

Towards Battery-Free Body Sensor Networks

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ABSTRACT

Wearable devices traditionally rely on batteries as the primary source of energy for operation. Batteries are often rigid, bulky, heavy, and require constant recharging, consequently hampering the development of novel device applications. This paper describes a new vision for Body Sensor Networks (BSNs); an interconnection of tiny, flexible, battery-free, cooperative, and programmable wearables via the concept of Intra-Body Power Transfer and Communication (IBPTC), which uses the human body as a medium to exchange energy and data. These wearable devices can receive energy from central, on-body power sources, and coordinate to support whole-system operation and programmer-defined sensing tasks. Of course, this vision entails significant challenges; notably in developing robust hardware and software for energy and information exchange across the body channel, enabling power failure resiliency and timely coordinated task execution. In this paper, we describe a roadmap of systems and tools towards the ultimate vision of battery-free BSNs that has the potential to transform current architectures and designs of BSNs, enabling innovative applications that would otherwise be impossible with on-device batteries.

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1 INTRODUCTION

Long-term remote monitoring based on wearable devices can support early detection of a variety of abnormal health events, improve timeliness of treatment strategies, and ultimately enable patient-centered care [1, 4]. Commercial devices like the Fitbit and Empatica E4 have enabled users and clinicians to capture markers of activity, sleep, stress, and other complex health conditions. However, these devices have problems; they are bulky and obtrusive, require frequent recharging, and only capture data at one point on the body—usually an extremity—which introduces critical usability issues and provides a limited snapshot of users’ health condition. Researchers have thought beyond these devices to envision BSNs comprising of tens of wearable devices that automatically obtain rich, situated information, which could assist in understanding

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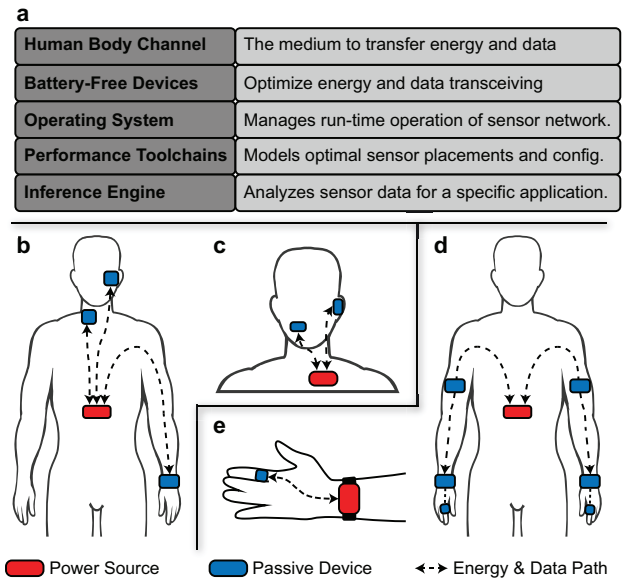


Figure 1: (a) Our envisioned re-designed stack to realize the vision of battery-free body sensor networks, with separate power source and sensing nodes. We consider impactful applications, such as (b, c) automated diet monitoring and (d, e) monitoring stroke recovery trajectory.

complex, multi-faceted behaviors, such as monitoring eating for people with obesity, and motor performance/symptoms in individuals undergoing rehabilitation. Unfortunately, these BSNs have rarely made it past the prototype stage, much less into users hands or clinical practice due to the impracticality, and challenge of managing tens of bulky battery-powered devices on the body.

In mobile electronic devices, the battery is usually the largest component, dominating the device’s overall weight and volume [3]. Batteries poses several challenges to long-term wear, making it difficult for sensors to be placed on the body comfortably (e.g., on the neck, or chest), and impossible to be placed on small body parts like teeth, and fingernails. These placements could enable new applications. Worse, periodic recharging and replacement of batteries is a tedious task even for only one device. Furthermore, battery-powered devices fail at inopportune times; for example, a smartwatch losing power before bed time fails to monitor sleep. Finally, owing to the growing number of mobile (including wearable) devices, battery chemicals have been a fast-growing waste stream, introducing significant environmental impacts.

Our Position. We must reconsider the fundamentals of wearable system architecture—from the energy source, to the operating system, to how applications are designed and tested—in order to empower users, patients, clinicians, and developers to deploy wearable

systems with minimal obtrusiveness and years of lifetime, and seamlessly monitor complex activities and behaviors (and more). This paper pushes for an alternative vision to the monolithic, battery-powered wearable model, proposing a swarm of battery-free and wireless tiny devices that uses the human body as a medium to receive power and communicate data. We pictorially depict layers of the system stack to support the envisioned battery-free BSN in Fig. 1a. At the lowest level is Intra-Body Power Transfer and Communication (IBPTC) [3], where one or more *network managers* provide baseline energy to tens of battery-free wearables and enable data communication over the human body. Band-Aid-sized devices could form a constellation around the network managers and coordinate to receive the necessary energy, perform sensing tasks, and communicate data. This interaction requires a power failure resilient architecture and an operating system to orchestrate the operation of the entire body network. On top of this, a suite of system tools is needed to allow developers to optimize the configuration of wearables (e.g., location and sensor types) within the battery-free body network to support the target applications.

Motivating Applications

While this vision enables a host of applications, in this position paper, we focus on applications in health because of urgency and impact. We discuss two potential applications in depth, that are exceptionally challenging with existing single location and battery-powered wearables.

Monitoring of the Stroke Recovery Trajectory. Stroke is a leading cause of long-term disability, affecting nearly 800,000 individuals every year in the US alone. Continuous monitoring of the amount and quality of stroke-affected upper-limb movements could serve as a means to evaluate the effectiveness of the prescribed rehabilitation regimen and enable personalized therapeutic programs [1]. To obtain a complete view of motor performance, inertial sensors need to be placed on the upper-arms, wrists, and fingers to monitor fine-hand and gross-arm movements, and on the sternum to monitor the presence of compensatory behaviors. Minimally-obtrusive management of the body sensor network is important because stroke survivors with motor and cognitive impairments would encounter challenges for donning and doffing multiple sensors themselves. Fig. 1d depicts a BSN with a network manager with an on-device battery on the sternum that could support energy and communicate data with the rest of the ultra-miniaturized and flexible battery-free (e.g., tattoo-like) sensors. Fig. 1e shows a simplified network configuration to capture the amount of use of the stroke-affected limb. In both configurations, users will have to manage only the power source to the entire body network.

Monitoring of Eating Behaviors. Obesity is a serious disease affecting nearly half of the US population, comprising 21% of annual medical spending in the US. Frequent overeating increases the risk of obesity. Researchers have attempted to develop automated dietary monitoring (ADM) techniques using a variety of sensors to help understand eating behaviors and introduce timely interventions to combat the obesity epidemic [4]. On-wrist accelerometers provide details about the individual's feeding gestures, behind-the-ear audio sensors detect chewing sound, and intra-oral and/or on-throat sensors detect the swallowing action. Complementary

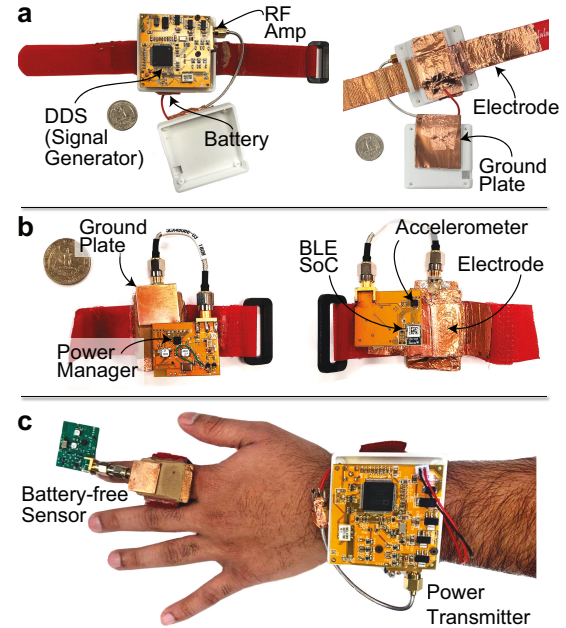


Figure 2: (a) Top and bottom view of the power transmitter; (b) top and bottom view of the battery-free sensor; and (c) placement of the power transmitter and battery-free sensor on the wrist and index finger, respectively.

body location sensing improves accuracy, and the reduction of battery charging increases adherence and comfort. Fig. 1b and c show our envisioned battery-free system that monitor diet-related tasks.

2 FOUNDATIONS OF IBPTC ARCHITECTURE

Shukla *et al.* recently developed *SkinnyPower*, a technology for Intra-Body Power Transfer (IBPT) [3]. *SkinnyPower* uses the human body as the medium to transfer power necessary to operate on-body, *battery-free sensors* from another on-body, battery-powered *power transmitter*. IBPT is inspired by Intra-Body Communication (IBC) and adopts the capacitive coupling architecture, where it constructs 1) a forward signal path and passes a specific Radio Frequency (RF) energy (e.g., at 100 MHz) to the human skin using copper electrodes, and 2) a return path via the environment using copper plates floating in the air, as shown in Fig. 2a and b. Because the return path is established via air, power and data propagation could be susceptible to ambient noise. IBPT is the first step towards realizing the vision of IBPTC (a combination of IBPT and IBC) and battery-free BSNs, where devices can simultaneously share power and communicate data with each other over the human body channel.

Preliminary Results. *SkinnyPower* was evaluated in an indoor laboratory setting, demonstrating the possibility of transferring hundreds of μW of power through human skin at 100 MHz. *SkinnyPower* was tested with the transmitter and receiver placed at a relatively short distance, and the authors found that the amount of power transfer was affected by an individual's body type. To validate their findings, we recently conducted a feasibility study in five healthy participants (23.0 ± 2.74 years old, and 2 males and 3

females). Participants were instructed to wear the power transmitter on the wrist and the battery-free sensor on the index finger, as shown in Fig. 2c. We collected data from the participants once in an indoor setting and once in an outdoor setting on a mostly sunny day. Participants held their wrist and fingers straight for approximately one minute. The battery-free sensor drained the harvested energy, while we monitored the charging and discharging cycles. First, we observed that the amount of power transferred by the system varied from person to person. While $432.6 \mu W$ (maximum) of power could be transferred for one participant, for another participant, we could transfer $241.9 \mu W$ (minimum) of power. Second, there was degradation in the received power in outdoor environments as compared to indoor environments. On average, we obtained $324.8 \pm 71.0 \mu W$ in the indoor setting vs. $267.1 \pm 30.7 \mu W$ in the outdoor setting. Although promising, these results indicate that, similar to several energy harvesting solutions, battery-free wearable devices powered by IBPTC need to be resilient to power failures, and carefully managed based on the condition of each body channel.

3 RESEARCH CHALLENGES

A reliable and robust full body battery-free Body Sensor Network (BSN) requires careful and systematic design in multiple levels of the development stack, which we describe in this section.

Using the Body Channel for Power and Communication. We envision a future where battery-free BSN nodes could simultaneously transfer power and communicate data over the human body. We believe a backscattering-based communication protocol over the human body (e.g., similar to an RFID) could be a compelling solution. While the traditional over-the-air radio channel suffers from ambient noise and free-space pathloss attenuation, the human body channel also suffers from variability in tissue composition across different individuals, body state, and external environment. The body channel is less understood and the creation of a radio stack that is robust to these variations is a fundamental challenge that needs to be addressed to develop dependable health applications.

Location Dependent Energy Transfer. The placement of nodes is primarily driven by an application's sensing requirements rather than the power needs of the system. Nodes placed on different parts of the human body will harvest vastly different amounts of power depending on channel characteristics (e.g., length and body composition of each body part). Energy transfer via the body channel presents opportunities to support energy-starved nodes; there are also opportunities to place additional network managers at body locations that suffer from severe energy shortages that cannot be mitigated through energy sharing with only one manager.

Operating Systems for Energy Sharing. Given the intermittency of power, battery-free BSNs will require an operating system [5] that ensures the real-time completion of sensing tasks. Such an operating system needs information including power availability, inter-node distances, and harvesting statistics over time to dynamically prioritize tasks. The network stack has to schedule and coordinate the transfer of power and data simultaneously between different disjoint pairs of nodes to avoid collisions and interference. Finally, some nodes may serve special functions as power banks or network repeaters; these nodes may contain batteries, and may need to be reserved for critical outages.

Tools for Understanding Energy Harvesting. Understanding temporal variations in power availability across battery-free nodes allows one to quantify the effectiveness of a battery-free BSN. Understanding whether power transfer will be efficient under specific conditions will require specific knowledge about the environment, the nodes, their on-body placement. With a large range of possible on-body placements and environmental changes, collecting a trace for each placement combination is intractable [2]; therefore, it is necessary to build tools that can model these diverse conditions. There is a need to understand the opportunities and limitations of the body for energy transfer and harvesting, which depends on the aforementioned factors, and identify the optimal configuration of the body network (e.g., placement of the battery-managers).

Inference Engines for Intermittently Powered Systems. Guided by a toolchain that optimizes the sensor placement, an inference engine is needed that aggregates data from sensors and extracts clinically meaningful information. While the requirement of the inference engine should be specific to different applications, the engine should be adaptive to the quality of service (e.g., sampling rate) available at particular sensor nodes, which may dynamically vary depending on the available energy or channel conditions [5]. Networks of intermittently powered sensors create the need for an inference engine that is aware of the overall power of the network, condition of different on-body sensor channels, loss in power when transferring between body parts, the quality of service at sensor nodes, and the priority of sensor data for the target inference.

4 CALL TO ACTION

The on-body computational swarm provides many challenges and opportunities for health and other applications. In this paper, we provide a roadmap of research that—if conquered—can form the foundation of ultra long term, invisible on-body sensing applications. Our initial findings on power transfer and sharing are a promising foundation for this vision.

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