryless ultra-low powered

ID tag and a battery-powered IBID interrogator, both of which are custom-designed. This represents a first step towards establishing a fully passive on-body sensor network.

For an application in human activity monitoring, the IBID system was configured to enable simultaneous power transmission and backscatter communication between a wrist-worn, skin-coupled interrogator and passive IBID tags attached to everyday objects. A key practical advantages of the capacitive IBID system is its flexibility to support a wide range of geometric complexities in tag electrodes (i.e., size and shape). As a demonstrative example, we instrumented two everyday objects with different geometries: a remote control with cylindrical electrodes and a light switch with rectangular electrodes, as illustrated in Fig. 1. This study not only reports on the physical layer of the IBID technology but also presents a preliminary performance evaluation of the custom hardware system, providing a promising glimpse into real-world applications. Notably, IBID can be flexibly configured so that the interrogator is placed in the environment while the tags are worn on the human body. Currently, the tags are programmed to transmit unique IDs to the interrogator, but they can also be equipped with low-power sensors for a variety of potential applications.

RF backscatter over the air and within body tissue mediums has provided valuable insights through the use of unique power transmission and communication technologies. However, there is a need to further investigate backscatter within complex air-skin dielectric interfaces using capacitive links at low frequencies to enable batteryless body-sensor networks. This research aims to showcase two practical implementations of capacitive intrabody backscattering communication utilizing a batteryless ID tag and a wrist-worn interrogator, advancing the state-of-the-art in human body communications (HBC) across complex dielectric environments.

II. IBID SYSTEM

The primary objective of conventional human body communication studies has been to enhance the coupling capacitance between earth ground and the body electrodes' ground. However, in both the C-IBPT and IBID systems, the contribution of an external physical ground is minimized by implementing galvanic isolation and resonant impedance matching in a short body channel. Our system relies only on a self-contained electrode setup, without the need for an external ground, and is designed to fit within a wearable form factor.

A. Electrode System

In the IBID system, data and power transfer is established via a loop formed by the human body and air, using a pair of skin-coupled, isolated electrode systems as illustrated in Fig. 2. The skin-coupled electrodes are matched to 50 ohm impedance by using an LC matching network. One electrode system plays the role of the interrogator (or reader), while the other serves as the tag. The interrogator electrode pair is connected to a custom-designed RF transceiver and is powered by an external source (e.g., a battery in our application).

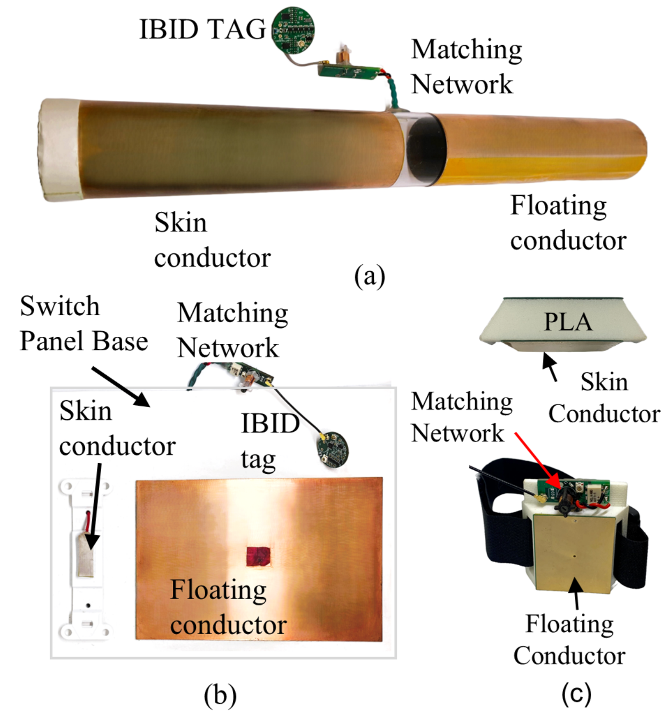

Fig. 2. (a) Instrumented cylindrical object (length: 30 cm), (b) switch panel, and (c) interrogator electrode (30 cm × 40 cm).

The dielectric substrate between the interrogator electrodes has an average permittivity of 3.1 achieved by PLA plastic with a thickness of 11 mm. In contrast, the tag electrode pair, integrated with the batteryless IBID tag, can be attached to objects of interest and does not have a fixed dielectric substrate. Instead, the dielectric properties of the tag electrode will be regulated by the intrinsic permittivity of the object and air.

Each electrode system comprises two conductors: a skin-coupled conductor and a floating air conductor. These conductors form a dominant loop for displacement current flow, relying on skin conductance and air capacitance over a short body channel length. In the proposed applications, the tuned electrodes are capacitively coupled in their near field region.

The interrogator electrodes serve two critical functions in the IBID system. They 1) power the batteryless tag via 40 MHz RF carrier transmitted through the intra-body capacitive loop, and 2) receive the modulated RF energy from the tag through the same current loop and decodes the tag ID. The tag, in turn, is responsible for modulating its reflection coefficient and encode its data in the 40 MHz carrier signal.

B. IBID Tag Circuit

Fig. 3(a) shows the PCB that implements the IBID tag circuit. The circuit comprises five sub-modules: an impedance matching circuit, a 5-stage modified Dickson charge pump with a 10 uF storage capacitor, a power management unit (PMU), a baseband generator, and a carrier modulator.

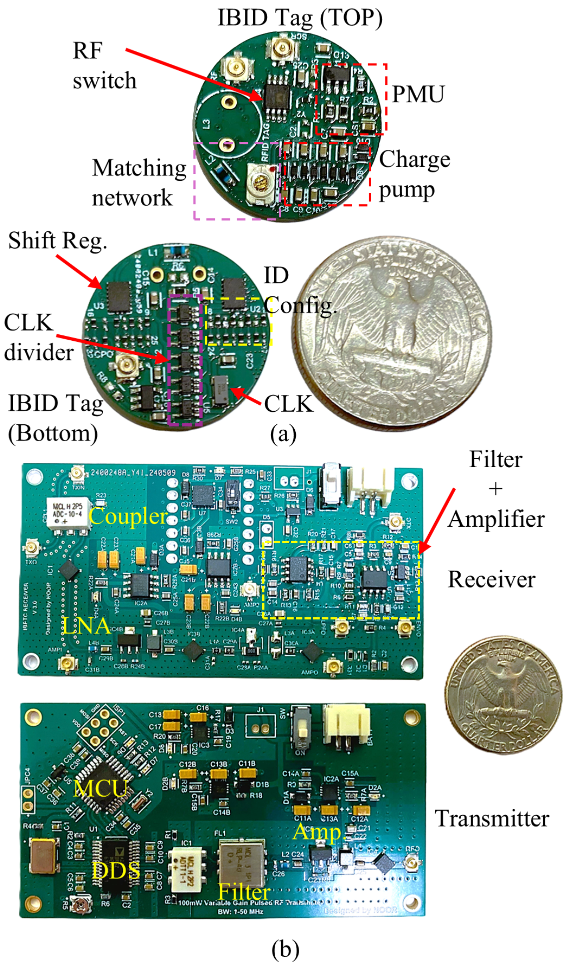

Fig. 3. (a) IBID tag ,and (b) IBID interrogator.

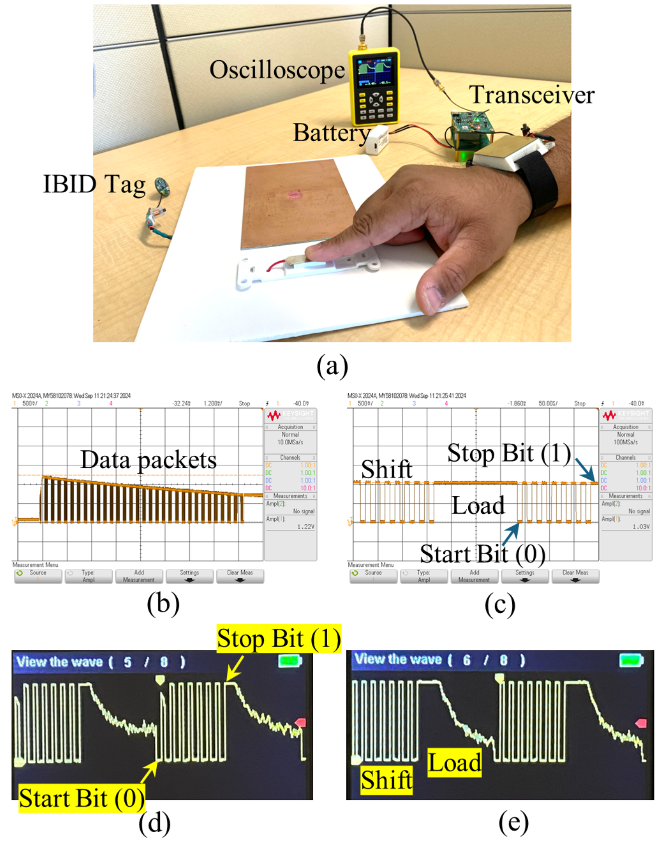

Fig. 4. (a) Experimental setup for IBID switch panel to measure demodulated bit stream. (b) Data packets within a single communication burst. (c) Zoomed view of data packets from IBID tag. (d) and (e) Demodulated bit streams from switch panel and cylindrical object model.

The impedance matching circuit includes an LC matching network to match the charge pump and its load to 50 $ohms$ at -10 dBm for a 40 MHz RF carrier. The Dickson charge pump is able to charge the 10 uF storage capacitor to 3V when coupled with the PMU at -10 dBm peak RF power. The PMU includes a nanopower supervisor and a 1.8 V LDO regulator, providing a stable power supply for the baseband unit, oscillator and clock divider, and the modulator. The baseband unit consists of a 100 KHz MEMS oscillator, a clock divider, a $16 - bit$ shift register, and a configurable $16 - bit$ static ID generator using a resistive network. The output bit stream from the baseband generator is used as a switching signal for a high-speed MOSFET switch in the modulator, with the modulator's output connected to the input of the impedance matching circuit.

C. IBID Interrogator

Fig. 3(b) shows the PCB of the interrogator. The interrogator consists of an RF generator with a microcontroller, a programmable frequency synthesizer, and a low-noise amplifier (LNA). It employs 50% carrier modulation of 23 dBm peak RF power for querying the IBID tag. The receiver front-end includes a directional coupler, LNA, envelope detector, low-pass filter, differential amplifier, AC-coupled amplifier, a microcontroller for storing the demodulated data in a flash memory, and separate power regulators for the analog and mixed signal blocks. The entire transceiver requires 5 V DC to operate.

III. Experimental Setup and Results

Fig. 4(a) shows the experimental setup for the IBID switch panel application. Similar setup has also been used for the cylindrical model (ref: Fig.1(a).Fig. 4(b) and (c) show the output from the baseband generator at -10 dBm peak continuous RF power. The baseband unit outputs the binary ID during the shifting phase of the shift register. The shift and load signal is derived from the 100 KHz oscillator using an array of D flip-flops. The 100 KHz oscillator also serves as the primary clock for the shift register.

Fig. 4(d) and (e) display the demodulated bit stream decoded by the transceiver and backscattered from the switch panel and the cylindrical model, respectively. The peak-to-peak amplitude of the demodulated bits are 3.3 V after amplification. Each bit length is 20 us, which is the period of half of the 100 KHz clock cycle.

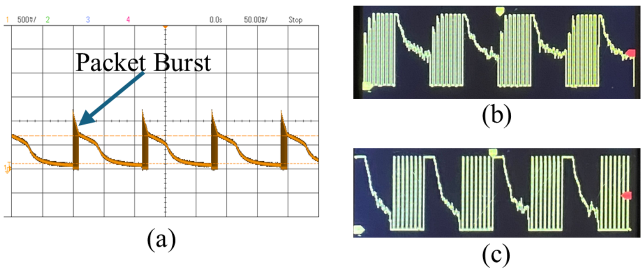

Fig. 5. (a) Multiple data packet bursts across successive charge-discharge cycles of the 10 uF storage capacitor. (b) and (c) Consecutive demodulated data packets resulting from a single ID burst obtained from switch panel and cylindrical object model respectively.

Fig. 5(a) shows a burst of data packets after each charging cycle of the 10 uF storage capacitor. Each burst generates 31 data packets of 16-bit length for continuous -10 dBm peak RF power. Using $Fig.$ $4(a)$ and the capacitor voltage discharge, we have estimated the power efficiency of communication to be $\sim$16.2 nJ/bit. Each bit stream is framed as a start bit, preamble bit, data bit, parity bit, and stop bit. The start bit is defined as a falling edge with a binary 0 level, whereas the stop bit is defined as a rising edge with a 1-bit length. The preamble bit and the parity bit are 3 consecutive bit lengths with an alternating high-low pattern. Apart from these fixed bits, the data bits are arbitrary, with a fixed length of 8-bits. Fig. 5(b) and (c) show consecutive packet streams observed within a single burst. Note that in this preliminary study, we have substituted an arbitrary ID with a canonical ones and zeros bitstream (i.e., 0101010101010101).

IV. Discussion

The baseband output shows a decaying amplitude. This is due to the loading of the storage capacitor at the charge pump output while the LDO is enabled in the PMU. The nano-supervisor in the PMU has a programmable time delay unit to set the output for a certain period, which serves as an enable signal for the LDO. However, the LDO can not regulate the voltage if the input falls below the rated output. As a result, the output of the LDO decreases instead of producing the desired stable voltage output.

In our ultra-low power design, the CMOS components in the baseband unit, along with the MEMS oscillator and clock dividers, can operate with a minimum of 800 mV DC supply and switch the MOSFET in the modulator above the gate threshold. Although the voltage difference between the drain and the gate results in different effective channel length within the MOSFET, the modulator successfully performs carrier modulation initiated by the IBID tag within the intrabody loop. This is evident from the demodulated bit stream obtained from the AC-coupled amplifier in the interrogator. Additionally, the dynamic CMOS logic level of an onboard microcontroller (ATSAMD21) in the receiver decodes the demodulated bit stream by clearly specifying the binary states.

V. Conclusion

This study introduces a innovative concept of IBID, leveraging capacitive intrabody power transfer and backscatter communication techniques. This preliminary yet pioneering work highlights key aspects of the physical layer and hardware architecture necessary to implement batteryless IBID technology in real-world applications. Future efforts will focus on validating the technology across a broader range of applications and with a larger number of human subjects.

References

[1] N. Mohammed, R. W. Jackson, J. Gummeson, and S. I. Lee, "Wireless intra-body power transfer via capacitively coupled link," in *2022 IEEE-EMBS International Conference on Wearable and Implantable Body Sensor Networks (BSN)*. IEEE, 2022, pp. 1–4.

[2] N. Mohammed, R. Wang, R. W. Jackson, Y. Noh, J. Gummeson, and S. I. Lee, "Shazam: Charge-free wearable devices via intra-body power transfer from everyday objects," *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 5, no. 2, pp. 1–25, 2021.

[3] R. Shukla, N. Kiran, R. Wang, J. Gummeson, and S. I. Lee, "Skinnypower: enabling batteryless wearable sensors via intra-body power transfer," in *Proceedings of the 17th Conference on Embedded Networked Sensor Systems*, 2019, pp. 68–82.

[4] J. Park, H. Garudadri, and P. P. Mercier, "Channel modeling of miniaturized battery-powered capacitive human body communication systems," *IEEE Transactions on Biomedical Engineering*, vol. 64, no. 2, pp. 452–462, 2016.

[5] M. D. Pereira, G. A. Alvarez-Botero, and F. R. de Sousa, "Characterization and modeling of the capacitive hbc channel," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 10, pp. 2626–2635, 2015.

[6] A. Datta, M. Nath, D. Yang, and S. Sen, "Advanced biophysical model to capture channel variability for eqs capacitive hbc," *IEEE Transactions on Biomedical Engineering*, vol. 68, no. 11, pp. 3435–3446, 2021.

[7] A. P. Sample, D. J. Yeager, P. S. Powledge, A. V. Mamishev, and J. R. Smith, "Design of an rfid-based battery-free programmable sensing platform," *IEEE transactions on instrumentation and measurement*, vol. 57, no. 11, pp. 2608–2615, 2008.