VitalPod: A Low Power In-Ear Vital Parameter Monitoring System

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***Abstract*—Monitoring of physiological parameters support early detection, prevention, and management of adverse healthcare related events. In-ear wearable sensor nodes that track changing bio-physiological signals can be advantageous over traditional monitoring methods in being compact, unobtrusive, and inconspicuous, increasing their appeal. However, in-ear ergonomics place rigid constraints on a device's physical design and size, limiting battery lifetime and restricting the incorporation of multiple sensor modules. This work presents the design and implementation of the wireless hearable VitalPod, an in-ear multi-vital sign monitor that measures heart rate (HR), respiratory rate (RR), blood oxygenation (SpO2), skin temperature and activity. The VitalPod is designed with low power and energy efficiency in mind, using novel sensing integrated circuits and processing modules that achieve operational longevity of up to 42 hours using a small form factor 32mAh rechargeable Li-ion polymer battery. It has a compact design and form factor, similar to many commercial wireless earbuds, featuring hardware required for wireless music playback using a standard balanced armature driver in addition to vital sign monitoring sensors. Experimental results show high performance in estimating vital signs for HR (-0.061± 1.12 beats per minute), RR (0.87±1.48 breaths per minute) and change in SpO2 (0.21±0.82%). Additionally, the presented work also evaluates the positional placement of sensors in the ear to reduce the effect of motion induced artifacts.**

***Index Terms*—hearable, in-ear, vital sign monitoring, health monitoring, low power system**

I. Introduction

Physiological functioning of an organism is objectively assessed by measuring vital signs such as heart rate, respiratory rate, blood oxygenation and body temperature. Continuous monitoring of vital parameters has immense potential in both clinical environments and at-home settings by providing a method for regulating personal health decisions, enhancing the quality of care and enabeling pre-emption of adverse events by early detection [1]. Technological advancements have made it possible to design multiple sensing modalities in compact wearable form factors, thereby making such measurements safe, non-invasive, unobtrusive, and comfortable [2].

Many different population groups greatly benefit from continuous monitoring of vital signs [3]. In an increasing geriatric population, in-ear sensing with the amalgamation of hearing aids could greatly assist care givers in monitoring temporal changes in health to provide timely intervention [4]. Similarly, a better quality of life and care can be provided for paraplegic and tetraplegic patients by understanding the underlying changes in physiology using vital sign data of high temporal density. In addition, increasing attention to fitness and a rising prevalence of chronic diseases such as diabetes and hypertension are necessitating the development of systems that can be worn on the body inconspicuously [5] [6].

A major challenge in the design of wearable miniaturized IoT devices for monitoring health via vital signs is the need for long-lasting operation with small form-factor energy storage [7]. This is even more restrictive when the wearable device is placed in-ear as the limited space in or around the ear entails designing a system with a compact form factor, and hence, even smaller battery capacity than other wearbles, such as smart watches. This, in turn, necessitates regular battery replacement or periodic charging [8] [9] which can result in an interruption in normal usage and loss of potentially critical data on the physiological state of the subject. Also, there is an added overhead for maintenance costs and environmental consequences related to battery disposal [10]. Moreover, stringent space restrictions impose limitations on the number and size of sensor modules that can be used for extracting different vital parameters. Another major impediment to reliable physiological monitoring with hearables is the increased susceptibility to artifacts induced by motion [11] [12] [13]. Wearable sensing extracts vitals from the surface of the body by means of electrical (i.e. ECG Heart Rate sensing [14]), optical (i.e. PPG Heart Rate and SpO_2 sensing [15]), or chemical bio-sensing (i.e. Blood Glucose Monitoring [16]). All these methods require transducers, such as electrodes and photo detectors, to be attached to the body's surface [17]. The ear region is subjected to not only motion artifacts due to ambulatory conditions such as walking, running and movement of the head but also local jaw motion during chewing and talking [18].

This work presents an in-ear sensor node VitalPod (VP) that can measure multiple vital signs such as heart rate, respiratory rate and blood oxygenation simultaneously in a long-lasting fashion. The VP is a power efficient system that exploits the most advanced hardware and software low power design

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for long duration vital sign monitoring. Using state of the art sensing and processing modules, VP was packaged in a small form factor that can easily be incorporated in an adult ear cavity. The Apollo 4, a cutting edge, ultra-low-power, 5μA /MHz ARM Cortex-M4F processor from Ambiq Micro with aggressive power management allow for high performance with long battery lifetimes. The main contributions of this paper are:

- Design and implementation of an energy efficient in-ear sensor node with a compact housing footprint and small battery size. The system exploits the novel Apollo 4 processor for high energy efficiency and wireless capabilities.
- Experimental evaluation of sensor node accuracy when extracting HR, RR and SpO_2 using in-ear PPG sensors.
- Experimental evaluation of system design to optimize placement of sensors in the ear cavity for enhanced robustness against artifacts.
- Experimental evaluation of system power to ensure long-term operation, achieving 2 days of continuous work with a single battery charge.

II. Related Work

Hearable technology has received a huge impetus for development in the recent years due to various scientific advancements and market forces [11] Research with photoplethysmography (PPG) sensors for in-ear vital sign monitoring to provide HR estimation [19] [20] shows good correlation from chest extracted or finger extracted HR, demonstrating the feasibility of HR monitoring in ear with PPG. The feasibility of measuring in-ear ECG was also demonstrated in [21] but the authors do not report a portable or wireless device that could be used for remote monitoring. Commercially available systems such the Bose sound sport pulse [22] and Jabra Pulse [23] provide only pulse rate estimation during sporting activity. These devices show a correlation coefficient ranging from R^2 of 0.62 to R^2 of 0.94 for different defined activities during the experimental protocol and provide 4.5 to 5 hours of continuous usage. However, very few systems provide multi-vital sign monitoring features for in-ear applications while also providing sound playback capabilities. Cosinuss One is an in-ear vital sign monitor that claims to monitor multiple vital signs such as HR, RR, and SpO_2 [24], but so far literature validating it's performance exists only for HR estimation and shows that results are accurate but imprecise due to the susceptibility to motion artifacts [25]. Furthermore, the device does not include additional modules like a speaker or microphone which would enable music playback or could be desirable for hearing aids for geriatric or paraplegic patients. It is also larger than many commercial true-wireless earphones, requiring a behind-the-ear module. To the best of the authors knowledge, there is no other device in published literature or commercially available that provides multi-vital sign monitoring (HR, RR and SpO_2) along with the inclusion of an audio speaker and microphone in a comfortable wireless form factor and without the need for a behind-the-ear module, that can provide multiple hours of operation.

III. System Description

A. System Overview

The system architecture of the VP sensor system is shown in Fig. 1. At the center sits a low-power, high-performance Apollo 4 Blue SoC from Ambiq Micro incorporating an ARM Cortex-M4F micro controller and Bluetooth Low Energy (BLE) 5.1 RF front-end. A Panasonic CG-425A 32mAh Li-ion battery is used as energy storage, and a MAX77651B power-management IC handles both battery management and charging, while also providing all system power rails using it's triple-output, single inductor switch mode power supply and LDO regulator. The system supports an audio codec (MAX98090A) driving a standard balanced armature speaker, digital microphone (ICS-41351), and a bone conduction microphone. Multiple vital sign monitoring was implemented using a body temperature sensor (MAX30208), a photoplethysmography (PPG) module (MAX30101) with three LED wavelengths at 537nm (green), 660nm (red) and 880nm (infrared) and a photo-diode to measure the reflected light, and a charge variation and inertial measurement unit (LS6DSV16X).

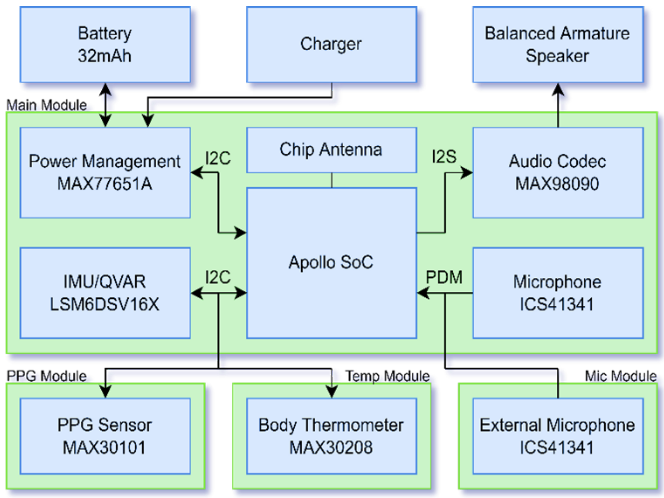

Fig. 1. System architecture of the power efficient wireless in-ear multi-vital sign monitor.

B. Power Management-Lifetime Considerations

Battery lifetime is a key performance metric of the wearable system and needs to be conducive to the application scenario. For consumer electronics and sports applications, the usage of the system is sporadic and for short durations of time, whereas for clinical usage or at home monitoring of at-risk population groups, a temporally dense data collection necessitates long term operation. This is especially critical for in-ear sensing and energy efficiency needs to be considered at every design phase. State-of-the-art low power integrated circuits, novel architecture, and low-power design techniques

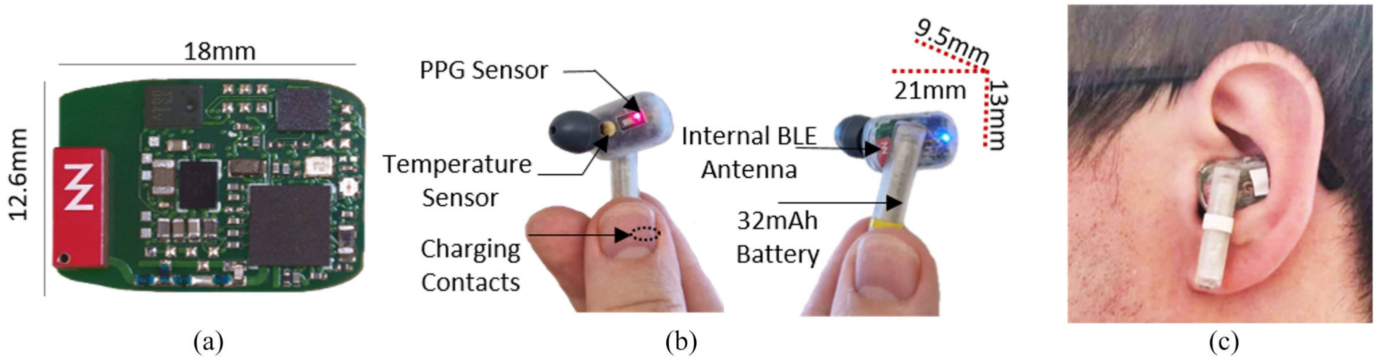

Fig. 2. (a) Main PCB with processing and power management units. (b) Assembled VitalPod sensor system with PPG sensor, temperature sensor, charging contacts and battery stem (32 mAh) in a compact modular form of 13 mm × 21mm ×9.5mm. (c) The VitalPod worn in-ear during measurements.

such as power duty cycling allow long operational duration with a single charging cycle [26] [27]. Power cycling disables sub-systems when they are not needed, thereby reducing the overall power consumption significantly. On the software side, all processing and control of the subsystems is handled by means of a real-time operating system (FreeRTOS) to allow the Cortex-M4F to stay in sleep mode as often and for as long as possible.

C. Hearable Design

The electronic design of the sensor node is optimized for use in hearable systems. Fig. 2(a) shows the layout for the core circuit featuring the Apollo micro-controller unit, battery management and wireless control systems. The entire in-ear sensor system excluding the external battery stem has a compact form factor of 13mm × 21mm × 9.5mm. Fig. 2(b) shows the assembled VitalPod with the battery stem, charging contacts, internal BLE antenna, PPG sensor and temperature sensor positions and Fig. 2(c) shows the VitalPod worn in the ear cavity.

IV. Methods

A. Experimental Methods

The VitalPod used the PPG sensor in the ear cavity with a sampling frequency of 50Hz. The raw sensor data was transmitted via Bluetooth, and processed afterwards. The VP was tested for HR and SpO_2 against a GIMA pulse rate and blood oxygenation monitor worn on the right index finger. RR was tested against an inertial measurement unit (LS6DSV16X) sampling at 240Hz that was worn on the chest. Three repeated measures as described below were performed with two adult subjects.

Each measure of lasted 3 minutes, and saw the subjects holding their breath for 30 seconds after a 90 second period of normal breathing, followed by 60 seconds of normal breathing.

Furthermore, four repeated measures 10 minutes in length were conducted, with the subject alternating between 180 seconds of normal breathing and 30s of holding their breath.

B. Sensor Placement positional analysis

Five different in-ear positions were evaluated as potential PPG sensor sites. These were chosen to be feasible with a standard in-ear headphone case design and are shown in Fig. 3(a): [A] Inside the ear canal, forwards towards the tragus, [B] inside the ear canal, upwards towards the scalp, [C] inside the ear canal, downwards towards the chest, [D] inside the ear canal, backwards towards the concha and [E] on the cavum conchae. Rubber casts of the inner ear were constructed, and cavities to hold the PPG carved into the desired positions. Three different movements were tested: a side-to-side jaw wiggle, a head nod, and a side-to-side head tilt and twist (Fig. 3(a), Fig. 3(b)). In addition, the PPG amplitude acquired at these positions was also compared to ascertain which site was the most sensitive to recording blood flow changes in the ear with the optical sensor (Fig. 3(c)). In each sensor position and for each movement, five recordings consisting of 30 seconds of rest and 3 movement artifacts 5 seconds apart were recorded. For each run the average signal peak-to-peak amplitude during the first rest period and the maximal peak-to-peak excursion of each artifact were determined. Then, the artifact excursion to signal amplitude ratio was calculated for each artifact, and averaged for each position and movement combination.

C. Algorithms for vital sign extraction

SpO_2 was calculated in real time from a 10 second moving window that shifted by one second per measurement of the raw PPG data.

For each window, the offset component of both the red and IR LED was determined using a one second moving average, and the signal separated from the offset by subtracting this moving average from the original data. The signal was then filtered using a 4-th order, 10Hz low-pass filter. Peak detection was used to identify the minima and maxima of the signal, and the signal amplitude (AC_{red} and AC_{ir}) was calculated as the average of the last six minima-to-maxima amplitude difference found. The DC component (DC_{red} and DC_{ir}) was calculated as the average offset component across the last

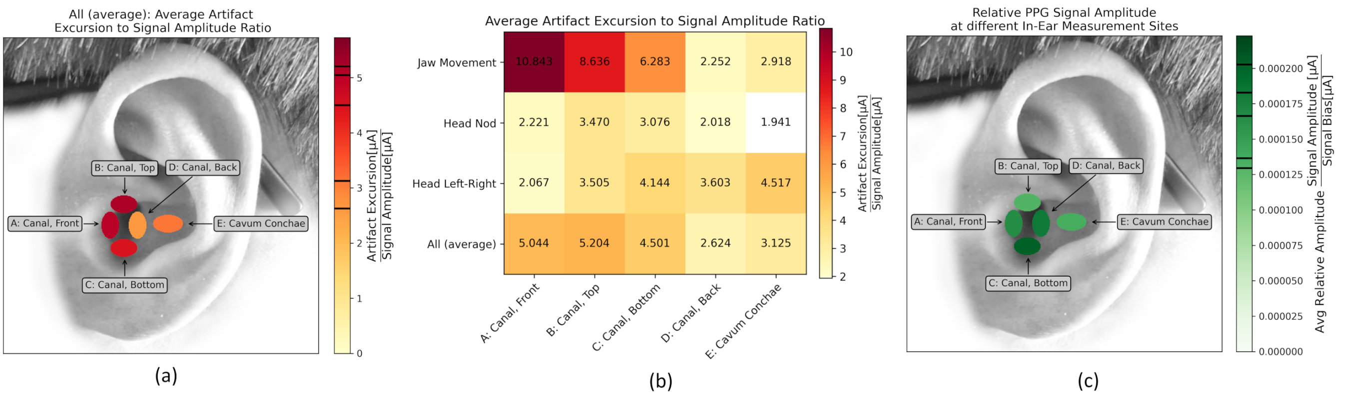

Fig. 3. Analysis for placement of PPG sensor in-ear to optimize for measured PPG signal and lowered susceptibility to artifacts for three movements: (a) Average over all three movement types, (b) All movement types (c) Positional comparison of measured PPG signal amplitude for maximum sensitivity measurement of physiological signal.

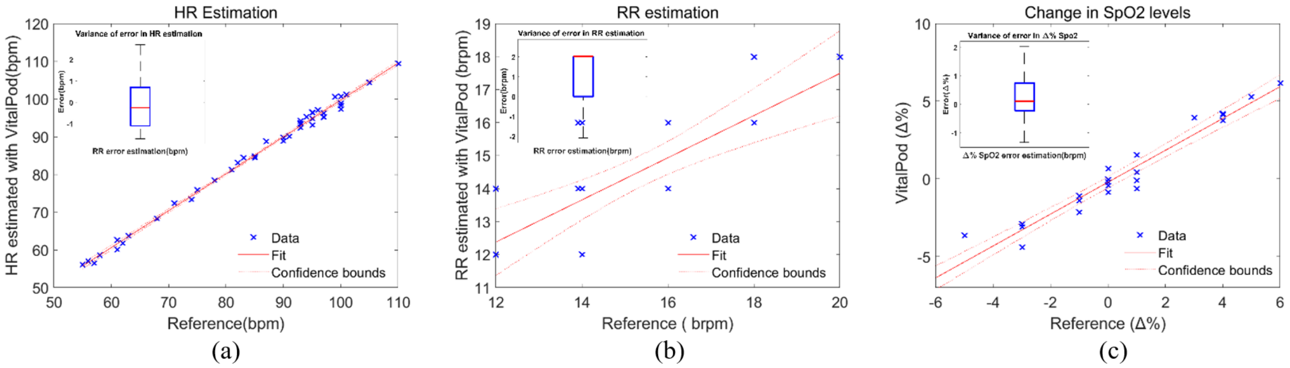

Fig. 4. Vital sign estimation in ear using the VitalPod hearable for (a) HR estimation with variance in error (inset), (b) RR estimation with variance in error (inset), and (c) changes in measured blood oxygenation with variance in error(inset)

6 minima locations. Using these values, the standard Ratio-of-Ratios metric R was calculated for this window [28]:

$$R = \frac{AC_{red}/DC_{red}}{AC_{ir}/DC_{ir}}$$

This metric was then further averaged over a sliding window 5 values long. Based on this value, the SpO_2 concentration can then later be reconstructed using an empirically determined linear approximation:

$$SpO_2 = B - R * A$$

HR was calculated from the average minima-to-minima and maxima-to-maxima interval from both red and IR LEDs.

Respiratory rate Estimation: RR was calculated using the Short Term Fourier Transform (STFT) from windows of fixed length of 30s with no overlap. Prior to RR estimation, a smoothing filter was used followed by a bandpass filter from 0.2Hz to 0.8Hz.

To prevent movement artifacts from being interpreted as valid PPG data, a ten second window was only considered valid if it conformed to experimentally determined heuristics which provided the most accurate estimation of extracted vital signs. First, should less than 6 minima or maxima be found, the window was rejected. Experimentation showed that signals of interest were above 10 LSBs, hence, a window was rejected if its AC component fell below this value from the PPG sensor. Next, the coefficient of variation of the six last minima to maxima differences was calculated for both LEDs, and the window rejected if it one or both exceeded an experimentally determined threshold of 0.25. This prevented short duration movement artifacts from being interpreted as an increase in signal amplitude. Lastly the coefficient of variation for the time between minima and maxima was calculated for both LEDs. The window was rejected if either coefficient exceeded an experimentally determined threshold of 0.1, which indicated that a movement artifact caused an extrema to be missed or a movement artifact to be misidentified as an extrema.

V. Experimental Results

A. *Positional analysis of PPG sensor in-ear*

To optimise the design for the VitalPod, the PPG sensor was placed at different positions within the ear cavity and the evaluated performance against three movements is shown in

Fig. 3. It can be seen that the position D is best with lowest susceptibility to movement artifacts and high signal amplitude, while position C features the highest signal amplitude.

However, incorporation of the PPG sensor inside the ear canal with the inclusion of the speaker was ergonomically challenging and uncomfortable to wear. Hence, the PPG sensor was placed in position E, which showed slightly worse performance but was much more practical to implement in a headphone case.

B. Vital sign estimation performance

Fig. 4 shows the correlation and error variance for SpO_2 , HR and RR. HR showed a mean bias of 0.062 beats per minute(bpm) underestimated with respected to the reference system and a variation of ± 1.12 bpm.

RR measurements using the VitalPod are very sensitive to motion artifacts. Hence, all windows that were severely affected by motion were discarded. Out of a total of 36 windows, 11 windows were discarded due to motion artifacts. RR estimation on the remaining windows showed a mean bias of 0.878 breaths per minute (brpm) with a variation of ±1.48 brpm. The difference in the RR and HR performance can be attributed to the fact that while HR variations are measured clearly in the ear, the variations in the PPG data due to respiration are weaker and further suppressed by improper contact in the ear cavity.

Blood oxygenation measured in the ear showed high correlation (R^2 = 0.97) with the percentage change in the blood oxygenation measured at the index finger with an accuracy of 0.21±0.82 %. Fig. 5 further shows the drop in blood oxygenation during simultaneous measurements from both the finger and in-ear measured blood oxygenation values.

C. Battery Lifetime

The VitalPod is a power efficient system with an average active power of 20.56 mW (5.41 mA @ 3.8V), standby power of 0.54 mW (142 μA @ 3.8V) and sleep mode power of 1.25 μW (0.33 μA @ 3.8V). While active, the major power burden is born by the PPG sensor (3.12 mA) followed by the Apollo SoC (1.46 mA, 1.05mA of which are due to BLE transmission), IMU (0.41 mA), and temperature sensor and support circuitry (0.42 mA). The operational longevity of the VitalPod can be optimized for the use case scenario. For continuous monitoring applications, data from the PPG sensor is measured at 50Hz at 100% duty cycle, the system lasts for almost 5 hours as seen in Fig. 6.

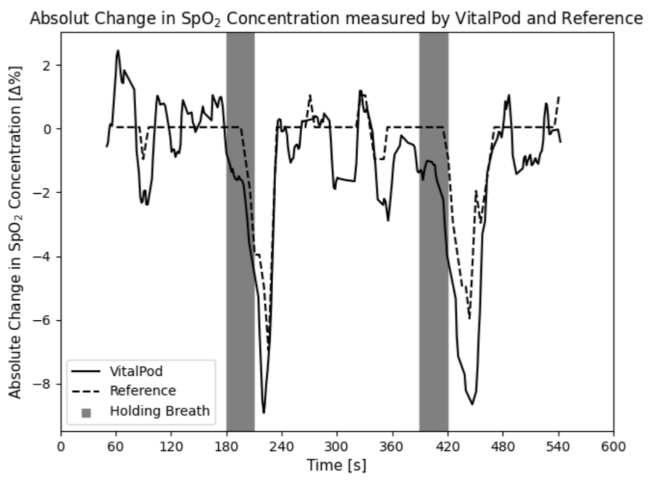

Fig. 5. Temporal percentage change in SpO_2 while holding breath seen in both finger derived SpO_2 and the in-ear blood oxygenation measured with the VitalPod.

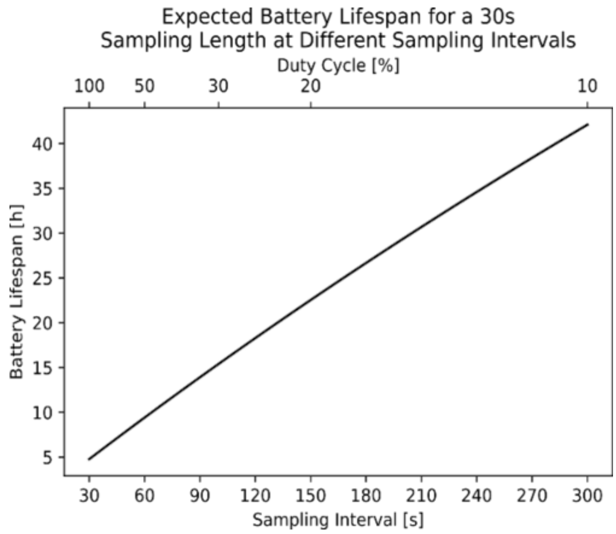

Fig. 6. Battery life estimate for a sensing time of 30s duty cycled over sampling times from 30s(100% duty cycle) to 5 minutes(10% duty cycle), projected from measured system performance.

This is optimum for sporting activity, and comparable to commercial systems, where high resolution measurements are required by the user. However, in scenarios of clinical monitoring or at-home monitoring of chronic health conditions and paraplegic/geriatric care, the temporal granularity can be lowered slightly to be measured every 5 minutes. This renders a system with 42 hours of battery life with a single charge cycle.

VI. Conclusion

VitalPod is a long-lasting in-earbud system that can measure multiple vital signs simultaneously, for example, heart rate, respiratory rate and blood oxygenation while also providing conventional earphone usage. The low power sensor node design of hearable enables tuning it to the target application scenario of either sporadic sports activity or long-term health monitoring. A small form factor batter of only 32 mAh can provide continuous measurements for almost 5 hours while intermitted measures taken every 5 minutes could enable vital sign measurement for health monitoring for up to 42 hours. Its compact form factor of 13 mm×21mm×9.5mm and optimized ergonomic design provide a safe and comfortable system. The VitalPod provides high performance in measurement of vital signs with the error estimation within 0.06±1.12 bpm for HR, 0.85±1.48 brpm for RR and 0.21±0.82% for change in SpO_2 . While designing the sensor node, emphasis was placed on minimizing the effects of artifacts by placing the sensors in the ear so as to measure the highest signal amplitude with the lowest possible impact of motion induced artifacts such as jaw movement (talking, chewing), moving the head up and down or left and right. Future work will further exploit the sensor fusion and develop algorithms to process artifacts and extract vital parameters with minimum loss of data, while also further optimizing the packaging design to improve contact between the ear surface and the sensor.

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