BioPulse: Towards Enabling Perpetual Vital Signs Monitoring using a Body Patch

C.Rajashekar Reddy[1,*], Vivian Dsouza[2], Ashok Samraj Thangarajan[3], Przemysław Pawełczak[2], Fahim Kawsar[3,4], Alessandro Montanari[3]
[1]National University of Singapore, [2]TU Delft, [3]Nokia Bell Labs, Cambridge, [4]University of Glasgow

ABSTRACT

Continuous monitoring of vital signs has become increasingly important for digital healthcare and enhancing self-awareness. Wearable devices like smartwatches, earbuds, and rings are gaining widespread acceptance for health monitoring. However, two significant challenges remain: (i) the limited battery life of these devices makes them unsustainable for long-term use, and (ii) many older adults, who would benefit most from health monitoring, often face barriers due to limited digital literacy. To address these issues, we introduce BioPulse—a perpetual, patch form-factor device designed for continuous monitoring. BioPulse estimates key parameters for cardiac health such as heart rate, heart rate variability, and blood pressure. By utilising a sparse sampling algorithm alongside NFC-based energy transfer and communication, the system operates without a battery, achieving a 57.9% reduction in power consumption. The system demonstrates a mean absolute error of 5.6 mmHg for systolic blood pressure (SBP) and 4.5 mmHg for diastolic blood pressure (DBP) compared to the ground truth device. This combination ensures a more sustainable and accessible solution for vital signs monitoring.

CCS CONCEPTS

• **Hardware → Sensor devices and platforms**; *Sensor applications and deployments*; • **Computer systems organization** → *Embedded hardware*; *Embedded software*.

KEYWORDS

Batteryless, Blood pressure sensing, Sparse Sampling

ACM Reference Format:
C.Rajashekar Reddy[1,*], Vivian Dsouza[2], Ashok Samraj Thangarajan[3], Przemysław Pawełczak[2], Fahim Kawsar[3,4], Alessandro Montanari[3]. 2025. BioPulse: Towards Enabling Perpetual Vital Signs Monitoring using a Body Patch. In *The 26th International Workshop on Mobile Computing Systems and Applications (HOTMOBILE '25), February 26–27, 2025, La Quinta, CA, USA*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3708468.3711891

1 INTRODUCTION

Wearable technology has revolutionized the way we monitor health, offering a convenient way to track vital signs and enabling wider access to health services [16, 19, 27], particularly in regions where traditional healthcare infrastructure is strained. Despite their potential, adoption among the populations that need continuous monitoring, such as the elderly [6, 21], remains limited. One of the primary challenges is energy consumption [28]. Most wearables are battery-powered, and frequent recharging interrupts monitoring. Extended downtime can be problematic, especially if users, particularly older adults, forget to put the device back on after recharging. While fast charging can minimize downtime [21], it accelerates battery degradation, leading to more frequent replacements. Reports estimate that for 1 trillion devices, there will be 913 million battery changes [30]. Given the rapid growth of the wearable and IoT markets, along with the push towards green energy, reaching the 1 trillion mark is not far off. Frequent battery replacements will only exacerbate this issue, raising significant environmental and sustainability concerns.

Although wearables are increasingly integrating new, low-power sensors, many of which perform on-chip computation of vital signs rather than providing raw data for off-board processing, this approach is not applicable to all vital signs. Previous works have effectively reduced the power consumption of sensors such as Photoplethysmogram (PPG) by sampling only specific parts of the signal while accurately measuring parameters such as blood oxygenation, heart rate, and heart rate variability [5, 13, 14]. However, measuring Blood Pressure (BP), one of the fundamental vital signs for cardiac health, is far more complex. Measuring BP requires a multi-modal sensing approach for accurate calculation. In this method, data from the PPG and a microphone are combined in a time synchronous way to calculate Pulse Transit Time (PTT), which is the time taken for the arterial pulse pressure wave to travel between two arterial sites. PTT is then used to estimate BP [31]. However, this approach presents significant challenges for battery-less systems. Additionally, communication and energy harvesting for on-body, battery-less devices present additional challenges, particularly in terms of energy management.

To address these challenges, we introduce BioPulse, a reference platform for continuous, battery-free vital signs monitoring designed for chest application. To achieve battery-free operation, BioPulse utilizes supercapacitors instead of traditional batteries, offering a significantly longer device lifespan and enabling ultra-rapid in-place charging. However, the supercapacitors have lower energy density when compared to conventional batteries, which results in the sensing and communication challenges discussed above. We developed novel algorithms that exploit the properties of vital signs and drastically reduce energy consumption. First, we use a combination of PPG and microphone to compute PTT, and adopt a sparse sampling approach that triggers the sensor to sample only when the required features of the signal are estimated to arrive. Second,

[*]Work done while the author was at Nokia Bell Labs, Cambridge.

HOTMOBILE '25, February 26–27, 2025, La Quinta, CA, USA

ACM ISBN 979-8-4007-1403-0/25/02.
https://doi.org/10.1145/3708468.3711891

to combat the communication and energy harvesting problem, we use NFC-based energy and data transfer.

With BioPulse, we aim to overcome the challenges of time-synchronous sensing and computational demands in a device with a strict energy budget (specifically for blood pressure calculation) and the energy-expensive communication, bringing the vision of battery-free vital signs monitoring closer to reality. We show that BioPulse is capable of continuously monitoring vital signs for up to 24 hours on a single charge, without loss of accuracy, and with 57.9% lower energy consumption compared to traditional sensing algorithms. The key contributions of this paper are threefold: (i) the introduction of a battery-free vital signs monitoring system in a patch form factor; (ii) the development and validation of novel sensing algorithms for blood pressure monitoring that significantly reduce energy consumption; finally, (iii) the implementation of an ultra-rapid in-place charging and data transfer approach.

The remainder of the paper is organized as follows. In Section 2, we provide background and related work on blood pressure monitoring using non-invasive techniques and battery-free wearables. Section 3 describes the design of the body patch and the sparse sampling algorithm for monitoring vital signs, and in Section 4 a reference implementation is provided. In Section 5, we evaluate the performance of the patch. Section 7 provides concluding remarks and future work.

2 BACKGROUND AND RELATED WORK

Hypertension is a major risk factor for cardiovascular diseases such as coronary artery disease and heart failure, as well as cerebrovascular incidents like strokes and transient ischemic attacks. Conversely, hypotension can lead to inadequate blood flow to organs, causing dizziness, syncope (fainting), and even shock in severe cases, therefore monitoring blood pressure is critical. However, such a monitoring device must also consider sustainability for the future, making the move toward battery-free solutions essential. This section provides an overview of the challenges in expanding the adoption of wearables for health monitoring, battery-free solutions in wearables, and previous work on blood pressure monitoring that puts our system within a broader context.

Battery-free Wearables for health monitoring: One of the significant challenges associated with wearables is their energy consumption [28]. As the number of sensors increases, battery depletion accelerates, requiring frequent recharges or replacements and therefore sustainability concerns. Sensors such as Photoplethysmogram (PPG) that are widely used for monitoring vital signs, are particularly energy-intensive. This is due to the need for LEDs and photodiodes to optically obtain a plethysmogram that can be used to detect blood volume changes in the microvascular bed of tissue. This high energy consumption contributes to rapid battery depletion.

Recent research [5, 13, 14] has focused on reducing power consumption using sparse sampling methods in PPG-based monitoring, primarily targeting metrics like heart rate and blood oxygenation, which typically only require a single PPG sensor. Alamouti et al. [5] proposes an on-chip reconstruction-free sparse sampling algorithm to reduce the overall system power consumption by ≈ 70% of the PPG sensors. Ebrahami et al. [13, 14] further improved and presented an adaptive predictive sampling algorithm with a power reduction of ≈ 87%. However, estimating more complex vital signs, such as blood pressure, often requires multi-modal data and synchronized measurements from two PPG sensors or a combination of PPG with other sensors, such as a microphone [7, 31]. Furthermore, these works are still battery powered. BioPulse addresses these issues by optimizing its sampling strategy for blood pressure estimation, enabling measurement on a sustainable batteryless patch.

Cuffless BP Monitoring: Traditionally, BP monitoring relies on cuff-based devices like sphygmomanometers, which are uncomfortable, bulky, and unsuitable for frequent use [29]. Prolonged use can even cause tissue damage, particularly in infants or newborns [17]. Several recent works [7, 8, 20, 31] have explored the use of wearables, such as smartwatches, earbuds, and smartphones, for estimating blood pressure.

PTT is an widely studied approach [11, 15, 26], which measures the time delay between the pulse wave's arrival at two different body sites, such as the wrist and finger, and is correlated to blood pressure. PTT can be measured using PPG sensors [15] placed at different sites like toe-finger, wrist-finger, or wrist-chest. Other approaches [18, 22, 31, 32] have explored multi-modal methods for blood pressure estimation, such as using Pulse Arrival Time (PAT) [9], which measures the time difference between the heart's electrical activity (captured via electrocardiogram (ECG)) or ballistocardiogram (BCG) [22], seismocardiogram (SCG) [32], phonocardiogram (PCG) [31] as substitutes for ECG and the pulse wave. BioPulse uses the PCG and PPG combination to ensure a comfortable and small form factor patch leveraging the hemodynamics of the human body.

On-device Compute and Communication: The sensors used in cuffless BP monitoring, such as PPG and microphones, are energy-intensive [1, 2] and require high sampling rates over extended periods to provide reliable estimates [7, 31]. However, most studies only use certain features extracted from a small portion of the recorded signals. For example, to calculate VTT (Vascular Transit Time), it is sufficient to track the signal peaks [31]. By configuring the device to sample only these critical points and enter a low-power mode the rest of the time, significant power savings can be achieved. Additionally, performing on-device computations to estimate blood pressure from VTT values reduces the amount of data that needs to be transmitted, further lowering communication energy costs. BioPulse applies these concepts alongside NFC-based simultaneous communication and energy transfer for a batteryless, continuous blood pressure monitoring system.

3 BioPulse DESIGN

The design of BioPulse is centered around two core principles: *sustainability* and *convenience*. These principles dictate that the device must operate with minimal energy consumption while maintaining a small, comfortable form factor suitable for everyday use. However, achieving this balance presents significant challenges. Vital signs necessary for effective ambulatory monitoring—such as heart rate, blood pressure, and respiration, require complex computations and substantial memory, which increases the device's energy demands.

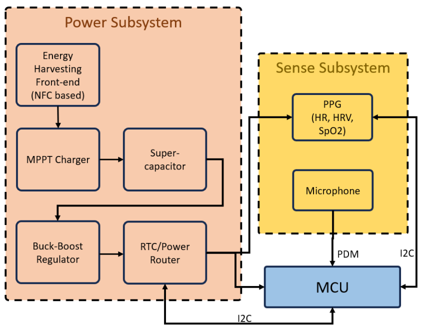


Figure 1: Hardware design block diagram.

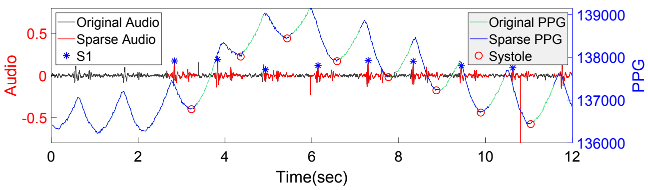


Figure 2: Simulated sparse sampling approach.

As a result, the following challenges must be carefully considered in the design of BioPulse to ensure it remains functional, efficient, and user-friendly:

- Some vital signs require multi-modal data, sampled at high data rates over extended periods. This necessitates processing the entire sensor buffer in a single pass, which significantly increases the computational, memory, and energy demands on the device.
- The need for a compact form factor limits sensor placement, making it challenging to accurately measure certain vital signs using traditional methods due to sub-optimal sensor positioning.
- A batteryless system introduces the challenge of energy harvesting, which requires a reliable energy source and must minimize energy-intensive operations, such as frequent wireless communication.

In the sections below, we will describe how BioPulse addresses these challenges with a novel sparse sampling algorithm that leverages the characteristics of vital signs, the principles of hemodynamics, and an innovative approach of simultaneous energy harvesting and data transfer.

3.1 Design Strategies for Overcoming Key Challenges

Figure 1 illustrates the reference hardware design of BioPulse. The subsequent sections describe the principles and considerations that guided the design of BioPulse.

3.1.1 Efficient Handling of Multi-modal Data. For measuring blood pressure using VTT, BioPulse uses time synchronous sampling from microphone and PPG sensor, with a sample window of 12 seconds. For example, PPG sampled at 100 Hz at 4 bytes per sample and microphone sampled at 16 kHz at 2 bytes per sample will generate 4.8 KB and 384 KB of data respectively for a 12 second

---

Algorithm 1 Sparse Sampling for PPG and Audio Signals

Initialize PPG (Sampling frequency = f_{ppg}) and MIC (Sampling frequency = f_{mic})
Collect PPG sensor data for $\mathrm{dur}_{\mathrm{HR}}$ with MIC OFF
▷ *Default $dur_{HR} = 3$ s*

▷ **Heart Rate Estimation**
$loc, peaks \leftarrow findpeaks(\text{PPG Signal})$
▷ *Assume Max. HR = 200 bpm*
$HR \text{ (Heart Rate)} = \frac{(f_{\mathrm{ppg}} \times 60)}{\mathrm{mean}(\mathrm{diff}(\mathrm{peak}_{\mathrm{loc}}))}$

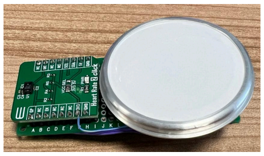
▷ **Initialize Sparse Sampling**
Set $guard_{\mathrm{win}}$ and calculate $skip_{\mathrm{mic}}$, $skip_{\mathrm{ppg}}$
$skipw_{\mathrm{mic}} = (p_m \times \frac{60}{HR}) + guard_{\mathrm{win}}$
$skipw_{\mathrm{ppg}} = (p_p \times \frac{60}{HR}) + guard_{\mathrm{win}}$ ▷ *Default $p_m, p_p = 0.5$*
$sparsew_{\mathrm{mic}} = \frac{60}{HR} - skipw_{\mathrm{mic}}$
$sparsew_{\mathrm{ppg}} = \frac{60}{HR} - skipw_{\mathrm{ppg}}$
Set $pivot = loc[\mathrm{end}]$ ▷ *Time instant of last PPG peak*

▷ **Sparse Sampling**
while time < dur_{meas} **do**
▷ *Default $dur_{meas} = 12sec$*
  MIC and PPG in sleep mode for $skipw_{\mathrm{mic}}, skipw_{\mathrm{ppg}}$ time
  Sample MIC and PPG for $sparsew_{\mathrm{mic}}$ and $sparsew_{\mathrm{ppg}}$ time
  Append $loc_{\mathrm{mic}} \leftarrow findpeaks(\text{MIC Signal})$
  Append $loc_{\mathrm{ppg}} \leftarrow findpeaks(\text{PPG Signal})$
  Update $pivot = loc_{\mathrm{ppg}}[\mathrm{end}]$
  Convert loc_{ppg} to audio sampling rate
  Append $VTT \leftarrow loc_{\mathrm{ppg}} - loc_{\mathrm{mic}}$
Calculate the BP estimate using the VTT array

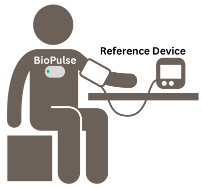
---

window, which cannot be handled by typical low power microcontrollers that have few hundred KB of RAM. To overcome this, BioPulse introduces a sparse sampling algorithm, where we exploit two properties of heart rate: (i) heart rate is periodic, (ii) heart rate does not change rapidly. While, we draw inspiration from the previous works [5, 13] where they implement predictive sampling to reduce the power consumption of PPG sensors, our requirement adds further complexity of synchronous sparse sampling for both PPG and audio signal. Figure 2 show the simulation of the sparse sampling algorithm. Only PPG is switched on for the first 3 seconds from which heart rate is calculated. From the calculated heart rate a *jump window* is estimated for when the next first heart sound (S1) will arrive. Until this point both sensors are switched off or put to low-power mode. After the jump window time has passed, both sensors are switched on for a period of *collection window* that ensures the heart sound and the systolic peak of PPG are captured. The jump window and the collection window are continuously adjusted when the algorithm captures the S1 peak and the systolic peak, thereby adjusting for any minor drifts. More importantly, in the sparse sampling approach, the need for extensive signal filtering, as required in traditional approaches [7, 31], is minimised. This is due to the smaller sampling window, which reduces the likelihood of noise within the window. The sparse sampling algorithm is listed in Algorithm 1.

3.1.2 Optimising Sensor Placement Challenges with Hemodynamic Insights. Non-invasive blood pressure measurement is achieved by



(a) Prototype



(b) Setup

Figure 3: BioPulse prototype and evaluation setup. White circular membrane (taken from PatchKeeper [4]) hosts a microphone; PCB on the left contains MAXM86161 [2] PPG sensor.

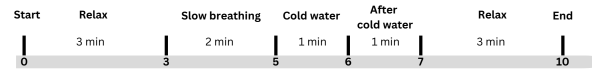
calculating the VTT, as explained in the previous sections. To perform this measurement, two sensors must be positioned at different locations: one to detect the heart sound on the chest and another, such as a PPG sensor, to measure pulse arrival at a finger. This ensures that the sensors are far apart from which a measurable time travelled can be calculated. However, in case of BioPulse, to ensure the patch remains compact and comfortable, it should be localized to a small area on the body. BioPulse uses the green LED of the PPG to detect the blood flow, which reaches the upper dermis and is reflected by the capillary blood vessels. We argue that the PPG measured pulse arrival from capillary blood vessels will have a delay from the observed heart beat sound, the time difference of which will be correlated to the blood pressure. Consequently, the calculated blood pressure reflects peripheral blood pressure, similar to readings from a sphygmomanometer. In Section 5, we show the effectiveness for monitoring blood pressure using this position.

3.1.3 Energy-Communication Conundrum. Wireless communication is energy-intensive, a challenge that is magnified in batteryless IoT devices due to their limited energy resources. BioPulse handles all of the computation on-board with optimised algorithms discussed in Section 3.1.1 and adopts a solution based on NFC, which enables BioPulse to both harvest energy and transmit processed data from the node to the host device, simultaneously. Given that the device operates on capacitors with low energy density, NFC enables rapid charging, allowing the device to quickly regain power while still attached to the body.

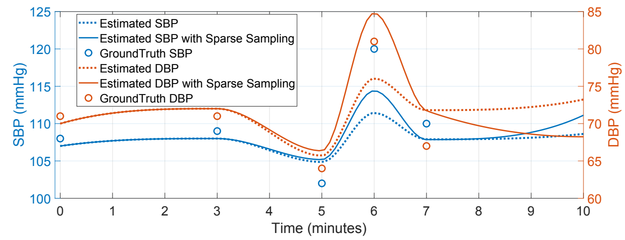
4 BioPulse IMPLEMENTATION

Figure 3(a) shows the BioPulse prototype that we used for experiments. The BioPulse components are selected with a core focus on low power consumption and maximizing the computation performed locally within the sensors to minimize the load on the main microcontroller unit (MCU). The BioPulse utilizes the Nordic nRF52840 [3] as its primary MCU. This MCU features a Cortex-M4F processor running at 64 MHz, with 1 MB of flash memory and 256 KB of RAM.

The BioPulse prototype that we built for experiments consists of MAXM86161 [2] PPG sensor that includes three LEDs and a photodiode, offering fine-grained configuration control. The microphone included is the IM69D130 [1] MEMS digital microphone clocked by the nRF52840's PDM module at 1.8 MHz. The PDM module is configured to output a 16 kHz PCM signal, which is the audio sampling rate used in the algorithms. The microphone is mounted on a chest piece designed to capture and amplify heart sounds. This chest piece design is adapted from PatchKeeper [4].



(a) User study protocol



(b) Collected user data

Figure 4: Estimated BP variation during the data collection with respect to the ground truth values.

We emphasize that the current BioPulse prototype is powered externally, while a separate NFC-powered energy provision unit is developed and evaluated to assess whether it can supply BioPulse with enough energy for operation. NFC-based power supply will become integrated with the rest of BioPulse at a later stage.

5 BioPulse EVALUATION

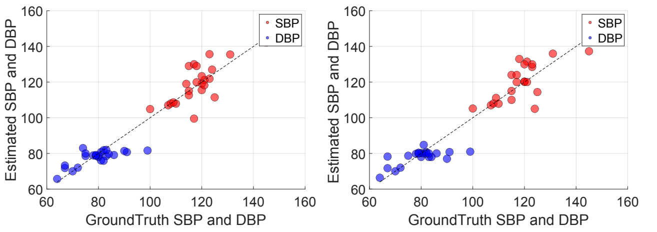
We recruited six healthy participants, none of whom had a history of heart or blood pressure conditions. Each participant was thoroughly briefed on the study and provided voluntary informed consent to participate.

Study Protocol: The participants were asked to place the prototype on their chest with the chest piece positioned above the base of the heart and the PPG closer to the sternum as shown in Figure 3(b). The participants had a cuff for BP measurement on their left arm. We used the Omron M7 Intelli IT [25] to measure BP as the ground truth. During the entire experiment, the participants remained seated with their feet flat and their backs supported. To induce temporary changes in BP, participants were asked to perform two major activities to observe the changes in the BP. The first involved taking slow, deep breaths, which has been shown to lower BP [24]. The second activity involved raising BP temporarily by immersing the right hand in cold water called the cold pressor test [23]. Figure 4(a) shows the protocol followed for the data collection. The ground truth BP measurements were taken before and after each activity resulting in six data points per participant.

5.1 Blood Pressure Accuracy

Figure 4(b) illustrates the timeline of the various phases of our experiment. The plot shows that the estimated blood pressure closely follows the trend recorded by the sphygmomanometer throughout the test, which confirms the argument in Section 3.1.2. Notably, the sparse sampling approach captures significant fluctuations in blood pressure more accurately compared to traditional methods [31] that estimate blood pressure using VTT.

Figure 5 reports the correlation between the ground truth values and blood pressure estimates obtained using BioPulse. The plot demonstrates that BioPulse aligns well with the ground truth values. In Figure 5(a), it can be observed that the VTT calculated



(a) Without sparse sampling. (b) With sparse sampling.

Figure 5: Blood pressure estimation results. (a) Correlation between estimated SBP and DBP values using BioPulse with the ground truth blood pressure values. (b) Correlation between estimated SBP and DBP using BioPulse with sparse sampling with the ground truth.

Table 1: Comparision of BP estimation approaches.

Approach	**Participants**	**SBP MAE (mmHg)**	**DBP MAE (mmHg)**
Truong et al. [31]	10	4.07	5.61
Stereo-BP [7]	20	3.97	3.83
BioPulse	**6**	**5.05**	**4.13**
BioPulse (Sparse Sampling)	**6**	**5.61**	**4.50**

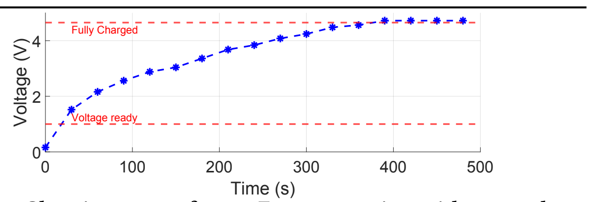


Figure 6: Charging curve of a 0.47 F supercapacitor with energy harvested from a smartphone.

on the chest using the traditional method also reflects the ground truth, supporting the argument made in Section 3. Furthermore, the implementation of the sparse sampling algorithm, as detailed in Algorithm 1, which does not require any additional filtering, shows that the estimated values still correlate with the ground truth (Figure 5(b)). The mean absolute error for both cases across participants is presented in Table 1 and is notably close to the values reported in previous approaches.

5.2 Energy Harvesting and Communication

To enable energy harvesting, communication, and non-volatile storage, we use the ST25DV04K NFC tag. This chip harvests energy via NFC from a reader, such as a smartphone. For our evaluation, we utilize a Google Pixel 6A in combination with the PCB antenna on the X-NUCLEO-NFC04A1 evaluation board. The energy harvested is stored in a 0.47 F supercapacitor [12], managed by the AEM30330 energy harvester. Using the buck-boost converter, the capacitor provides operating voltage in 16 seconds and is fully charged in 6 minutes, as seen in Figure 6. Over a 24-hour period, if the device samples once per hour, it will generate 144 bytes of data to store heart rate, heart rate variability, SpO2, and blood pressure. The 8 KB of on-chip non-volatile memory is used to store these measurements and can be accessed via a smartphone. Data is read out simultaneously when the smartphone is brought close to the tag for charging.

5.3 Energy Consumption

For the energy consumption analysis, we consider a 0.47 F supercapacitor [12] and assume a sensing window of 10 seconds for every blood pressure measurement, with BioPulse being recharged daily. We assumed a resting heart rate of 80 beats per minute, as the increase in heart rate will proportionally increase the duration the sensors are powered on and therefore the energy consumption. Capacitors typically exhibit significant leakage, and as the charge depletes, the capacitor's voltage drops, which in turn affects the efficiency of the regulator. To account for this, we assume a 30% effective capacity and a regulator efficiency of 80% in our calculations. For a single blood pressure measurement the sparse sampling approach reduces the energy consumption by 57.9%. Without the sparse sampling approach, BioPulse can perform 25.12 measurements, while with sparse sampling the number of measurements that can be performed drastically increased to 59.67 measurements, a 137.5% increase in the number of measurements over a 24-hour period.

6 DISCUSSION

On the practicality of BioPulse: BioPulse integrates sparse sampling and NFC-based energy harvesting into a compact, patch-style device, offering significant potential for continuous health monitoring. However, practical deployment in real-world applications requires addressing challenges such as sensor placement and motion artifacts. PPG signals can degrade significantly during motion, leading to inaccuracies in dynamic conditions. To mitigate this, future iterations of BioPulse will incorporate an inertial measurement unit (IMU) to detect and compensate for motion. By combining motion data with physiological signals, the system will differentiate valid signals from noise, ensuring accurate readings during everyday activities.

Traditional cuffless methods based on PTT and PTD require two sensors to calculate the time difference [7, 29], necessitating the use of separate devices. BioPulse overcomes this limitation by co-locating the PPG and microphone sensors, enhancing usability. We hypothesize that the volumetric changes observed from the PPG using reflective spectrometry are derived from capillary vessels, providing the desired time difference between the acoustic signature captured by the microphone and the blood volume changes detected by the PPG as detailed in Section 3.1.2 and evaluated in Section 5.1. While the current evaluation relied on careful placement of the device, we acknowledge that such precision may not always be feasible in real-world settings. Future work will identify optimal placement positions and develop algorithms to provide real-time feedback, guiding users to adjust the device as needed for accurate measurements.

This study validated the feasibility of the sparse sampling algorithm and energy-efficient platform under controlled conditions, using external power for simplicity. While this approach successfully demonstrated the concept, it limits the system's autonomy. Future iterations will fully integrate the NFC-based energy module and evaluate user experiences over extended durations. Additionally, the mechanical design of the patch will be refined to ensure consistent sensor placement and improved comfort, making BioPulse more practical for diverse populations and prolonged use.

User Study: As this work is in its early stages, the evaluation was conducted on a limited sample of six healthy participants under controlled conditions. While the study successfully demonstrates the feasibility of the sparse sampling algorithm and the batteryless BioPulse platform, its primary focus was not on benchmarking BP estimation, as these principles have been extensively validated in prior research. Consequently, the study did not include individuals with extreme blood pressure values or cardiovascular conditions, limiting the generalizability of the results. Furthermore, factors such as cardiac arrhythmias or medications like blood thinners may influence blood pressure accuracy [10]. Future studies will expand the participant pool to include diverse health profiles and evaluate the system's performance under real-world conditions, such as during physical activity or extended use, to ensure robustness and applicability across varied scenarios.

7 CONCLUSION AND FUTURE WORK

In this work, we introduced BioPulse, a wearable system that leverages a sparse sampling approach, on-board computation, and NFC-based energy harvesting and communication to enable batteryless vital signs monitoring in a patch form factor. Adopting a sparse sampling algorithm significantly reduces the sensing and processing overhead, thereby reducing the energy consumption by 57.9%, while maintaining the accuracy within a mean absolute error of 5.6 mmHg for SBP and 4.5 mmHg for DBP. The use of NFC for both power harvesting and data communication eliminates bulky batteries, offering a sustainable solution for long-term health monitoring. BioPulse represents a step towards fully autonomous wearable devices, supporting cardiovascular health tracking while holding the potential for monitoring pathological abnormalities such as heart murmurs and arrhythmias. Furthermore, the patch design opens avenues for continuous monitoring of cardiac, pulmonary, and gastrointestinal sounds, enabling early diagnosis of conditions affecting the heart, lungs, and bowel.

ACKNOWLEDGMENTS

We thank our shepherd, Rajalakshmi Nandakumar, and the anonymous reviewers for their insightful comments. C. Rajashekar Reddy is partially supported for travel by an unrestricted gift awarded to Ambuj Varshney through the Google Research Scholar Program (A-8002307-00-00), hosted at the National University of Singapore.

REFERENCES

[1] 2017. *IM69D130 High performance digital XENSIV MEMS microphone.* https://www.infineon.com/dgdl/Infineon-IM69D130-DataSheet-v01_00-EN.pdf?fileId=5546d462602a9dc801607a0e46511a2e

[2] 2023. *MAXM86161 Single-Supply Integrated Optical Module for HR and SpO2 Measurement.* https://www.analog.com/media/en/technical-documentation/data-sheets/maxm86161.pdf

[3] 2024. Nordic Semiconductor nRF52840 Product Specification v1.10. https://docs.nordicsemi.com/bundle/ps_nrf52840/page/keyfeatures_html5.html#:~:text=nRF52840%20Product%20Specification%20v1.10

[4] 2024. The Patchkeeper: An Integrated Wearable Electronic Stethoscope with Multiple Sensors. *arXiv preprint arXiv:2407.11837* (2024).

[5] Sina Faraji Alamouti et al. 2022. A Sparse Sampling Sensor Front-End IC for Low Power Continuous SpO_2 HR Monitoring. *IEEE Trans. on Biomedical Circuits and Systems* 16, 6 (2022), 997–1007.

[6] Mirza Mansoor Baig et al. 2019. A Systematic Review of Wearable Sensors and IoT-Based Monitoring Applications for Older Adults — a Focus on Ageing Population and Independent Living. *J. Med. Syst.* 43, 8 (Aug. 2019), 1–11.

[7] Ananta Narayanan Balaji et al. 2023. Stereo-BP: Non-Invasive Blood Pressure Sensing with Earables. In *Proc. of the 24th International Workshop on Mobile Computing Systems and Applications* (Newport Beach, California) *(HotMobile '23)*. Association for Computing Machinery, New York, NY, USA, 96–102.

[8] Nam Bui et al. 2019. eBP: A Wearable System For Frequent and Comfortable Blood Pressure Monitoring From User's Ear. In *The 25th Annual International Conference on Mobile Computing and Networking* (Los Cabos, Mexico) *(MobiCom '19)*. Association for Computing Machinery, New York, NY, USA, Article 53, 17 pages.

[9] W. Chen et al. 2000. Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. *Medical & Biological Engineering & Computing* 38 (2000), 569–574.

[10] Yang Chen et al. 2020. Validation of Pulse Transit Time Based Blood Pressure Estimation on Atrial Fibrillation Patients. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 2679–2682. https://doi.org/10.1109/EMBC44109.2020.9176221

[11] Xiaorong Ding et al. 2017. Pulse transit time based continuous cuffless blood pressure estimation: A new extension and a comprehensive evaluation. *Scientific reports* 7, 1 (2017), 1–11.

[12] Eaton. 2019. *PM Supercapacitors - Technical Data.* Retrieved 10 October, 2024 from https://www.eaton.com/content/dam/eaton/products/electronic-components/resources/data-sheet/eaton-pm-supercapacitors-cylindrical-pack-data-sheet.pdf

[13] Zobair Ebrahimi et al. 2024. A Low-Power Predictive Sampling PPG Sensor. In *2024 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 1–5.

[14] Zobair Ebrahimi et al. 2024. An Ultralow-Power PPG Sensor With Adaptive Predictive Sampling. *IEEE Sensors Journal* 24, 9 (2024), 14137–14150.

[15] Mohamed Elgendi et al. 2019. The use of photoplethysmography for assessing hypertension. *NPJ digital medicine* 2, 1 (2019), 60.

[16] Alessandro Montanari et al. 2024. OmniBuds: A Sensory Earable Platform for Advanced Bio-Sensing and On-Device Machine Learning. arXiv:2410.04775 [cs.ET] https://arxiv.org/abs/2410.04775

[17] N. Pilz et al. 2024. Cuff-based blood pressure measurement: challenges and solutions. *Blood Pressure* 33, 1 (2024), 2402368. https://doi.org/10.1080/08037051.2024.2402368 PMID: 39291896.

[18] Winokur et al. 2012. A wearable vital signs monitor at the ear for continuous heart rate and pulse transit time measurements. In *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2724–2727.

[19] Andrea Ferlini et al. 2021. In-ear PPG for vital signs. *IEEE Pervasive Computing* 21, 1 (2021), 65–74.

[20] Lorenz Frey et al. 2022. Blood pressure measurement using only a smartphone. *npj Digital Medicine* 5 (07 2022), 86.

[21] Asangi Jayatilaka et al. 2019. Designing batteryless wearables for hospitalized older people. In *Proc. of the 2019 ACM International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 91–95.

[22] Chang-Sei Kim et al. 2015. Ballistocardiogram as proximal timing reference for pulse transit time measurement: Potential for cuffless blood pressure monitoring. *IEEE Trans. on Biomedical Engineering* 62, 11 (2015), 2657–2664.

[23] S Mishra et al. 2012. Blood pressure response to cold water immersion test. *International Journal of Biology, Pharmacy and Allied Sciences* 10 (2012), 1483–1491.

[24] Hisao Mori et al. 2005. How does deep breathing affect office blood pressure and pulse rate? *Hypertension research* 28, 6 (2005), 499–504.

[25] Omron. 2016. *Omron M7 Intelli IT Product Information.* Retrieved 10 October, 2024 from https://www.frafito.net/Transfer/00%20-%20DOCUMENTATION/21%20-%20OLD%20OHE/M7%20IT/5-%20Divers%20doc/PM-1463-01-04-2016%20HEM-7322T-E.pdf

[26] RA Payne et al. 2006. Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure. *Journal of Applied Physiology* 100, 1 (2006), 136–141.

[27] Julia Romero et al. 2024. OptiBreathe: An Earable-based PPG System for Continuous Respiration Rate, Breathing Phase, and Tidal Volume Monitoring. In *Proceedings of the 25th International Workshop on Mobile Computing Systems and Applications*. 99–106.

[28] Patrick C Shih et al. 2015. Use and adoption challenges of wearable activity trackers. *IConference 2015 proceedings* (2015).

[29] Josep Solà and Ricard Delgado. 2019. *The Handbook of Cuffless Blood Pressure Monitoring A Practical Guide for Clinicians, Researchers, and Engineers.*

[30] Abishek Swaminathen. 2022. *The massive environmental cost of batteries.* Retrieved 10 October, 2024 from https://www.onio.com/article/environmental-cost-of-batteries.html

[31] Hoang Truong et al. 2022. Non-invasive blood pressure monitoring with multi-modal in-ear sensing. In *ICASSP 2022-2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE, 6–10.

[32] Chenxi Yang et al. 2016. Pulse transit time measurement using seismocardiogram and in-ear acoustic sensor. In *2016 IEEE Biomedical Circuits and Systems Conference (BioCAS)*. IEEE, 188–191.