WatchLink: Enhancing Smartwatches with Sensor Add-Ons via ECG Interface

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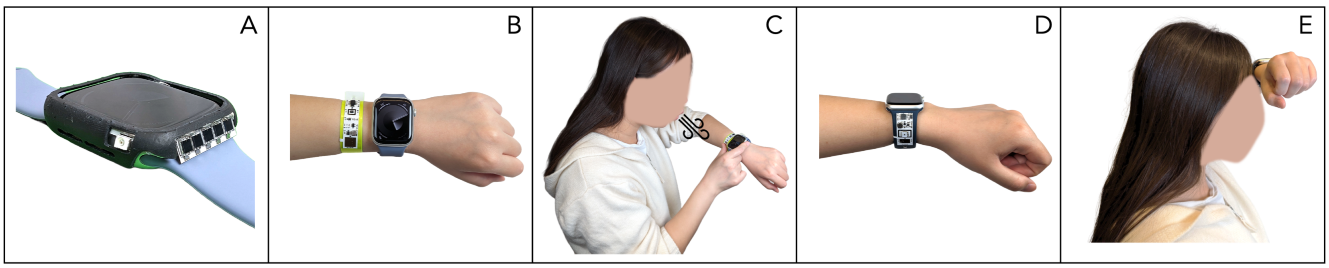


Figure 1: WatchLink lets users add sensors to commodity smartwatches via the ECG interface. Sensors can be (A) integrated into a watch case or (B) worn as a companion accessory, like this alcohol sensor. (C) A user blows on the breath alcohol sensor, and ECG communication is coupled through the user's fingers. (D) Users can also add sensors to watch straps, like this body temperature sensor, which (E) can be touched to the forehead for measurement.

ABSTRACT

We introduce a low-power communication method that lets smartwatches leverage existing electrocardiogram (ECG) hardware as a data communication interface. Our unique approach enables the connection of external, inexpensive, and low-power "add-on" sensors to the smartwatch, expanding its functionalities. These sensors cater to specialized user needs beyond those offered by pre-built sensor suites, at a fraction of the cost and power of traditional communication protocols, including Bluetooth Low Energy. To demonstrate the feasibility of our approach, we conduct a series of exploratory and evaluative tests to characterize the ECG interface as a communication channel on commercial smartwatches. We design a simple transmission scheme using commodity components, demonstrating cost and power benefits. Further, we build and test a suite of add-on sensors, including UV light, body temperature, buttons, and breath alcohol, all of which achieved testing objectives at low material cost and power usage. This research paves the way for personalized and user-centric wearables by offering a cost-effective solution to expand their functionalities.

UIST '24, October 13–16, 2024, Pittsburgh, PA, USA

ACM ISBN 979-8-4007-0628-8/24/10
https://doi.org/10.1145/3654777.3676329

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile devices**; *Interaction devices*; • **Hardware → Sensor devices and platforms**.

KEYWORDS

ECG Sensing, Low-power devices, Wearable sensor add-ons, User-centric wearables

ACM Reference Format:
Anandghan Waghmare, Ishan Chatterjee, Vikram Iyer, and Shwetak Patel. 2024. WatchLink: Enhancing Smartwatches with Sensor Add-Ons via ECG Interface. In *The 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24), October 13–16, 2024, Pittsburgh, PA, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3654777.3676329

1 INTRODUCTION

Wearable devices, such as ubiquitous smartwatches, are becoming integral to our modern lifestyle and ongoing assessments of health. Central to their functionality is an array of sensors, each designed to capture a specific aspect of the wearer's environment or physiological state. From tracking heart rate and sleep patterns to monitoring physical activity and environmental exposure, these wearables gather a wealth of information that offers insights into an individual's well-being.

Wearable manufacturers negotiate the marketability versus utility trade-off by catering their designs to broad market demands, not the needs of niche audiences, which can vary considerably in requirements. For instance, individuals who spend significant time outdoors, such as field researchers or construction workers, could greatly benefit from a wearable device equipped with a UV light sensor; such a device would help them monitor and log their exposure to harmful UV radiation, thereby aiding in the prevention of skin-related health issues. Similarly, people living in areas with high air pollution might find value in wearables that monitor air quality across different locations, alerting them to potentially hazardous environmental conditions. Further, certain functions could be very useful at specific times, such as a breathalyzer sensor after drinking, but not necessarily something needed at all times. Or those with specific motor abilities may prefer physical buttons for specific watch functions over use of a touchscreen.

Single-function devices that contain specialized sensors along with a dedicated processor, communication stack, and wearable housing hardware would be expensive. Further, the likelihood of incorporating these specialized sensors into mass-produced smartwatches is low due to increased production costs, integration complexity, and potentially limited market appeal for highly specific features. This gap presents a compelling opportunity for niche add-on sensors that can significantly enhance a smartwatch's usefulness for specific needs. It is possible to design cost-effective add-on sensors by leveraging the existing display, data logging, and processing power of most smartwatches. Furthermore, focusing on low-power design could further enhance the user experience by reducing the need for frequent charging. However, the key challenge lies in creating a way to connect these sensors to the watch at a low cost and power.

We therefore propose a novel approach that leverages the widely available electrocardiogram (ECG) hardware on smartwatches for receiving data from external sensors, enabling low-power communication with minimal and inexpensive components. This technique operates by transmitting the sensor data encoded in voltage variations through frequency modulation, allowing ECG hardware to capture it. This approach is practical because the ECG interface is precisely engineered to identify voltage potentials—tiny electrical signals generated by the heart. Compared to traditional methods like Bluetooth Low Energy (BLE) and WiFi, this method offers significant advantages useful for add-on sensors: it consumes over two orders of magnitude less power during active communication and needs only a handful of inexpensive modulation components costing about ten times less than a typical BLE solution.[1]

To validate this concept, we design and implement four different sensor modules that use both continuous background and on-demand sensing: (1) a UV light sensor, (2) a body temperature sensor, (3) external buttons for smartwatch input, and (4) a breath alcohol sensor. These sensor modules communicate with commodity smartwatches—Apple Watch Series 9 and Google Pixel Watch 2—via ECG, showcasing the feasibility and versatility of our proposed communication method. We also characterize the ECG interfaces for these watches and demonstrate the design space of possible form factors (from bands to cases) and different power sources (from self-powered to primary batteries) for these sensors. See Figure 1.

This paper makes the following contributions:

- A *novel technique for data transmission* from a sensor to a smartwatch via its ECG hardware. We further *evaluate and characterize the capabilities of these ECG interfaces* for communication purposes in terms of signal type, amplitude and frequency.
- *Characterization of the design space for integrating add-on sensors.* We define three categories for seamlessly linking add-on sensors with smartwatches, i.e., watch strap sensors, watch case sensors, and companion sensors.
- *Demonstration and validation of our technique*, for which we develop and build four add-on sensor devices, each featuring unique methods of interfacing and powering.

2 RELATED WORK

WatchLink aims to expand the sensing possibilities for smartwatches in a way that is inexpensive, low-power, and does not affect the watch's original utilities. To maximize marketability, we explore add-on sensors that *extend widely available watches*. This need is well motivated: Detachable Watch [25] specifically explored modifying existing smartwatches to detach the watch body from the wristband to increase functionality and discussed how this system could enable an ecosystem of sensor-laden bands. Their study found that users were excited by the concept of sensor modularity for watches. Similarly, early smartwatch manufacturers sought to develop this space. The now defunct Pebble smartwatch team crowdfunded an initiative around "smartstraps," which would connect power and serial data via a pogo pin interface [1]. ReserveStrap attached an additional battery to early Apple Watch models via a hidden debugging port before Apple software-disabled access [2]. Our work seeks to address this continued desire for modular smartwatch sensors.

However, lacking physical access to ports on modern commodity smartwatches, e.g., direct MCU connection is not supported on most smartwatches, some new designs have instead sought to connect wirelessly. Connecting to smartwatches for external devices typically involves methods like Wi-Fi and BLE, which consume over 100 mW and 5 mW of power, respectively, for active transmissions. Our ECG-based approach uses ~50μW during active transmission [17, 30, 32, 39]. In addition to the ECG communication channel, the ECG hardware integrated into smartwatches also boasts lower power consumption than BLE or Wi-Fi components. This energy efficiency is illustrated by the low current draw of industry-standard ECG ICs like the MAX30001 (70uA) and MAX30003 (120uA)[7, 8].

Another technique, near field communication (NFC), operates without a battery but is limited in current smartwatches to functioning only as a tag and does not support NFC tag reading [19, 44].

[1]WatchLink communication uses a low-dropout voltage regulator (LDO) (TPS7A0318PDBVR, $0.118/unit) and a 555 timer (ICM7555IBAZ-T, $0.010/unit), for a total cost under $0.13. This combination consumes less than 100 μW during active transmission. In comparison, BLE communication with the NRF52805 chip (from $1.214/unit) consumes about 5.7 mW during active transmission (datasheet from Nordicsemi.com). All component costs in this paper are sourced from Octopart.com (on a 10,000-unit basis).

Ultrasound-based communication[18, 22] offers a potential solution for interacting with smartphones by transmitting audio signals affordably. However, its higher power demand leads to the need for frequent battery replacements.

Technologies such as WiFi [13, 23, 24, 49–51] and BLE backscatter [16, 47, 48] have been explored to create energy-efficient, cost-effective tags that interact with common devices like smartphones. But these methods depend on the presence of WiFi or Bluetooth signals, either from a dedicated transmitter or from the receiving device, leading to substantial power consumption and quick battery depletion. Ultra-wide band (UWB) emerges as an appealing alternative, characterized by low transmission power requirements and compatibility with newer smart devices equipped with UWB. Nonetheless, its adoption is hampered by its higher costs, which are attributed to specialized hardware needs [31].

Using any of the preceding wireless protocols additionally requires the add-on sensor to contain its own microcontroller, radio, analog sensing front end, ADC, and associated power management; these increase bill of material (BOM) cost, power, and complexity over a wired solution. By leveraging the ECG front-end, our approach obviates the need for these components. Instead, the simple discrete components in our designs use less power and together cost less than a BLE microcontroller IC-based system itself [14, 33], thereby enabling low-cost, one-off designs for a wide variety of sensors. As a point of reference, the commercial AURA Strap product, a body composition and hydration watch BLE strap, costs 159 USD [3].

Significant research explores ways to leverage existing power and sensing infrastructure for low-cost and low-power communication and sensing [10, 12, 21, 27, 29]. Inspired by the cybersecurity [11] and medical diagnostics [34] communities, we refer to this approach as "side-channel sensing." These techniques have been applied to smart devices, as well, to specifically enable ultra low power systems that interface with unmodified commodity devices. A wide variety of modalities have been studied: audio [20], RF [42], optical light [4, 45], LiDAR [9], capacitive [41], vibration motor [46], IMU [26], and more.

Of the preceding approaches, GlucoScreen[41] aligns the most to our requirements. GlucoScreen is a blood glucose test device that can be powered via a phone's flash and communicates via the phone's touchscreen as touch events. The electrochemical assay's potentiostat output modulates the touch events via only an oscillator and transistor, avoiding the need for higher cost and power components such as a microcontroller, communication radio, and display. Though communication through the touch panel is effective for smartphones, it may not be appropriate for smartwatches where (1) touchscreen real-estate is limited or (2) continual sensing without affecting the watch's functionality is needed. Our work offers inexpensive and low power wearable sensors by co-opting the ECG sensor on commodity smartwatches, which has yet to be explored in the literature.

3 ECG SENSING FOR COMMUNICATION

Electrocardiography (ECG or EKG) is a medical diagnostic and monitoring technique that captures and records the heart's electrical activity over time, indicating how its muscles contract and pump blood. Performing an ECG typically involves placing electrodes on the patient's skin at key locations on the chest, arms, and legs. These electrodes sense the minute electrical changes on the skin caused by the heart muscle's activity during each heartbeat. Standard ECG procedures use ten electrodes, providing 12 different views (leads) of the heart's activity, each offering unique insights into the heart's health and functioning.

The typical circuitry in an ECG setup includes electrodes, amplifiers, and filters. The heart's electrical signals are typically weak and can vary from 1μV to 100mV, with a typical value of 1mV [15]. Amplifiers are crucial for boosting the heart's faint electrical signals to a level that can be processed and visualized. Filters help eliminate noise and interference, ensuring the signals accurately represent the heart's activity. The captured signals are then digitally processed to enhance the signal-to-noise ratio (SNR), ensuring clearer and more accurate readings.

In recent years, integrating ECG technology into smartwatches has greatly improved personal health monitoring. Smartwatches with ECG functions generally provide a single-lead ECG. This method, less comprehensive than the standard 12-lead ECG used in clinical settings, still offers valuable insights into the user's heart rhythm and rate.

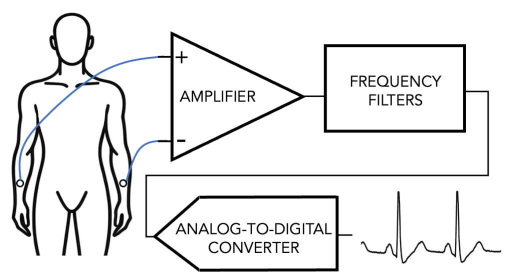


Figure 2: Simplified view of ECG sensing system in a smartwatch.

ECG recording in smartwatches is achieved through a more straightforward setup, as shown in Figure 2. In current smartwatches, one electrode is integrated into the watch's back plate, in contact with the wrist, and another is embedded on the side or on a button on the watch. When the user starts an ECG recording and touches the second electrode with the other hand, a closed loop is formed across the heart, enabling measurement of the heart's electrical signals. This setup effectively creates a single-lead ECG. The watch measures the electrical potential difference between the wrist and the finger during a heartbeat, recording the heart's electrical activity.

At a higher level, the ECG system measures voltage potentials and is specially tuned for low-amplitude heart signals, featuring a high gain. *This sensitivity to voltage fluctuations lets us repurpose the ECG interface for information transmission by encoding data as variations in the voltage of a signal that the watch can interpret.* Furthermore, *the high gain of the system lets it detect even weak signals, enhancing the robustness and reliability of the communication.* These characteristics make the ECG system suitable not only for heart rate monitoring but also for communication applications.

Figure 3: The ECG contact points (highlighted in yellow) for the Apple Watch Series 9 (two left images) and for the Google Pixel Watch 2 (two right images).

4 ECG CHANNEL CHARACTERIZATION

To assess the practicality and limits of communication capabilities with smartwatches through ECG interfaces, we conduct a series of exploratory and evaluative tests using commercially available smartwatches. These tests focus on the following channel characteristics:

- **Signal Type**: The ability of the ECG interface to detect both DC (direct current) and AC (alternating current) signals.
- **Signal Amplitude**: The minimum and maximum signal amplitude the ECG interface can read.
- **Signal Frequency**: The range of AC signal frequencies, from lowest to highest, that the ECG interface can detect.

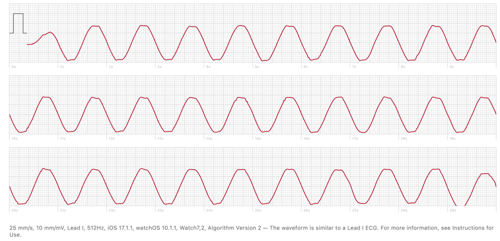
4.1 Test Setup

For our exploration and testing, we used two widely recognized smartwatches available in the market—the Apple Watch Series 9 and the Google Pixel Watch 2. These watches were used as-is, with no modifications made to their hardware or software.

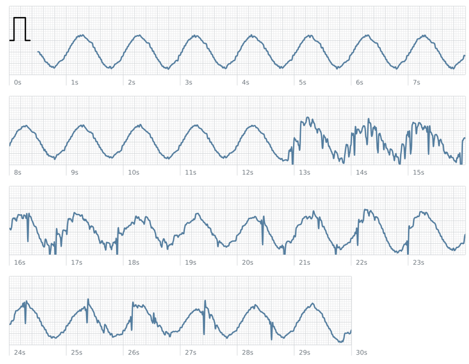
We established two connection points for each watch, one on the back of the watch and the other on the crown. Contact was made using thin pieces of copper sheet affixed securely with tape. Figure 3 shows these contact points on both smartwatches. We then connected these two contacts to a function generator, designating the contact on the watch back as the ground and on the crown as the signal.

We used the built-in ECG applications on both smartwatches to record data captured by the ECG interface. The native apps on the Apple Watch Series 9 and the Google Pixel Watch 2 offer a feature that enables the capture of data for a duration of 30 seconds, which can then be exported as a PDF file. Currently, neither the Apple nor Google Pixel watches offer a straightforward method to export individual ECG recordings as CSV files. The Apple watch allows only bulk export of all health data, while the Pixel watch requires use of the Google Takeout utility, both of which can be time-consuming. To accelerate the prototyping process, we developed an image processing pipeline[2] to convert ECG waveforms from PDF files into CSV format. This streamlined approach was validated by comparing the resulting CSV data to ECG data obtained directly from Apple Health Kit and Google Takeout, confirming the accuracy and consistency of our parsed signals.

[2]The PDFs containing ECG data are first cropped to the region containing the ECG signal. Since the ECG signal is present in multiple sections within the document, individual regions are sub-cropped using a contouring approach. Then, the signal is extracted from the background using color-based segmentation. Finally, all signal parts are concatenated. The code for this procedure is available at https://github.com/ubicomplab/WatchLink.



(a) Apple Watch



(b) Google Pixel Watch

Figure 4: Excerpt of a signal (1 Hz sine wave) from the ECG pdf exported from the Apple Health and Fitbit ECG apps.

4.2 Signal Type

4.2.1 Direct Current. For our initial testing phase, we transmitted a DC signal into the watch, beginning at a low amplitude of 1 microvolt (μV) and gradually increasing it to 1 volt (V). We incremented in stages: first, in 100 microvolts (μV) steps, ranging from 1 μV to 1000 μV, and then in 100 millivolts (mV) steps, from 1 mV to 1V. Although both watches detected changes in voltage, the captured data revealed that they rapidly recentered the signal to eliminate the DC offset. This observation indicates that the watches are equipped with a filter designed to negate any DC offset, suggesting an inherent limitation in their ability to process DC signals directly.

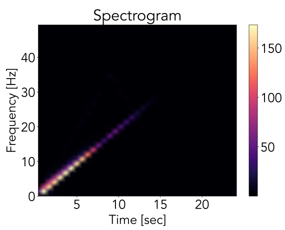
4.2.2 Alternating Current. In our second set of tests, we introduced an AC signal into the watches, specifically a sine wave at 1 Hz, which aligns with the typical frequency range of human heart rates. To mimic the voltage levels similar to those found in ECG signals, we set the peak-to-peak amplitude of this signal to one millivolt (mV)[15].

From the collected data (Figure 4), it is evident that the AC signal was successfully captured. Further examination of the signal, conducted through a Fast Fourier Transform (FFT), confirmed its frequency at 1 Hz. The signal captured for the Apple watch was cleaner than for the Pixel watch, as the figure shows.

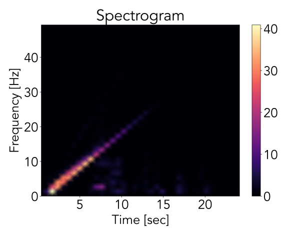
These findings demonstrate that while both watches can capture an AC signal, albeit with minor distortions, they cannot effectively capture a DC signal. Based on these results, our subsequent tests focused exclusively on AC signals.

4.3 Signal Frequency

In this experiment, we injected a linear chirp signal into the watches, sweeping from 0.1 Hz to 50 Hz over 25 seconds, with an amplitude of 10 millivolts (mV). Figure 5 displays the spectrogram for both watches. The highest distinguishable frequency for either watch is around 20Hz. The results also indicated a decrease in signal amplitude with increasing frequency.



(a) Apple Watch



(b) Pixel Watch

Figure 5: A spectrogram of a frequency sweep (0.1 Hz - 50Hz) signal captured by an Apple watch and a Google Pixel watch.

We highlight that *the data we captured is post-software filtering by the watches, representing these devices' minimum capabilities.* The watches capture data at a higher data rate, up to 512 Hz for the Apple watch and 250 Hz for the Google Pixel one, but the embedded software potentially applies band-pass or low-pass filters, as is common in ECG signal processing [15]. Industry-standard ECG ICs, like Texas Instruments' AFE4500, can reach an even higher 2 kHz sampling rate[38]. Therefore, *the performance of the communication technique outlined in this paper has the potential for further improvement.*

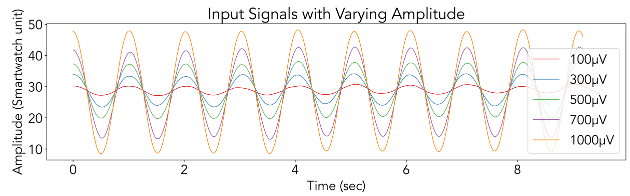
4.4 Signal Amplitude

In our amplitude test, we injected five distinct frequencies into each watch, i.e., 0.1 Hz, 1 Hz, 5 Hz, 10 Hz, and 20 Hz. For each frequency, we tested voltage amplitude from 100μV to 5mV in increments of 100μV from 100μV to 1000μV and then in increments of 1mV from 1000µV to 5mV. Figure 6 shows the signals captured from this experiment for 1 Hz frequency.

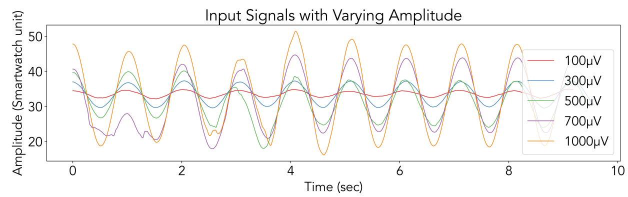
Results indicate that for either watch to detect a signal effectively, the amplitude must be at least 100μV. The signal is still read at amplitudes lower than this, but the SNR is weak. At higher signal amplitudes, i.e., above 1mV for the Apple and 5mV for the Pixel watch, the watch ceased displaying data, possibly due to the signal being interpreted as noise.

5 WATCHLINK

The ECG interface on a smartwatch, which features accessible electrodes and the ability to access raw data via built-in ECG apps, presents a unique opportunity for low-level communication. This



(a) Apple Watch



(b) Pixel Watch

Figure 6: A 1Hz sine wave signal at different amplitudes as captured by an Apple and a Google Pixel watch.

approach bypasses the complexities and power demands of standard communication protocols like BLE, NFC, or WiFi and enables more energy-efficient data transmission. When exploring the use of an ECG interface as a communication channel, two primary considerations emerge:

(1) **Choosing a communication protocol for devices**. We aim to develop sensor devices that are both cost-effective and low in power consumption. Given these constraints, implementing a complex communication protocol may be less practical. Therefore, our protocol should be streamlined and straightforward, focusing on efficient data transmission without the more elaborate hardware required by advanced protocols.
(2) **Establishing a physical connection to the watch**. We aim to form a stable physical connection with the watch's back and ECG electrodes. To do so, we must devise a reliable method for connecting sensors to these points, ensuring consistent data transmission.

5.1 Communication via ECG Sensing

This work leverages the ability of the ECG interface to receive data, enabling one-way communication from external sensors to the smartwatch. We develop the communication strategy informed by the ECG channel characteristics detailed in Section 4, which reveal that the ECG interface can read AC signals and will occasionally contain noise; we also note that while the time-domain signal could have distortion, the dominant components in the frequency domain were mainly intact. Therefore, we selected frequency modulation (FM) as our encoding method, which operates effectively in the frequency domain and is less susceptible to amplitude variations. Furthermore, we can implement the FM modulation technique using elementary circuit components, making it a cost-effective solution.

Both square waves and sine waves (used for characterization) can be used for FM modulation, but we favor square waves for our

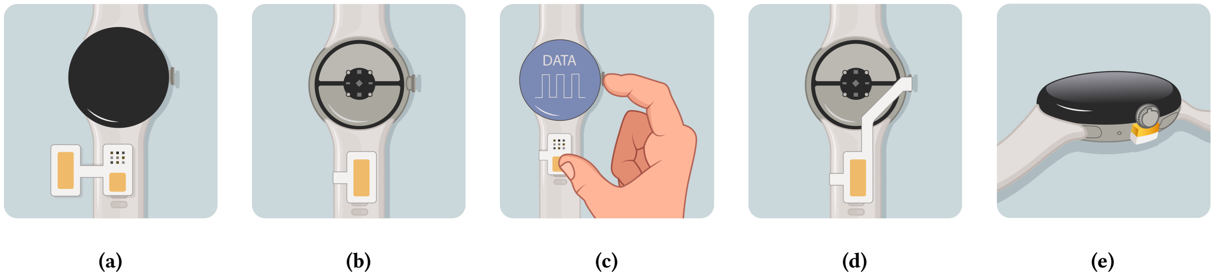


Figure 7: The configuration of a strap sensor. (a) and (b) Affixing a strap sensor to a watch's strap using double-sided adhesive tape. (c) Establishing a connection between the watch and the sensor through manual activation, utilizing fingers. (d) Maintaining persistent contact for continuous sensing. (e) Maintaining persistent contact (side view), highlighting an electrode making a sliding contact with the watch's crown.

implementation due to their more straightforward generation using basic circuits like timers, reducing component count and complexity. However, square waves introduce harmonic frequencies that require careful consideration to avoid interference, necessitating a trade-off between simplicity and spectral efficiency. To evaluate this trade-off, we conduct experiments (Section 5.3.1) to assess the ECG interface's performance using FM with square waves.

5.2 WatchLink Sensor Design

We aim for WatchLink to allow the integration of various sensors into a smartwatch, catering to diverse use cases and being used at different times and frequencies. For instance, certain sensors, like those for ambient UV radiation monitoring, function continuously in the background. Others, like forehead temperature sensors, are activated manually, as needed. Additionally, some sensors, such as breath alcohol level detectors, are helpful under certain conditions, e.g., at particular events or locations.

To cater to various applications and usage scenarios, we propose three distinct methods for attaching WatchLink sensors to smartwatches: (1) attaching the sensors directly to the *watch strap*, and (2) attaching the sensors to the *watch case*, allowing the strap to be interchangeable. Both methods enable continuous sensing and manual activation. The third option is a *separate accessory* worn alongside the smartwatch, specifically for manual activation scenarios. We elaborate on each below.

5.2.1 ***Watch Strap Sensors****.* These sensors can be directly attached to the watch strap. This design lets users switch between different straps for various sensors, using them interchangeably, as required. Figure 7 illustrates a design for such a sensor. These sensors establish contact with the body through an exposed electrode 7(b) positioned under the watch strap to make direct contact with the skin.

For sensors requiring continuous sensing, this sensor's design includes an extension that makes continuous contact with the watch's crown for data transfer. The extension includes a fixture that goes under the watch that makes contact with the watch crown. Figure 7(e) shows one such design for a watch to make sliding contact with the crown. This fixture consists of a 3D printed part that is affixed under the watch without affecting any existing sensors located there, like PPG, SpO2, and EDA; the 3D part contains a conductive surface supported by soft foam to make reliable but subtle ohmic contact with the crown without hindering the crown's standard functionality for the user.

For sensors that need manual activation, the design includes an exposed electrode 7(c) on the side facing the user. To connect with the watch, the user simply touches the electrode on one side and the watch crown on the other with their fingers. The sensor signals then travel through the user's body to reach the watch.

5.2.2 ***Watch Case Sensors****.* These sensors consist of sensor components and electrical circuits housed within a watch case, as show in Figure 8(a). This design lets users attach or detach the sensors from the watch simply by changing the case, providing the flexibility to switch watch bands without replacing sensors. To install the case, users snap it onto the watch and attach the ground contact to the watch's back. This design accommodates both continuous and manual activation sensing.

For continuous sensing, the watch case can be designed to maintain constant contact with the watch's crown. Figure 8(c) illustrates a design for continuous contact with the Apple watch. In this design, we create a 3D-printed case for the watch and incorporate a gold finger on the side of the case. This gold finger can make sliding contact with the center of the crown, ensuring an ohmic connection while still allowing for the crown's regular use. For manual activation, a method similar to that used with strap sensors can be employed. An exposed electrode can be positioned on the watch case, letting the user create a connection by touching the electrode and the crown simultaneously with their fingers, as shown in Figure 8(b).

5.2.3 ***Companion Sensors****.* This method enables the use of add-on sensors without the need to attach them directly to the watch. Instead, the sensor can be positioned on a separate band or accessory and placed anywhere, not just on the wrist. Figure 8(d) shows an example of this design. Data transfer is achieved by the user simultaneously touching an exposed electrode on the sensor with one finger and the watch's crown with the other, as shown in Figure 8(e). This design requires the user to manually establish a connection between the sensor and the watch with their finger, which is ideal for discrete or on-demand activation sensing. It is particularly effective for sensors that are used on an occasional or

(a) (b) (c) (d) (e)

Figure 8: The design and usage of case and companion sensors. (a) Embedding the case sensor electrical circuitry inside the case. (b) Establishing electrode contact between the sensor and the watch for manual activation. (c) Achieving continuous sensing through sliding contact with a crown. (d) Wearing a companion sensor as a wristband accessory in conjunction with a smartwatch. (e) Establishing a connection between a sensor and a watch for a companion sensor.

periodic basis, such as a breath alcohol sensor that can be worn before going to a social gathering or a smart bandage with sensors designed to track the progress of wound healing.

5.3 Background Experiments

5.3.1 ***Frequency Resolution.*** A crucial factor in frequency modulation is the *frequency resolution*, defined as the smallest frequency change that can be reliably detected. Theoretically, frequency resolution can be determined by dividing the sampling rate by the number of samples utilized in computing the Fast Fourier Transform (FFT) to identify frequencies. However, our investigations observed that the signal obtained from smartwatches undergoes significant processing, including filtering that is likely optimized for detecting heart signals, the specifics of which remain unknown. Consequently, we decided to ascertain the frequency resolution empirically.

To do so, we injected a square wave into the watch and then introduced another square wave, gradually decreasing the frequency difference between the two until the system could no longer distinguish between them. This experiment was conducted with various frequencies spread across the bandwidth to explore how the frequency resolution varies throughout the bandwidth. We executed this procedure for both the Apple and Google Pixel watches, utilizing the setup outlined in Section 4.

During our initial attempt at this experiment with a frequency sweep signal, we observed that each watch unexpectedly ceased recording midway through. This interruption could likely be attributed to the generation of harmonics at frequencies exceeding what the ECG system was designed to handle. Consequently, we tailored our experiments to employ discrete frequencies instead.

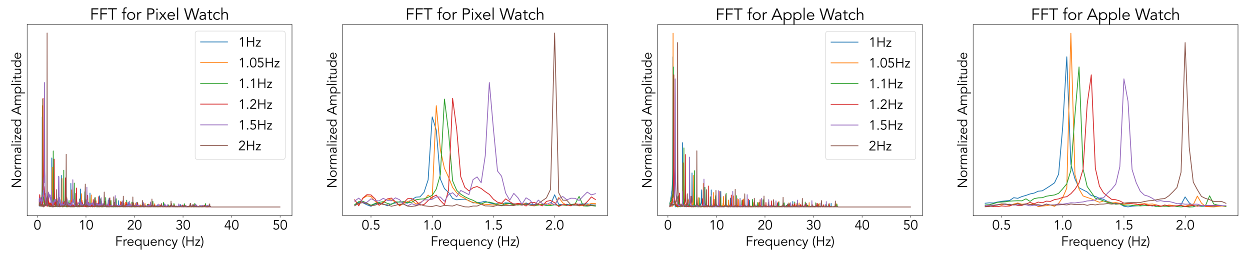
We conducted experiments using square waves at frequencies between 1Hz and 20Hz. The recorded data for square wave showed significant harmonic content captured; however, the intensity of the primary frequency remained dominant, as seen in Figure 9. Additionally, potential mitigation techniques, like low-pass filtering with an RC network or sine wave shaping with a diode-resistor network, can be employed to further reduce the impact of harmonics and enhance the reliability of ECG signal transmission.

Our experiments indicate that while the Apple watch accurately displayed signals on its screen at higher frequencies, it applied an additional filter before storing the data—likely a measure to counteract higher frequency content—resulting in significant information loss for frequencies above 10Hz. On the other hand, the Google Pixel watch did not implement such filtering. However, the signals captured beyond 10 Hz exhibited a shift in the frequency domain, a phenomenon not observed at lower frequencies. Figure 9 presents the outcomes of this investigation, showing that each watch could differentiate frequencies separated by at least 0.05Hz. Based on these results, we decided to restrict our sensor's frequency operation to 10Hz and below, ensuring a minimum frequency gap of more than 0.05Hz.

5.3.2 ***Through Body Signal Propagation.*** When characterizing the ECG interface 4, we investigated signal transmission into the watch through direct ohmic contact with its crown. However, in scenarios involving a 'companion sensor,' where the sensor's connection to the watch is facilitated through the user's fingers, the transmission through the body could introduce losses, necessitating an increase in signal strength for dependable signal transfer from the sensor to the watch.

We therefore conducted a user study with five participants to determine the signal strength required for consistent performance across different users. During this study, participants formed a connection to an electrode linked to a function generator with their thumb and made contact with the watch's crown using their index finger. A separate electrode, establishing a ground connection to the function generator, was placed in contact with the user's wrist. Participants tested both Google and Apple smartwatches for this purpose.

We introduced varying frequencies (1Hz, 5Hz, 10Hz) and amplitudes (50mV, 100mV, 300mV, 500mV, 700mV, and 1000mV) to the ECG interface. Signals below 300mV were inconsistently detected, while each watch reliably detected 300mV signals across all participants. Higher amplitudes (500mV, 700mV) were detected for only two participants. A 1000mV signal could not be detected by either watch for any participant. Consequently, due to its consistent detection, 300mV was chosen as the optimal transmission voltage for companion sensors.



(a) Pixel Watch (original) **(b) Pixel Watch (zoomed)** **(c) Apple Watch (original)** **(d) Apple Watch (zoomed)**

Figure 9: Spectrograms from the frequency resolution study for Apple and Pixel watches (images on right are zoomed-in versions of those on left). Each graph illustrates six frequency responses triggered by a single frequency application on the watch. The plots (b) and (d) demonstrate that both watches can distinguish frequencies as close as 0.05 Hz.

WatchLink Designs | WatchLink Example Applications

Sensing	Connection Type	Application	Energy Source	Domain
Continuous	Watch Case Sensor	UV Light	Ambient Light	Environmental
Continuous	Watch Strap Sensor with crown contact electrode	Watch Buttons	Ambient Light	Input
On-Demand	Watch Strap Sensor with finger contact electrode	Body Temperature	Battery	Health
On-Demand	Companion Sensor	Breath Alcohol	Battery	Health

Figure 10: An overview of WatchLink designs and example applications.

6 WATCHLINK APPLICATIONS

We introduce four unique sensor applications that enhance the functionality of smartwatches and utilize WatchLink's ECG communication for connectivity. These applications also serve as examples of various WatchLink design approaches for integrating with a smartwatch. Figure 10 shows these applications, which include an ambient UV light sensor, a body temperature sensor, a breath alcohol sensor, and additional buttons on the watch for user input. In developing each sensor add-on, we focus on ensuring they are both low-cost and energy-efficient. This approach aims to maximize the accessibility and longevity of the sensors, making them more practical and sustainable for everyday use.

6.1 UV Light Sensor

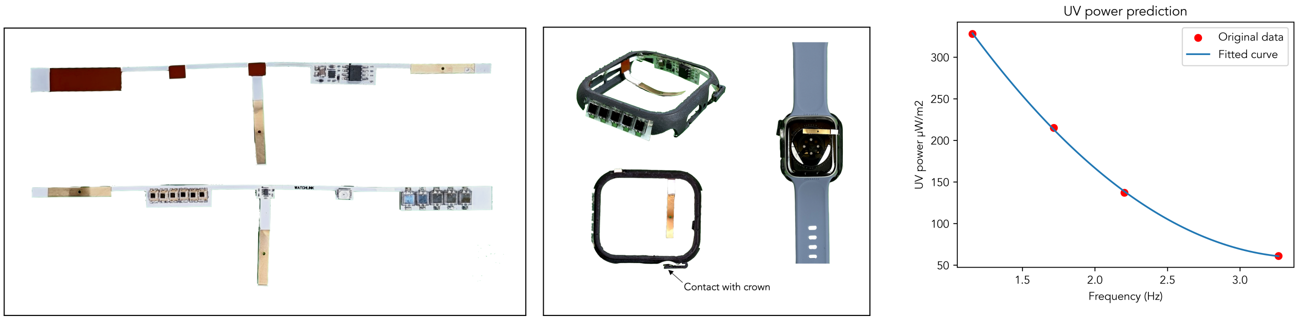
UV light exposure can cause severe skin damage, such as sunburn, early signs of aging, and an increased risk of skin cancer. Prolonged exposure to UV rays can also harm the eyes, potentially leading to conditions like cataracts, and may suppress the immune system, reducing the body's ability to fend off certain infections [43]. Therefore, monitoring UV exposure, especially when outdoors, is essential to minimize these health risks.

UV radiation is measured using the UV Index, which quantifies the risk of sunburn from UV rays at a specific location and time. It is designed to help people understand the potential for skin and eye damage from the sun's UV rays and to indicate the necessary precautions to take. Higher numbers indicate a greater risk of harm and the need for sun protection.

We developed a sensor add-on with WatchLink that outputs the UV Index. We designed the sensor add-on as a case for the Apple Watch that continuously measures and communicates index values. The sensor is built as a flexible printed circuit board (PCB) with a layout that fits entirely in a 3D-printed watch case, as shown in Figure 11. The 3D-printed case makes contact with the watch's crown via a gold finger and has a flexible electrode to make contact with the watch's ground. We use GUVA-S12SD as our UV light sensor, whose nano-level output is amplified by an op-amp amplifier (TLV521DCKR) that is frequency modulated by a 555 timer (CSS555) via the circuit described in [28] and transmitted to the watch.

The prototype is entirely powered by ambient light, from which energy is harvested using a set of 11 photodiodes, 5 (VBPW34S) of which are optimized as a current source and the remaining 6 (PD15-22C/TR8) as a voltage source. This distribution helps to optimize for low cost while providing the required power to the circuitry. The output from the photodiode array is voltage-regulated by an LDO (TPS7A0318PDBVR) to 1.8V. The total bill of materials for this circuit is $6.077. The power consumed by the circuit for continuous operation is 90μW, and the circuit can operate in light intensities over 8000 Lux, which means it can operate in average outdoor daylight conditions.

We evaluated this sensor add-on connected to an Apple watch in varying UV light conditions and recorded the ground truth UV



(a) (b) (c)

Figure 11: (a) The UV light sensor from both front and back built on a flexible PCB with a design that allows it to be integrated into a 3D printed case designed for the Apple Watch. (b) The case equipped with the PCB, demonstrating how the case engages in sliding contact with the watch's crown and how the PCB establishes a connection with the watch's ground. (c) The correlation between the sensor's prediction of UV light intensity and the actual measured values.

Index using a commercial UV light meter [6]. The results, presented in figure 11, show that UV Index measurements from the prototype sensor are correlated with the reader from the UV meter.

6.2 Body Temperature Sensor

The latest smartwatches, such as the Apple Watch Series 8 and Garmin models, integrate skin temperature sensors into their health monitoring features. Though they can provide valuable health insights, body temperature sensor readings are less accurate for measuring core body temperature than methods like forehead or ear thermometers because readings at extremities like the wrist can vary due to external factors. This limitation is particularly relevant for detecting fever or other medical conditions, where precise temperature readings are crucial.

Recognizing this limitation, some smartphone manufacturers, such as Google with its Pixel 8 Pro smartphone, have started incorporating dedicated temperature sensors in their devices that can measure forehead temperature. This trend highlights a growing interest in more accurate and convenient body temperature monitoring. However, most devices still lack such integrated sensors, presenting an opportunity for sensor add-ons that can provide temperature measurements. These add-ons can complement smartwatches, offering a more reliable solution for temperature monitoring for health purposes.

We design the body temperature sensor add-on as a watch strap sensor. It attaches to one side of the strap and wraps around it to establish skin contact for ground connection. Figure 12 shows the prototype of this sensor add-on. The sensor is tailored for on-demand temperature measurement and equipped with an easily accessible electrode that lets users make contact to initiate communication with the watch crown. Once the sensor is added to the watch, users can hold it against their forehead, as shown in Figure 1E, to take a temperature reading. To transfer this data to the watch, they simply need to establish a connection between the watch and sensor with their fingers, per Figure 7.

Our prototype uses a temperature sensor (LMT70YFQR) with an accuracy of ±0.13°C. The sensor generates an analog voltage reading, which is amplified using a TLV521DCKR op-amp amplifier, frequency modulated using a 555 timer (ICM7555IBAZ-T) using the circuit described in [28], and transmitted to the watch upon user connection. The sensor's circuitry is powered by a small 3mAh coin cell battery (MS421R IV03E), with its output regulated by a 2.7V LDO (NCP663SQ27T1G). To conserve battery life, the battery is normally disconnected and becomes active through a switch (CKN12215-1-ND) located just beneath the contact electrode. Users can activate the circuit by pressing down on the electrode until they feel a click, indicating that the circuit is operational; Figure 12 shows the placement of this button.

Importantly, we note that pressing the button to activate the circuit is not required during measurement since the measurement process does not require battery power. Instead, it operates by the body warming the temperature IC to reach thermal equilibrium. The power must be turned on only to transmit data to the watch. With a power consumption of a mere 243μW, the circuit can run for years on a single battery charge, while enabling multiple daily temperature measurements. The bill of material for components in this sensor add-on is $1.983.

We assessed the prototype temperature sensor by altering the temperature via contacting the sensor with a commercially available hot plate and recording its readings. Figure 12 shows the data from both devices. These temperature readings demonstrate that the prototype device makes precise temperature measurements.

6.3 Breath Alcohol Sensor

An alcohol breath sensor, commonly known as a breathalyzer, is a device for measuring Blood Alcohol Content (BAC) from a person's breath. BAC is typically measured as a percentage of alcohol in the bloodstream. Breathalyzer devices work by assessing a chemical reaction with alcohol, leading to a color transition or an alteration in electrical signals; key variants in this domain include sensors based on semiconductor oxide and fuel cell technology [40]. To use this sensor, an individual blows into it, which then measures the alcohol level in the exhaled breath, converting it into a BAC

(a) (b) (c)

Figure 12: (a) The body temperature sensor from both front and back views. (b) The method of attaching the sensor to the watch strap, where the sensor, constructed on a flexible PCB, wraps around to adhere to the inner side of the strap, establishing a ground connection with the user's body. (c) The relationship between the sensor's temperature predictions and recorded temperatures.

reading. Such sensors are instrumental in advancing public safety and encouraging responsible alcohol use.

Our design developed an alcohol breath sensor as a separate accessory, fashioned as a wristband, that works in conjunction with a watch. Figure 13 shows the sensor prototype. This design choice gives users the convenience of wearing or removing the sensor independently without altering the watch itself. The add-on features an electrode on one side to establish a connection with the watch's crown and another electrode on the opposite side to maintain a ground connection against the skin.

Our prototype employs a commercial Metal Oxide (MOX) gas sensor (CCS803), which detects alcohol levels and outputs them as an analog voltage. This output is amplified by an op-amp amplifier (TLV521DCKR) and then frequency modulated with a 555 timer (CM7555IBAZ-T) using a technique described in [28]. The circuit is powered by a compact (4.8mm x 2.1mm) 3mAh battery (MS421R IV03E), which is activated via a switch (CKN12215-1-ND) positioned under the finger contact electrode. This switch can be conveniently pressed at the same time as the finger establishes a connection with the watch's crown. The gas sensor is the main driver of the circuit's power consumption, at 20 mW. This allows the battery to power roughly 20 breath measurements, each lasting 30 seconds. The bill of materials for the components in this sensor add-on is $6.595.

To validate our prototype, which is connected to a Google Pixel watch, we conducted tests with varying ethanol concentrations on our prototype and on a commercial breath analyzer [5]. The data from these tests, shown in Figure 13, indicates a strong correlation between our prototype sensor and the commercial device's readings.

6.4 Touch Buttons for Interaction

With their compact screens, smartwatches often present challenges for user input. The limited screen space not only makes precise touch interactions difficult, especially for those with larger fingers, but also restricts the addition of extra control elements like buttons. Though voice control offers a solution, it can raise privacy concerns and is not always the most convenient option in public settings.

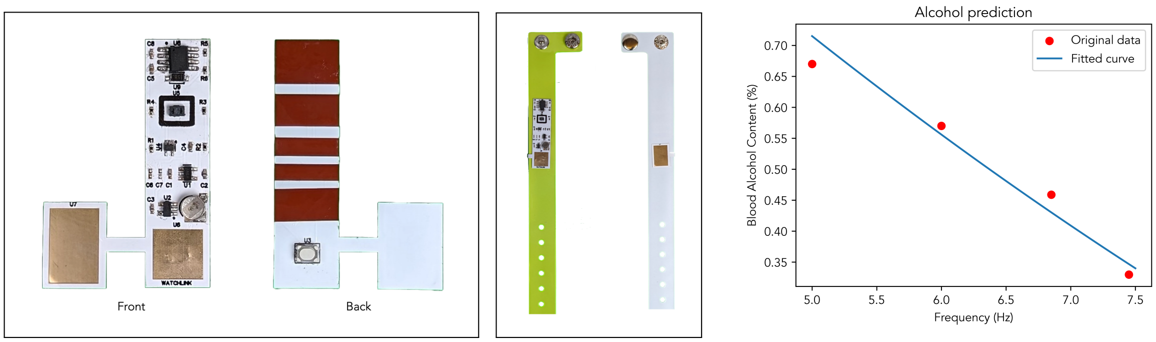
To address these issues, we propose incorporating additional buttons into the watch strap. Specifically, we add four buttons to form a directional pad (D-pad). Users can navigate via this D-pad, with each button doubling as a shortcut for quick access to functions. Furthermore, they can use these buttons in combination with other watch features, like the crown, to enhance existing interactions. For instance, a button could modify the crown's scrolling speed or access different menus, optimizing the user experience without compromising the watch's compact design.

Our design 14 integrates additional buttons onto the watch's strap. These buttons are entirely powered by ambient light using photodiodes (6 x VBPW34S + 6 x PD15-22C/TR8), eliminating the need for maintenance. Additionally, we incorporate a storage capacitor (2mF) to store charge, ensuring functionality even in the absence of ambient light. The output from the photodiode array is voltage-regulated by an LDO (TPS7A0318PDBVR) to 1.8V.

In designing this sensor add-on, we change from our previous use of a 555 timer to employ an op-amp-based (TLV521DCKR) relaxation oscillator [37], with frequency control achieved by altering the feedback from the output of the op-amp to its negative terminal. Each button press enables an alternate feedback path with separate resistance, resulting in different oscillator output frequencies. This choice results in lower power consumption than the 555 timer, though it has a lower frequency resolution. However, this resolution is adequate for our purpose of distinguishing four discrete frequencies corresponding to four button presses.

The entire circuit's power consumption is 10μW, enabling it to operate continuously using only the energy harvested from photodiodes, eliminating the need for sleep cycles. The minimum ambient light necessary for adequate power generation by the diodes is 400 lux; for context, a well-lit office environment typically is 500 lux, and a living room is around 300 lux, indicating that the circuit can function under most common lighting conditions[35]. The bill of material for the components in this sensor add-on is $2.402.

To test the circuit, we evaluated it by pressing each of the four buttons individually and recording the frequencies of the generated



(a) **(b)** **(c)**

Figure 13: (a) The breath alcohol sensor, from both front and back views. (b) The sensor attached to a wristband, with the sensor built on a flexible PCB, wrapping around to stick to the inner side of the strap, thus making a ground connection with the user's body. (c) The correlation between the sensor's predicted alcohol levels and the readings obtained from a commercial breath alcohol meter.

(a) **(b)** **(c)**

Figure 14: (a) The external button attachment from both front and back sides. (b) The buttons attached to the watch strap. (c) The sensor establishing a sliding contact with the watch's crown affixed to a 3D-printed component.

signals. This testing indicates that the four button presses can be accurately distinguished by correlating them with their unique frequencies.

7 DISCUSSION AND FUTURE WORK

Our prototypes currently integrate single sensors, but the design inherently allows for the incorporation of multiple sensors operating simultaneously. This can be achieved by leveraging frequency division multiplexing, where each sensor's data stream is modulated onto a distinct carrier frequency, similar to how different channels are separated in FM radio. Additional strategies involve using amplitude modulation for narrower bandwidths or implementing time-division multiplexing, such as using a counter and multiplexer. These strategies can help mitigate intermodulation distortion and cross-talk in multi-sensor configurations.

Since WatchLink utilizes the ECG channel for data transmission, it can interfere with concurrent heart ECG measurements due to overlapping frequency bands. However, several mitigation strategies can be employed to address this issue. One option is temporary sensor deactivation, where users can easily turn off the WatchLink sensor during the typically short duration of a heart ECG measurement (approximately 30 seconds). A user interface can be designed to encourage and facilitate this practice. Another strategy involves strategic frequency band selection, which is choosing a transmission frequency that does not overlap with heart signals (0.5 Hz to 150 Hz [36]). This is particularly feasible if WatchLink utilizes the full bandwidth offered by the sampling rate. Additionally, alternative modulation schemes, such as amplitude modulation, could be employed to narrow the bandwidth to a single frequency, ideally one that does not overlap with the heart signal, allowing for straightforward filtering if needed.

While WatchLink signals are more robust than faint heart signals, unreliable contact during ECG measurements on smartwatches could still impact signal quality. To address this challenge, we incorporate three strategies. First, we maximize signal strength by transmitting at the highest power level permissible for watch recognition, mitigating signal loss caused by contact variations. Second, we employ FM due to its inherent resilience to amplitude fluctuations and noise, ensuring reliable signal transmission even in challenging conditions. Finally, we optimize contact mechanisms by testing various configurations and parameters for the signal electrode's contact with the watch crown, prioritizing connection strength while maintaining user experience. Notably, watches with dial-integrated electrodes, such as the Garmin Venu 3, offer a more straightforward path to stable connections than crown-based electrodes due to the absence of moving parts. The ground contact, on the other hand, remains consistent as long as the watch is worn snugly on the wrist.

Currently, both Apple and Google Pixel watches lack real-time access to ECG data due to a lack of APIs as a software limitation. While rooting the Pixel watch (with ADB support) might offer a workaround, future updates from these manufacturers could enable real-time access, opening up new possibilities for real-time applications. In contrast, Samsung's Privileged Health SDK offers developers real-time ECG access at 500Hz upon approval as a partner, presenting a viable alternative for immediate real-time ECG application development.

Though Apple and Pixel watches sample ECG data at higher rates (up to 512 Hz for Apple and 250 Hz for Google), they provide access to filtered data only at 20 Hz, which is a software limitation. Aligning with these software limitations, WatchLink is compatible with numerous sensors, including temperature, UV light, pH, humidity, and various electrochemical gas sensors (e.g., CO, CO2, NO2) for environmental monitoring and pressure, flex, and strain sensors. Sensors within the supported sampling rate can be used without the risk of aliasing. For sensors requiring higher sampling rates, WatchLink communication may require buffering.

While we have demonstrated WatchLink's successful implementation on two popular smartwatches, the Apple Watch and Google Pixel watches, numerous other ECG-enabled smartwatches exist with varying physical designs and ECG capabilities. Adapting WatchLink to these diverse platforms may necessitate design modifications to ensure optimal fit and functionality. The multiple sensor designs presented in this paper, although not exhaustive, serve as a robust proof of concept, illustrating the adaptability and potential of WatchLink across a broad range of smartwatch ecosystems.

In the present iterations of our battery-less prototypes, we harvest energy for operation from ambient light. However, alternative energy-harvesting methods could be employed, including generating power through watch vibrations by activating the vibration motor, capturing sound energy via speaker output, or collecting energy during the watch's charging process for storage in a supercapacitor or battery. These alternatives would enable the sensor to operate independently of ambient conditions, ensuring continuous availability.

Currently, our prototypes are bare flex printed circuits. To function in the same environments as our wearables, more robust mechanical integration is necessary. To keep costs low, these flexes could be potted into injected molded parts to gain water and dust resistance. The simplicity and firmware-free nature of these devices means they do not need to support their own firmware updates apart from what would be required on the watch.

8 CONCLUSION

This paper explored the potential of smartwatch ECG hardware for acquiring data from external sensors. We demonstrated a design for data transfer that utilizes minimal electronic components and operates at low power consumption. This approach enables the addition of external sensors to smartwatches with minimal modifications, empowering users to extend their device's functionality beyond the manufacturer's original design. To validate this concept, we successfully built and tested a suite of add-on sensors for measuring UV light, body temperature, user input through buttons, and breath alcohol concentration. Our research paves the way for a new generation of personalized and user-centric wearables by providing a cost-effective solution to expand their functionalities based on individual needs.

ACKNOWLEDGMENTS

The authors extend their sincere gratitude to the anonymous reviewers for their insightful comments and suggestions. We also thank the study participants for their time and participation. Special thanks to Qiuyue Xue and Sanjay Varghese for appearing in the pictures in this paper and the accompanying video.

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