Enabling High Temporal-Resolution Remote Monitoring in Resource-Constrained Implantable Medical Devices with Human Body Communication

Ayan Biswas*, Baibhab Chatterjee†, Shreyas Sen*
Emails: {ayanb, shreyas}@purdue.edu, {chatterjee.b}@ufl.edu
*Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA
†Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL, USA

***Abstract*—Continuous remote monitoring of implantable medical devices, such as pacemakers, is limited by the high power consumption and security concerns of traditional wireless technologies like Bluetooth. In this work, we investigate Electro-Quasistatic Human Body Communication (EQS-HBC) as an alternative, leveraging the body itself as a communication channel between implants and wearable devices. EQS-HBC achieves real-time, high-throughput data transmission at power levels approximately 100 times lower than Bluetooth, enabling millisecond-resolution monitoring with minimal impact on device longevity. Through system-level optimization of sensing, memory, and communication, we demonstrate that EQS-HBC can support high temporal-resolution, secure data exchange without the high battery life penalties of current Radio-Frequency (RF) based solutions. These results highlight EQS-HBC's potential to transform remote care for patients by making truly continuous, personalized monitoring feasible.**

***Index Terms*—EQS, HBC, Remote Health Monitoring**

I. Introduction

Cardiovascular diseases (CVD), particularly ischemic heart disease and stroke, remain the leading causes of death globally, responsible for over 30% of all fatalities [1]. Millions depend on implanted pacemakers to manage conditions like arrhythmia and heart block. Despite their critical role in patient care, current smart pacemakers typically provide only intermittent or event-triggered remote monitoring. This limitation stems from battery constraints and the high energy demands of conventional wireless communication methods, which restrict the ability to deliver continuous, personalized, and proactive treatment outside clinical settings.

Recent advances in tissue-coupled communication, specifically Electro-Quasistatic Human Body Communication (EQS-HBC), present a promising solution for continuous, real-time monitoring in implantable devices. EQS-HBC enables secure, ultra-low-power data transmission (100× lower energy than Bluetooth Low Energy (BLE)), supporting data rates up-to 20 Mbps. This significant reduction in power consumption addresses a major barrier to continuous monitoring, making EQS-HBC an ideal candidate for next-generation implantable medical devices, including pacemakers, neural stimulators, and glucose monitors. By facilitating real-time data transmission and enhanced patient-specific care, EQS-HBC has the potential to transform remote management and outcomes for individuals living with chronic cardiovascular and other health conditions.

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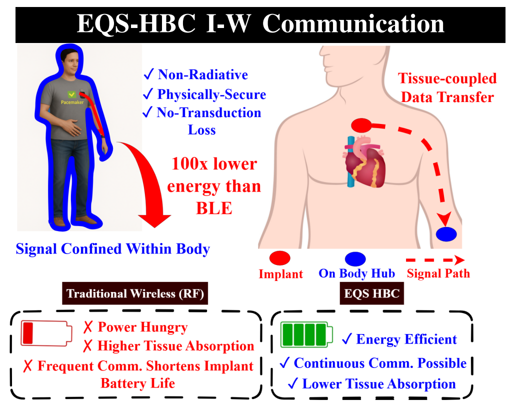


Fig. 1: Secure, low-power implantable-to-wearable (I-W) communication using EQS-HBC

In this paper, we investigate the potential of EQS-HBC as a low-power, secure alternative to conventional wireless methods like Bluetooth for continuous remote monitoring in implantable devices. We also analyze its impact on device performance and longevity. The key contributions of this study are:

- We Discuss recent developments in the area of HBC transceivers and their capabilites.
- We present a comprehensive analysis of the effects of EQS-HBC on pacemaker battery life, communication power consumption, and device longevity.
- We propose an optimal system design for continuous monitoring, focusing on power and memory co-optimization using EQS-HBC.

The rest of the paper is organized as follows: Section II reviews prior works on EQS-HBC and highlights the need for continuous remote monitoring in implants; Section III analyzes EQS-HBC for enabling true continuous remote monitoring in implants; and Section IV concludes the paper.

II. Prior Works on EQS-HBC and the Need for Continuous Remote Monitoring for Implants

A. Prior works on development of EQS-HBC transceivers

Prior works [2]–[7] have demonstrated the feasibility of achieving sub-100 pJ/bit energy efficiency in body area networks using EQS-HBC nodes. An EQS-HBC transceiver utilizing on-off keying (OOK) was implemented to achieve secure and ultra-low power operation, consuming just 415 nW and supporting data rates between 1-20 kb/s. This approach delivers approximately 100× greater efficiency compared to conventional WBAN/BLE solutions, while ensuring both physical security via HBC and cryptographic security through encryption methods [2], [3].

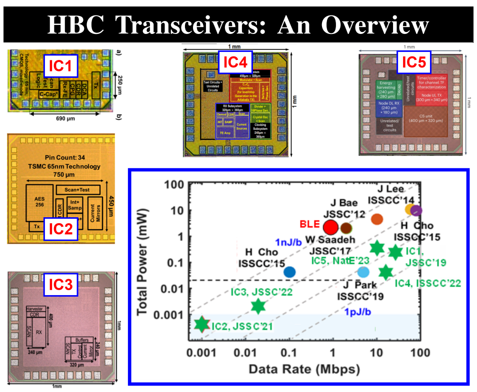


Fig. 2: Prior HBC ICs achieved 10–100 pJ/b efficiency and up to 30 Mbps data rates, using 100× less energy than BLE.

A range of EQS-HBC transceiver integrated circuits (ICs) (as shown in Fig. 2) has been developed in the recent past which are capable of supporting data rates up to 10 Mbps, with power consumption around 500 μW [8]–[11], thereby extending the applicability of this technology to high-throughput implantable devices.

B. Need for Continuous Remote Monitoring in Implants

A recent analysis [12] of Medtronic's CareLink network compatible implants, reveals that the average alert delivery time of 14.8 hours after a cardiac event, with 90.9% of alerts received within 24 hours (as depicted in Fig. 3a). Transmission times were longer for implantable pulse generators (17.0 hours) and cardiac resynchronization therapy pacemakers (CRT-P: 17.2 hours), while implantable cardioverter-defibrillators (ICD: 13.7 hours) and CRT-defibrillators (13.5 hours) had shorter delays. These findings indicate that the current state-of-the-art in remote monitoring typically results in ($\approx$ 1 alert/day), with an average delay of 14 hours—mainly due to connectivity challenges, which remains far from the capabilities of continuous sensing and real-time communication.

It is generally assumed that in-sensor analytics obviates the need for sending the data to the server by processing it locally. However, using the MIT-BIH arrhythmia database [13], we observed that different machine learning models may result in optimal results for different patients, highlighting the need for patient-specific models and/or algorithms, which are costly to implement. Low-power continuous communication from the implant, on the other hand, enables raw data transmission to the cloud where multiple personalized algorithms can be run, leading to more accurate and individualized arrhythmia detection.

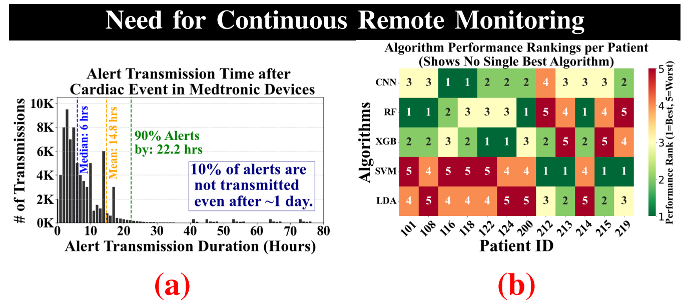


Fig. 3: (a) Medtronic Device Analysis for Transmission Delays [12] (b) Patient-specific variability in optimal algorithm selection for arrhythmia prediction

III. Potential of EQS-HBC for true-Continuous Remote Monitoring in Implants

Traditional RF techniques drastically reduce implant longevity, while EQS-HBC enables reliable and energy-efficient all-day monitoring. This section quantifies the battery life advantages of EQS-HBC over RF techniques.

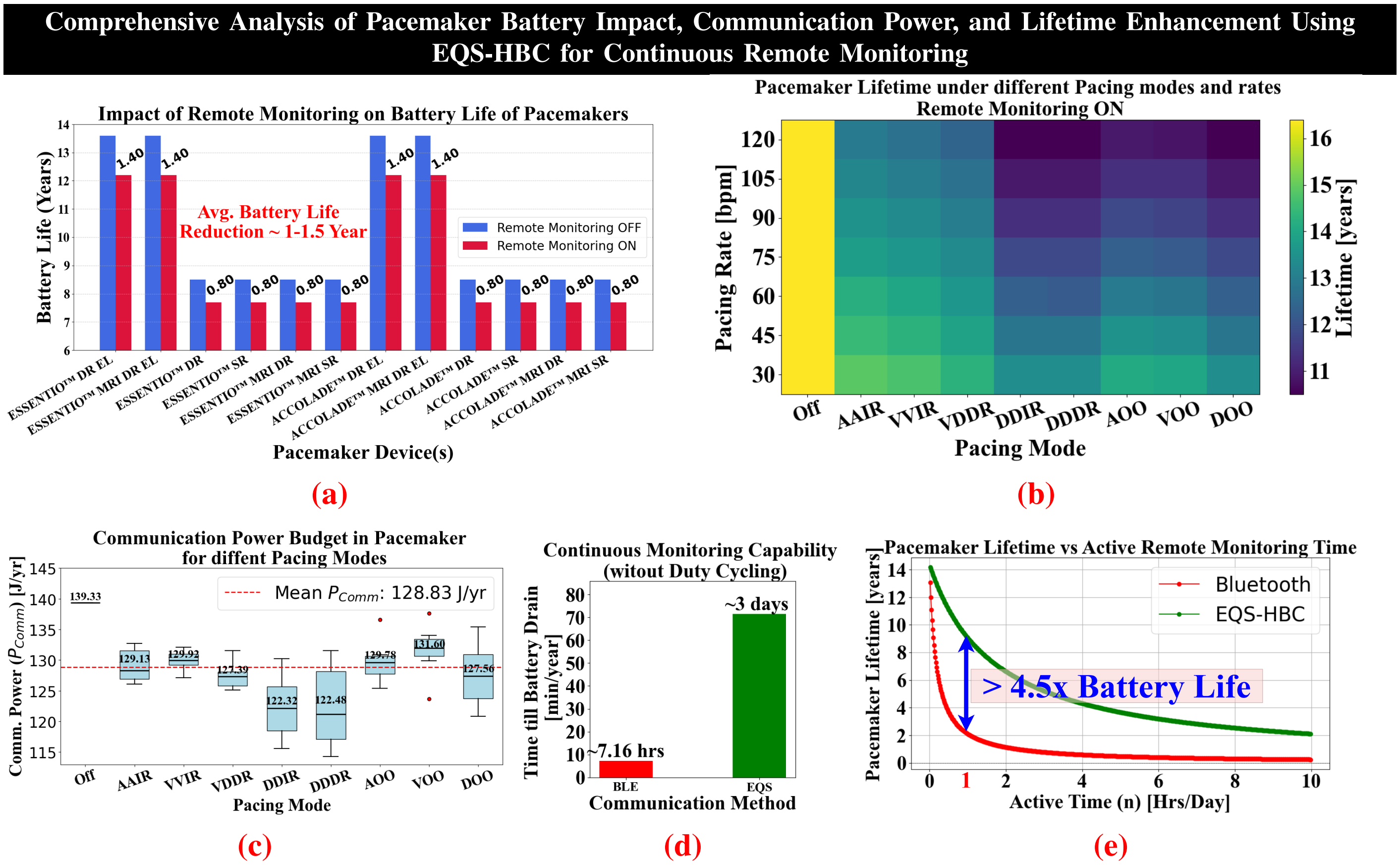
A. Survey on Battery Life of Smart Pacemakers

The plot, as shown in Fig. 4a, illustrates the impact of remote monitoring on the battery life of various Boston Scientific pacemaker models. As shown, enabling remote monitoring leads to a consistent reduction in battery life across all devices. On average, remote monitoring shortens pacemaker battery life by approximately 1–1.5 years (that too with only 1-2 transmissions per day), underscoring the need to carefully consider energy consumption when implementing continuous monitoring features. Data for this analysis was collected from the Boston Scientific Device Longevity Calculator [14].

Fig. 4b shows that higher pacing rates and complex modes (e.g., DDDR/DOO) significantly reduce pacemaker battery life—from over 16 years (in "Off" mode) to about 11 years (in "DDDR" mode)—while simpler modes and lower rates extend longevity. This analysis shows that complex pacing settings and higher rates greatly reduce pacemaker battery life, highlighting the need for reliable, low-energy communication methods like EQS-HBC to enable continuous monitoring without much shortening of device lifespan.

B. Theoretical Analysis of Implant Longevity

To estimate pacemaker lifetime, we conducted a theoretical analysis using power and energy equations, with average power values for the ESSENTIO™ DR EL model (sourced from the BSCI Longevity Calculator [14]).



All data used for plots (Fig. 4a– 4c) are collected from online BSCI Longevity Calculator [14], plots (Fig. 4d– 4e) are created from the data of Longevity Calculator and with the help of Eq. 1– 6.

Fig. 4: (a) Implant lifetime reduction from remote monitoring (b) ESSENTIO™ DR EL lifetime across pacing rates and modes (c) P_{Comm} budget by pacing mode (d) Continous Monitoring Capability (no duty-cycling) (e) Implant longeivity (duty-cycled)

Assuming average pacemaker energy use of $E_{Implant} = 33.5\,\mu J$, the annual power budget is given by Eq. 1. Pacemaker lifetime (Eq. 3) is then determined by battery capacity and the combined implant ($P_{Implant}$) and communication (P_{Comm}) power consumption.

$$\begin{aligned} P_{Implant} &= E_{Implant} \times Time \\ &= 33.5\,\mu J \times (365 * 24 * 3600)\, secs. \\ &= 1057\, J/Year \end{aligned} \tag{1}$$

$$BatteryCapacity = 2.8V * 1.6A - hr * 3600 = 16185\, J \tag{2}$$

$$Lifetime_{Implant} = \frac{BatteryCapacity}{P_{Implant} + P_{Comm}} \tag{3}$$

Also, by rearranging Eq. 3, the communication power budget of the pacemaker can be determined (as per Eq. 4).

$$P_{Comm} = \frac{BatteryCapacity}{Lifetime_{Implant}} - P_{Implant} \tag{4}$$

For this pacemaker, P_{Comm} is calculated (Eq. 4) for various pacing modes and bpm, as shown in Fig. 4c. The battery-capacity is based on a 1.6 A-hr battery at 2.8 V (Eq. 2). Analysis shows the average P_{Comm} budget across modes is 128.8 J/year (see Fig. 4c).

C. Implant Lifetime Comparison: RF vs. EQS-HBC

Now considering BLE energy usage $E_{BLE} = 5\,mW$ and for EQS-HBC average energy usage is $E_{EQS-HBC} = 500\,\mu W$, then the total amount of device lifetime supported in this power budget (of 128.8 J/Year) without duty-cycling can be calculated (as per Eq. 5) as shown in Fig. 4d.

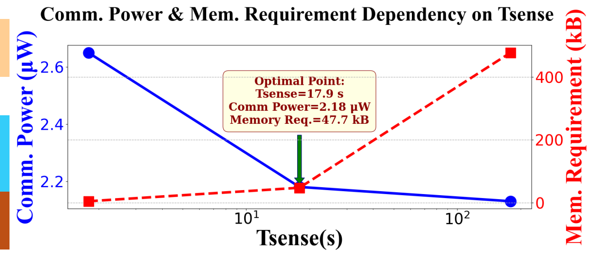
$$Lifetime_{\alpha} = \frac{P_{Comm}}{E_{\alpha}}, \quad \alpha \in \{\text{BLE, EQS-HBC}\} \tag{5}$$

From Fig. 4d, EQS-HBC enables up to 10× longer device lifetime than traditional RF methods like BLE. With duty-cycled communication, true continuous remote monitoring (up to 1 hours/day) is possible without significant lifetime reduction (see Fig. 4e). The implant lifetime under duty-cycling is given by Eq. 6, where (n = daily active communication time).

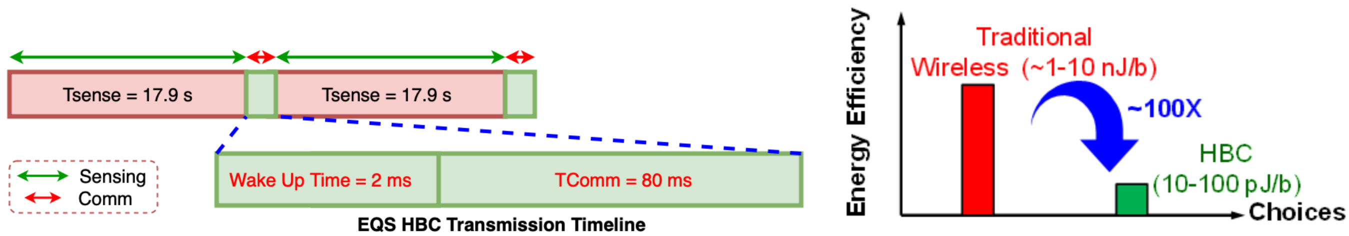
System-Level Co-Optimization of Power and Memory for Continuous Remote Monitoring Using EQS-HBC

EQS HBC Capability for Remote Monitoring	Data Rate (Kbps)	Data Volume	Protocol Packet Efficiency	EQS HBC Data Rate (Kbps)	EQS HBC Wake-up Time (mS)	Sensing Energy (nJ/Samp)	Comm Energy (pJ/bit)
	16	1KSps @ 16 bit	0.75	5000	2	2	100
Raw Data each Comm for Tsense (Kb)	**Mem with Protocol Overhead (KB)**	**T Sense (s)**	**Tcomm (ms)**	**Data Comm (KB)**	**Power Sense (uW)**	**Power Comm (uW)**	**Power with BLE (uW)**
2864	477.3	179	800	500	2	2.13	213
286.4	**47.7**	**17.9**	**80**	**400**	**2**	**2.18**	218
28.64	4.8	1.79	8	40	2	2.65	265

(a)



(b)



(c) **(d)**

Fig. 5: (a) Table: EQS-HBC features and memory/power analysis (b) Optimal sensing/communication point (c) Sensing and communication timeline (d) Energy efficiency: Traditional wireless vs. HBC

$$Lifetime_{Duty-Cycled} = \frac{BatteryCapacity}{P_{Implant} + n * P_{Comm}} \quad (6)$$

D. Proposed Memory and Comm. Power Requirements

Figure 5 shows that with 16-bit, 1 kSps sampling, the system generates 286 kb of raw data in an 18-second sensing period, requiring a 48 kB memory buffer. This data is then can be transmitted via 5 Mbps EQS-HBC at just 500 μW (100 pJ/bit) in an 80 ms window.

With a 2 ms EQS-HBC wake-up latency, duty-cycled average communication power drops to just 2.18 μW—matching the 2 μW sensing power of state-of-the-art ADCs (2 nJ/sample). This power-matched design is a major advance, as continuous BLE monitoring would require about 218 μW, 100× higher (see Fig. 5d), making it impractical for pacemakers. Choosing $T_{\text{sense}} = 17.9$ s (Fig. 5b) minimizes memory needs and keeps data latency at 18 s, enabling continuous, millisecond-resolution monitoring with only 48 kB memory and ultra-low power.

IV. Conclusion

Overall, EQS-HBC marks a major step forward for implantable devices by enabling truly continuous remote monitoring while maintaining battery life. Analytical results show it supports secure, high-throughput data transmission at energy levels up to 100× lower than Bluetooth (500 μW vs. 5 mW), making real-time communication feasible. The optimized system architecture achieves low average power consumption (as little as 2.18 μW for communication and 2 μW for sensing) and supports millisecond-resolution monitoring with only a 48 kB memory footprint. This advancement overcomes the traditional trade-off between device longevity and monitoring frequency, enabling proactive, personalized care and potentially transforming implantable device management.

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