Invited: Can Wi-R enable perpetual IoB nodes?

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Abstract—While the number of wearables is steadily growing, the wearables/person wearing them faces a limitation due to the need for charging all of them every day. To unlock the true power of IoB, we need to make these IoB nodes perpetual. However, that is not possible with today's technology. In this paper, we will debate, whether with the advent of Wi-R protocol that uses the body to communicate at $100X$ lower energy that BTLE/Wi-Fi, is it going to be possible to enable the long-standing desire of perpetual sensing/actuation nodes for the Internet of Bodies.

Index Terms—Internet of Bodies (IoB), Wi-R, Electro-Quasistatic Human Body Communication (EQS-HBC)

I. INTRODUCTION

Wearable devices are increasing exponentially over the last decade. This interconnected network of devices around the body forms the subsection of Internet of Things (IoT) termed as Internet of Bodies or IoB (Fig. 1). IoB [1]–[8] is fast becoming a reality with the continuous scaling of devices resulting in increasing number of devices in and around the body. However, for an efficient implementation of IoB, it is critical to analyze the bottlenecks currently preventing its widespread adoption and the potential solutions.

The most important application for IoB nodes is in the continuous health monitoring by sensing biopotential signals from the human body. Smartphones and smartwatches tracking and providing updates on daily health has become commonplace. However, more accurate and denser sensing technologies require higher number of IoB nodes across the body. Considerable research is being done to develop more biopotential signal measurement devices. However, increasing number of wearable devices per person means charging more and more devices and further keeping track of these devices through the day. This is a serious threat to the adoption of IoB as charging these devices can become an extremely tedious task. Thus, perpetual operation of IoB nodes has become a topic of extensive research.

The vision of perpetual IoB nodes is being pursued in the research community in a multipronged approach. Wearable IoB nodes are size constrained and thus have small batteries. Extensive research is being done to store higher energy in confined spaces to increase energy density in batteries. However, battery technology scaling has not caught up to the scaling of semiconductor technology. Researchers have investigated reducing the power of sensing and communication for IoB nodes, as well looking at new methods for energy harvesting
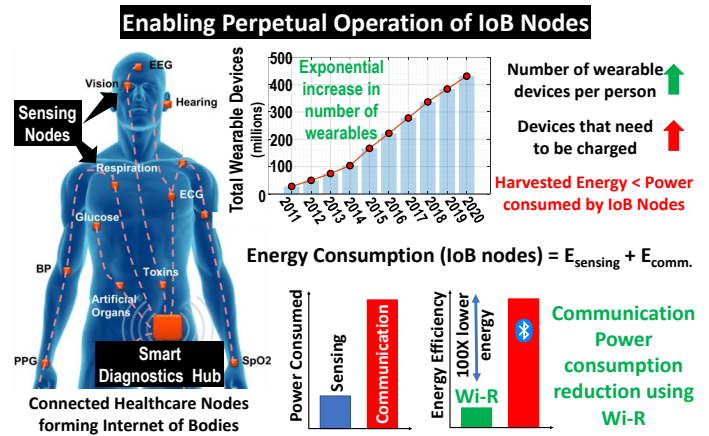
Fig. 1. Increasing wearables/person, has resulted in a need for techniques to enable perpetual operation for the nodes to reduce time spent in charging devices. Wi-R has come up as an exciting alternative to traditional RF based techniques, demonstrating higher communication energy efficiency.

for charging. Radio frequency (RF) based wireless powering methodologies have been looked into with commercial applications developed over the last few years. RF based wireless powering however has still got a long way to go before they enable perpetual operation of current IoB nodes. This is because of the difficulty in transmitting power over the air, with channel losses frequently above $60dB$ due to fading and shadowing from objects in the vicinity. Further, the transmit power is also limited by safety concerns, which are guided by the Federal Communications Commissions (FCC).

Therefore, the logical conclusion is to design lower power devices that can run for longer time with the current wireless powering and harvesting systems. It is well known that the power consumption in the IoB nodes is dominated by the communication power, which is typically $3 - 4$ orders of magnitude above the computation power consumed [8], [9]. Thus, a major research thrust has been in the development of innovative communication methodologies tailor-made for operation of devices in and around the body. Typically, data is communicated between IoB nodes using radio frequency (RF) based radiative communication protocols, which transmit signals over the air. Common examples of such communication protocols include Bluetooth, ZigBee and LoRa. However, these communication methodologies have been shown to be insecure due to their radiative nature, and have high power consumption, a large part of which is lost to the signal that is radiated across the room. This decreases the communication

energy efficiency by increasing the amount of power required to successfully communicate each bit.

Thus, in the pursuit of energy efficient communication, directed methods of communicating between two nodes placed around the body have been explored so that power is not lost in radiating data across the air channel. This has prompted research into using the body as a wire to communicate data between IoB nodes, as the human body serves as a common medium connecting all the devices. The use of body as a wire to communicate data was efficiently exploited by using Electro-Quasistatic Human Body Communication (EQS-HBC) [10]–[14]. EQS-HBC has been demonstrated to be orders of magnitude more energy efficient than typical RF based protocols and has been shown to be physically secure by confining the signal within the body, making it unavailable to attackers unless they are almost in contact with the body. Wi-R technology is the first commercial implementation of EQS-HBC. Wi-R has orders of magnitude higher energy efficiency when compared to traditional RF based methods of communication. Wi-R technology operates at $1-20MHz$ frequency range which falls firmly within the realms of Electro-Quasistatic frequencies for Human Body Communication. In this study, we present a method for unified analysis of sensing and communication systems to investigate the use of Wi-R in place of RF based communication strategies and the doors that this will open for the perpetual operation of IoB nodes.

II. IoB Devices and the need for Wi-R

IoB devices can be broadly categorized into two different types based on their functions and form factor: (i) Larger hubs, and (ii) Smaller nodes. The smaller nodes are the various sensors in and around the body, which may be fitness trackers, connected healthcare devices, implanted or ingested medical devices, physiological sensors or a combination of all of them. These devices are ultra-low power nodes required to run without having to be charged for a long period of time, ideally perpetually. The larger devices are the hubs, which bear most of the computation demands and are responsible for connecting IoB to the larger IoT for further data analytics on the cloud. These are devices like Smartphones and Smartwatches, AR/VR smart glasses and headsets and consume higher power than the smaller IoB nodes.
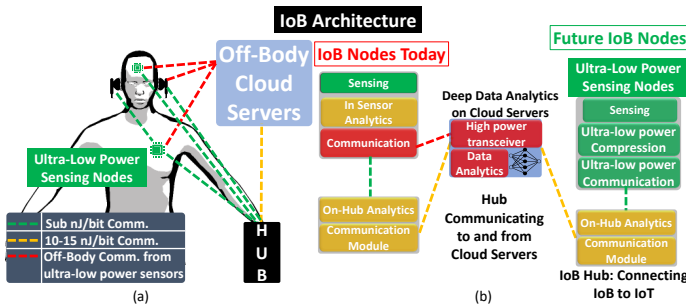

Fig. 2. Architecture and functions of low-power sensing nodes and hubs in IoB. (a) IoB network architecture. (b) Current sensing structure and possible future low-power sensing nodes.

An architecture of the proposed IoB system is illustrated in Fig. 2. The smaller nodes cannot communicate data at all times to and from cloud servers off the body, as illustrated in Fig. 2 (a). To design ultra-low power small IoB nodes, a bulk of the communication and computation needs to be offloaded to the hubs. A comparison between current sensor node designs and future ultra-low power IoB sensing nodes is shown in Fig. 2 (b). Thus, the main tasks of these nodes can be divided into three parts: (i) Sensing, (ii) Ultra-low power compression, and (iii) Communicating sensed data to the hub. This ensures that the higher power demands in data analytics and communicating data off the body are offloaded to the larger hubs. Ultra-low power compression specially for audio and video signals is key in reducing data volume. However, in this study, we focus on the benchmarking of sensing and communication systems without delving into the details of compression.

The energy requirements for the ultra-low power IoB nodes can be mathematically denoted as illustrated by Eqn: 1,

$$E_{total} = E_{sensing} + E_{comm.} \tag{1}$$

where, the total energy consumption (E_{total}) is the sum of the energy requirement for sensing $(E_{sensing})$ and the communication energy required $(E_{comm.})$. This can be further broken down to analyze the dependence of E_{total} on the energy efficiency or the energy spent per bit of sensing and communication $(\eta_{sensing}, \eta_{comm.})$, as shown by Eqn. 2.

$$E_{sensing} = bit_{sensed} \times \frac{E_{sensing}}{bit}$$
$$E_{sensing} = bit_{sensed} \times \eta_{sensing}$$
$$E_{comm.} = bit_{sensed} \times \frac{E_{comm.}}{bit}$$
$$E_{comm.} = bit_{sensed} \times \eta_{comm.}$$
$$E_{total} = bit_{sensed} \times (\eta_{sensing} + \eta_{comm.}) \tag{2}$$

Thus, it is essential to increase energy efficiency or decrease η of sensing and communication to ensure that the smaller nodes have a high lifetime before they are charged. In this study, we investigate energy efficient methods of communication between IoB nodes.

Bluetooth has been the gold standard for communication between devices around the body in commercial devices. However, in recent times, EQS-HBC has been demonstrated to be an energy efficient and physically secure alternative to traditional RF based communication techniques specifically for IoB devices. In EQS-HBC, data is transmitted through the body using the tissue's conductive properties to communicate information between two devices on the body. The signal is coupled to the body at frequencies $< 40MHz$. At these frequencies, the human body is an inefficient antenna and the data is confined within the body. Thus, no power is lost to data being transmitted through the air. This ensures that EQS-HBC is physically secure and has a higher energy efficiency than RF based radiative communication techniques.
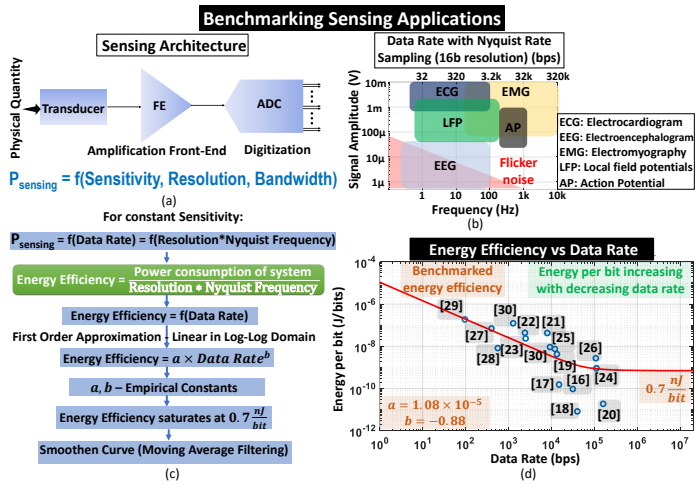
Fig. 3. Benchmarking $\eta_{sensing}$. (a) A typical sensing node. (b) Data rates and sensitivities for common biopotential signals. The algorithm in (c) is used to simplify and benchmark $\eta_{sensing}$. (d) Survey of literature and commercial space and benchmarked energy efficiency.

Wi-R is the first commercial application of the EQS-HBC technology [15]. Wi-R uses non-radiative near field communication using EQS fields across the human body. Wi-R has shown immense potential in bringing the EQS-HBC technology proposed in literature to the masses. Wi-R has orders of magnitude higher energy efficiency when compared to Bluetooth, which makes it the prime candidate for around the body communication in IoB nodes. Current Wi-R technology also allows for comparable or higher data rates around the body at a fraction of the power spent when compared to Bluetooth. This can potentially be a game changer for smaller IoB nodes communicating to the hub by bringing us a step closer to perpetual operation of these ultra-low power nodes. We now analyze the sensing and communication power requirements as well as the available power to the nodes, either via energy harvesting from wireless powering methodologies or traditionally using smaller batteries.

III. BENCHMARKING DIFFERENT ENERGIES

A benchmarking of sensing and communication power as well as amount of harvested energy is performed to estimate the performance of ultra-low power IoB nodes operating with Wi-R and Bluetooth. The absolute values of energy-efficiency for sensing and communication systems vary vastly with changing architectures, and is not essential to this study. We perform a study to simplify and approximate the energy-efficiency as a function of data rate, considering no variance in other parameters. This simplified view aids in developing a unified analysis of sensing and communication techniques.

A. Sensing

A typical sensing architecture is illustrated in Fig. 3 (a). For such sensing nodes, the power consumption is a function of the sensitivity, resolution and the bandwidth. IoB nodes typically deal with sensing biopotential signals, some of which are illustrated in Fig. 3 (b). Fig. 3 (b) also shows the required

sensitivity for these applications and the minimum data rate required to capture these signals with a $16-bit$ ADC. To benchmark sensing power as a function of data rate, we perform a survey of studies in the literature and for commercial analog front ends for biopotential signal acquisition [16]–[30]. The energy efficiency for the whole system is estimated based on the algorithm present in Fig. 3 (c). The vast variability in sensing power due to different applications and circuit architectures leads us to attempt to simplify the analysis. The algorithm is a first order approximation to estimate the variation in energy efficiency as a function of data rate for iso-sensitivity and iso-design analog front ends. The collected data for energy efficiency as a function of data rate is fitted to a line in the log-log domain using MATLAB, to estimate the energy efficiency of such a system. The curve plateaus at $0.7nJ/bit$ to approximate the energy efficiency for higher data rates and we smoothen the curve generated using a moving-average filter. This curve, illustrated in Fig. 3 (d), is used as a benchmark for energy efficiency of sensing systems ($\eta_{sensing}$) for future analysis of ultra-low power IoB sensing nodes.

B. Communication

Communication technologies for IoB nodes require energy efficient communication for channel lengths of $1cm-2m$. Benchmarking current communication technologies requires us to look at the commonly used communication techniques for IoB nodes which are typically RF based protocols like Bluetooth, LoRa and ZigBee. However, these RF based communication protocols can consume $> 1nJ/bit$ energy efficiency and up to $15nJ/bit$ for Bluetooth.

Emerging technology in the form of EQS-HBC has been shown to be much more energy efficient [31], [32]. Wi-R, the first commercial implementation of EQS-HBC has $< 100pJ/bit$ energy efficiency for communication around the body [15]. Future iterations of Wi-R are aimed at bridging the gap between literature and consumer applications to bring the energy efficiency closer to $10pJ/bit$. A concept diagram
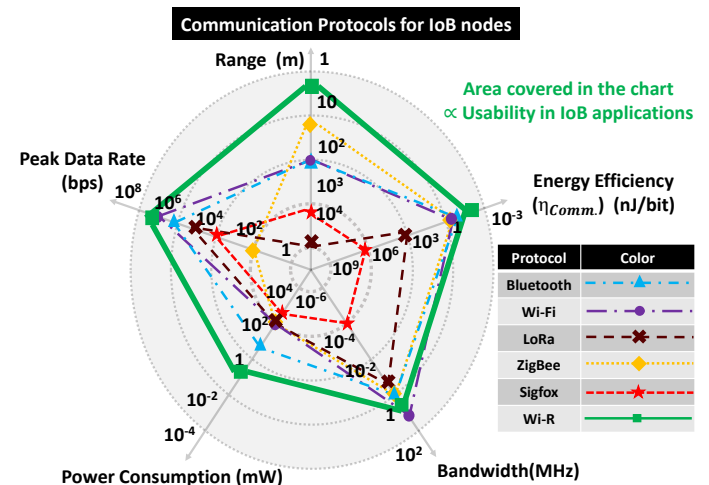

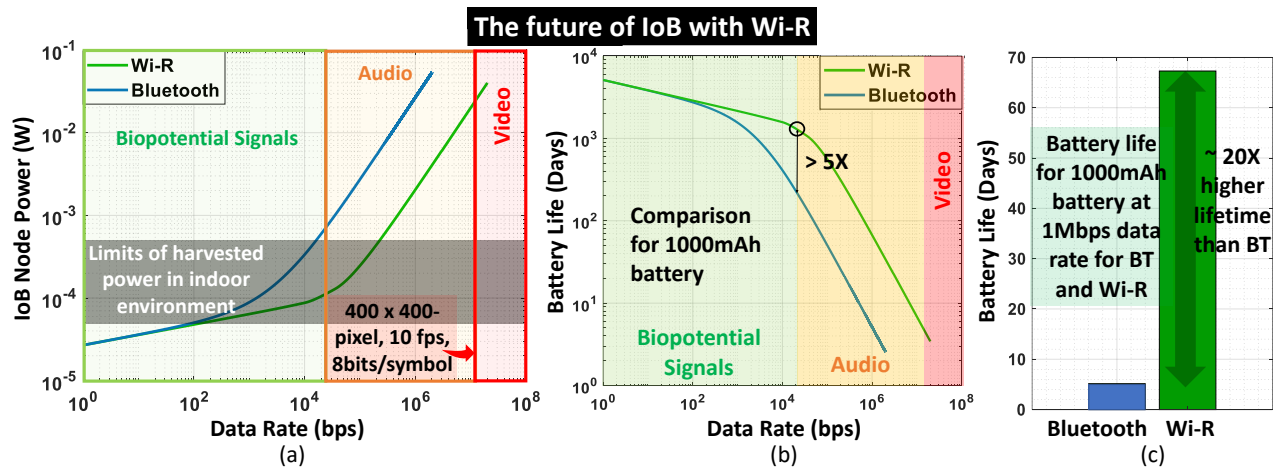Fig. 4. Communication protocols for IoB nodes.

Fig. 5. (a) Comparison between power consumption for IoB sensor nodes operating with Bluetooth (blue) and Wi-R (green) as a function of data rate. (b) Device lifetime as a function of data rate for a $1000mAh$ battery. (c) Comparison of battery life for a $1000mAh$ battery for a data rate of $1Mbps$ with Bluetooth (red) and Wi-R (green).

describing the various different communication protocols and their key parameters (Energy Efficiency, Data rate, range etc.) is illustrated in Fig. 4, where the higher is the area occupied by a particular protocol, the better it is for use in IoB nodes. Wi-R being specifically designed to operate around the body can be seen to have immense potential in IoB applications.

C. Available Energy for Wearables

Wearable and implantable ultra-low power IoB devices being size constrained require using small sized batteries and further depend on wireless powering and energy harvesting mechanisms to operate. Typically, the batteries used are small coin cell batteries ($200mAh$ [33] to about $1000mAh$ [34]), as these are safe to use and can be operated for long durations.

To further extend the lifetime of ultra-low power IoB sensor nodes, various different methods for harvesting energy for IoB nodes has come up over the last decade. These can be broadly categorized into mechanical, thermal, radiative, chemical, magnetic and electric. A study of energy harvesting modalities and the peak power density for the different modalities has been conducted by Chatterjee et al. [8]. In an indoor setup with variability due to position of devices and postures, realistically, the amount of harvested power is between $50\mu W$ to $100s$ of μW [35], [36].

IV. IMPACT OF WI-R ON IOB NODES

The impact of Wi-R on IoB nodes is illustrated using Fig. 5. Fig. 5 (a) shows the estimated power of an ultra-low power IoB node as a function of data rate using the benchmarked energy efficiencies for communication and sensing. We consider the energy efficiency for Bluetooth to be $10nJ/bit$ and for Wi-R to be $100pJ/bit$. The data and the source code used to generate the graphs are provided publicly [37]. We consider a system efficiency factor: $\eta_{system} = 0.4$ which emulates the additional losses coming from LDOs, DC-DC converters and the platform power consumption. Harvested power is limited to between $50\mu W$ to $100s$ of μW for indoor environments, as shown in the figure. We observe that with state-of-the-art harvesting

techniques, Bluetooth allows reliable perpetual operation for low data rate ($< 1kbps$) biopotential sensing applications. Continuous biopotential signal monitoring with higher data rates is unlikely using Bluetooth. In comparison, Wi-R can be used to operate ultra-low power biopotential sensors perpetually for almost the whole spectrum of biopotential signals. Further, current Wi-R technology with an energy efficiency of $< 100pJ/bit$ has the potential to transmit low data rate audio signals ($\leq 200kbps$) reliably and operate perpetually with state-of-the-art harvesting techniques. Fig. 5 (b) and (c) shows the improvement in device lifetime for a battery operated ($1000mAh$) node when using Wi-R as compared to Bluetooth. Using Wi-R can increase battery life by more than an order of magnitude for audio and low data rate video (400×400 pixels, $10fps$, 8 bits/symbol) applications without compression. Incorporating ultra-low power compression techniques can further enhance the reach of Wi-R to higher data rate applications, increasing the spectrum of applications possible.

The current sensing systems with Bluetooth can operate perpetually only for low data rate applications with current energy harvesting techniques. We have demonstrated that implementing Wi-R enables perpetual operation for most biopotential sensing applications and improves battery life by more than an order of magnitude for audio/video applications.

V. CONCLUSION

We present a framework for a unified analysis of sensing, and communication methodologies to study the existing state-of-the-art for communication around the body and compare with Wi-R, an exciting new alternative which uses the body as a directed wire for communication between devices around the body. Wi-R is $100X$ more energy efficient ($< 100pJ/bit$) as compared to traditional Bluetooth ($> 15nJ/bit$) based communication platforms, and opens up the potential for a future where more devices can operate perpetually.

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