Battery Optimization in Remote Health Monitoring Systems to Enhance User Adherence

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ABSTRACT

Remote health monitoring has emerged as a solution to help reduce the cost burden of unhealthy lifestyles and aging populations. Enhancing compliance to prescribed medical regimens is an essential challenge to many systems even those that use smartphone technology. In this paper, we propose a new method for battery optimization in an attempt to enhance users' adherence to remote monitoring systems. We deploy WANDA-CVD, a remote health monitoring system that monitors patients at risk for cardiovascular disease (CVD) using a wearable smartphone for detection of physical activity. We tested the battery optimization technique both in an in-lab pilot study as well as in a Women's Heart Health study. The results indicate that the proposed battery optimization technique enhanced battery lifetime by approximately 300%, resulting in a 53% increase in compliance in the study.

Keywords

Remote Health Monitoring, Battery Optimization, User Adherence

1. MOTIVATION AND BACKGROUND

In the U.S., 75% of our health care spending focuses on chronic conditions, among which cardiovascular disease (CVD) is one of the highest in societal burden yet is among the most preventable [1]. Remote health monitoring of patients with chronic heart failure has been shown to improve heart failure patients' health by reducing hospital readmissions, and having an overall positive effect on clinical outcomes in communities [5]. Smartphones are increasingly used in remote health monitoring as an information gateway to extract patient context especially physical activity [12].

Unfortunately patient compliance in remote health monitoring systems that use smartphones can be affected by several factors including: lack of proper education, poor mobile phone coverage (lack of Wi-Fi or cellular network), and loss of battery power [12, 11]. Remote health monitoring systems for heart failure patients have resulted in poor outcomes [3] when a system is underused [6].

In this paper we investigated the effects of battery lifetime of smartphones on remote health monitoring system compliance. By decreasing the frequency with which a user must charge the smartphone, we potentially increase compliance of the system. We focus on enhancing compliance of a remote health monitoring system that uses a smartphone through battery optimization. This battery optimization technique has been tested both in an in-lab setting as well as in a Women's Heart Health study. The Women's Heart Health study is focused on preventive sustainable self-care through lifestyle changes in young black women aged 25-45 years. The study focuses on the feasibility of education and technology in cardiovascular disease risk factor reduction in young black women.

2. RELATED WORK

Recent advances in pervasive and networking technology have enabled many remote monitoring systems [7, 9]. Despite the increasing research in remote health monitoring systems, it remains to be seen whether the technical feasibility and effectiveness of such systems can enhance patient care. Most mobile-based interventions are limited to data transfers that are not able to provide wireless coaching and feedback [8]. Roychoudhury et al. designed MediAlly [4], which is a prototype that would dynamically activate the collection of data from other external sensors based on a specified context. In contrast, our WANDA-CVD system is designed to detect active and inactive states and adjust the sampling rate of the sensors accordingly. Our system also delays processing power until needed by nurses, or until the smartphone is charged at night in order to enhance battery lifetime.

There have been many studies that perform detailed analysis of energy consumption in smartphones; Carroll et al. [2]
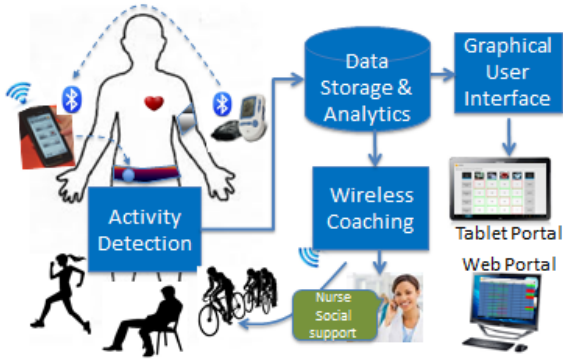
Figure 1: WANDA-CVD System Architecture

shows how usage patterns affect overall energy consumption and battery life. In this paper, we focus on battery longevity in a real world scenario under the continuous monitoring of physical activity. According to Desai et al. [6], a major challenge of remote monitoring systems is to design systems that improve patient's compliance and self-care. Ensuring that participants minimize the need to charge the smartphone throughout the day, increases their potential to use it. Many home-based monitoring systems have been designed that are of substantial burden to participants. In Chaudhry's heart failure telemonitoring study [3] patients were required, for 6 months, to make daily phone calls to answer a series of questions. Mortara et al. [10] designed a similar home monitoring system that attempts to supervise patients with heart failure, however measurements were transmitted once a week over slow telephone lines. WANDA-CVD attempts to tackle a more preventive approach by reducing risk factors as a preventive measure in accordance with the Institute of Medicine Report and the goals of Healthy People 2020.

3. WANDA-CVD AND BATTERY OPTIMIZATION TECHNIQUE

In order to reduce risk factors for patients, we designed and developed our own remote health monitoring system called WANDA-CVD. There are several parts of the WANDA-CVD system illustrated in Figure 1. The first component is the smartphone hub which involves a smartphone application measuring, communicating and collecting data from sensors. It stores data locally as well as transmits this data through a network for data storage and processing center, where the raw data collected from multiple smartphone gateways is collected, and data analytics and wireless coaching is performed. The data analytics determine what messages to transmit to the participants as well as to the nurse practitioner. In this paper we focus primarily on the smartphone gateway as a means to optimize battery consumption for enhanced compliance.

In order to maximize compliance, it is absolutely critical that the smartphone is able to last a full day of regular use. The majority of battery life is spent processing accelerometer data and transmitting data to the servers. Initially we designed the system to consistently process the data and upload it to the servers at a fixed time interval to be viewed by the nurse. Realizing that individuals spent much of their day inactive, the smartphone could enter sleep mode to decrease

the sampling rate of the accelerometer when the user is not in motion. We developed a battery optimization technique so that when the phone is connected to a charger, it enters an initial state, where the accelerometer can be turned off. Once the phone is disconnected, it enters an active state, where the accelerometer is turned on and the sampling rate is set at 10Hz. If the user becomes stationary, where they are sitting on a couch or at the dinner table, not much physical activity is captured and the smartphone enters an inactive state.

In order to determine the participants' physical activity level, we used the algorithm proposed by Panasonic [13], which has been shown to have high correlation ($R^2 = 0.86$) with Doubly Labeled Water, which is one of the most accurate methods for evaluating total energy expenditure under free living conditions. K_m values, shown in Equation 1, are calculated for a given time window and are mapped to activity levels. We achieved optimal results using a 10Hz sampling rate and a time window of 5 seconds. Therefore the number of samples n in five seconds is 50.

$$
\begin{aligned}
K_m &= \sqrt{\frac{1}{n-1}[Q - \frac{1}{n}(P)]}, \quad where \\
Q &= \sum_{i=0}^{n} x_i^2 + \sum_{i=0}^{n} y_i^2 + \sum_{i=0}^{n} z_i^2, \ and \\
P &= (\sum_{i=0}^{n} x_i)^2 + (\sum_{i=0}^{n} y_i)^2 + (\sum_{i=0}^{n} z_i)^2
\end{aligned}
\tag{1}
$$

Procedure 1: Battery Optimization

1: **if** System is Connected: Initial State **then**
2:     Turn Off accelerometer
3:     **if** Previous Day of data is not processed **then**
4:         Calculate K_m values for previous day of data
5:     **end if**
6:     Synchronization Step: Transmit all queued data
7: **end if**
8: **if** System is Disconnected: Active State **then**
9:     $W = 5$ // window size, $h = 10$ // sampling rate, $B = 60$ // buffer rate
10:     Turn on accelerometer with h sampling rate
11:     Buffer accelerometer data after B seconds then store to SqlLite Database
12:     Calculate K_m for a single window size
13:     **if** $K_m < Threshold$ **then**
14:         Transition to Inactive State
15:     **end if**
16: **end if**
17: **if** System is Disconnected: Inactive State **then**
18:     $W = 5$, $h = 1$, $B = 60$
19:     Buffer accelerometer data after B seconds then store to SqlLite Database
20:     Calculate K_m for a single window size
21:     **if** $K_m > Threshold$ **then**
22:         Transition to Active State
23:     **end if**
24: **end if**

Because our study looks at physical activity trends over

time, we chose to accept an increase in latency when receiving data to significantly increase battery life and thus achieve higher compliance. By delaying until an external power source is connected, the processing and uploading of accelerometer values into meaningful data can be done without impacting battery life or generating excess heat that can be bothersome to participants. The battery optimization technique is presented in *Procedure 1*. Recorded data is queued for upload in a SQLite database which is used to maintain a synchronized state with WANDA-CVD servers. Upon connecting the device to a charger, data values are processed and uploaded. The process is completely invisible to the end user and requires no intervention on their part. In the case of network connectivity concerns, synchronization of all queued data will automatically occur the next time the phone is charged.

4. EXPERIMENT SETUP AND RESULTS
4.1 Experiment Setup

In preparation for the Women's Heart Health study, we perform an in-lab pilot study with 5 participants to test the smartphone application with and without battery optimization. To test effects of battery lifetime on compliance in real-life we selected 7 participants from the Women's Heart Health clinical trial to test the system without battery optimization for two months and with battery optimization for the remaining four months. The system transmits participant measured data using Wi-Fi and 3G/4G technology. The women are taught to wear a smartphone, the Motorola Droid Razr Maxx with 3300 mAh Li Ion battery, in their pocket or around their waist throughout the day. They are able to send/receive unlimited text messages along with unlimited data plans. We also record and transmit battery usage events, when the phone is connected, disconnected, runs out of battery and powers up.

We tested the WANDA-CVD smartphone application under four configurations: 1-Airplane mode, 2-Wifi only, 3-NG only, and 4- Wi-Fi and NG both enabled. NG represents the cellular network coverage which can range based on local coverage from 2G, 3G to 4G/LTE networks.

In the in-lab setting participants wore the smartphone in a pouch all day, performing typical day-to-day activities, and as a result were subject to intermittent Wi-Fi and NG communication. Participants in the in-lab setting did not use features such as talk-time, camera, browsing and gaming. We acknowledge that in a real setting such limitations do not exist, for this reason we also test our system in a real world setting in the Women's Heart Health study.

In order to quantify the feasibility of our system, we defined a metric of compliance in coordination with our nurses and medical experts. We provide an overall compliance rate, as well as a per category compliance rate. There are currently four categories each requiring feedback from the participant: daily questionnaire (DQ), weekly questionnaire (WQ), blood pressure monitor (BP), and physical activity (Activity). In order to have complied with the daily questionnaires, the participants had to complete at-least 3 out of the 6 daily questionnaires a week. In order to have complied with WQ they had to complete the questionnaire once a week. To comply with BP they had to have measured their blood
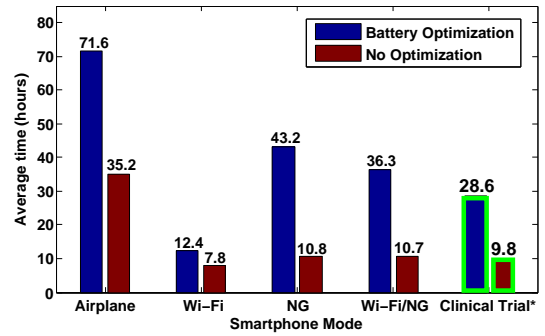

Figure 2: Results with and without battery optimization for the pilot study and the Women's Heart Health Clinical Trial (shown in the right two bars).

pressure at-least once a week. Activity compliance was defined as a minimum of 1200 activity points per day, which required the phone to be charged and represented 20 minutes of low intensity activity. Many completed much higher intensity levels. An overall compliance rate gives credit to the participant if they complied with at-least one of the four categories.

4.2 Results
4.2.1 Battery Lifetime

In the in-lab setting our battery optimization results show strong improvement in battery lifetime . Figure 2 compares results with/without battery optimization for both the pilot study and the Women's Heart Health clinical trial.

In Airplane mode, with no battery optimization, our system lasted on average 35.2 hours, whereas with the optimization it would last 71.6 hours, doubling the lifetime of the battery. It can be seen from Figure 2 that in an in-lab setting the results do not exceed 11 hours of battery lifetime in any non-Airplane mode. This is concerning as real-world participants would need to charge the phone before the end of the night. From Figure 2, with battery optimization, we see that we are able to achieve improvements of 160%, 400%, and 340% in Wi-Fi, NG and Wi-Fi/NG mode, respectively.

In a more realistic clinical trial setting, the Women's Heart Health study, we see that on average the participants were able to achieve a battery lifetime of 28.6 hours compared to 9.8 hours without battery optimization. The battery lifetime results in the clinical trial were less than our in-lab setting for Wi-Fi/NG mode, due to the fact that some participants have Wi-Fi turned on, but also because we do not control their phone usage in terms of: browsing, camera time, downloading applications and playing games. Participants have shown to be quite happy with battery longevity, with some realizing that if they forgot to charge their phone at night, their phone battery does not go down. By increasing our expected battery life to 28.6 hours, we are able to ensure that most participants will be able to complete a full day with the ease of charging the phone at bedtime.

4.2.2 Compliance

Participant adherence to the study protocol is a very critical matter in order to ensure that a remote health monitoring
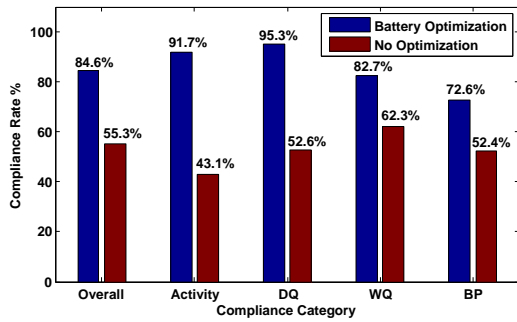
Figure 3: Comparing compliance rates between the system with and without battery optimization based on each category.

system can be successfully deployed in a real world environment. Figure 3 shows our battery optimization technique resulting in a 53% increase in overall compliance from 55.3% to 84.6%.

The effects are even more evident in the compliance of physical activity, where compliance increased from 43.1% to 91.7%. This result is expected due to the fact that battery lifetime was not lasting the entire day, and many of the participants were complaining that they would have to charge the device mid-day. Many of the participants found the battery life without the battery optimization to be a main concern, and also found that the phone would overheat from the continuous processing and transmission of data. The participant's response to the daily questionnaire showed significant improvement from 52.6% to 95.3%. Participant response to the weekly questionnaire also increased from 62.3% to 82.7%. It is interesting to note that compliance of blood pressure measurements is significantly lower than the other categories, despite increasing from 52.4% to 72.6%. Factors that enter into noncompliance would be that these women have children and are very busy. While they are taught to relax for 5 minutes prior to taking their blood pressure measurement, it is difficult to find the time and a quiet place to remember to take and transmit the blood pressure reading using both the phone and the device.

5. CONCLUSION

In this paper we show the high correlation between battery lifetime and compliance in a remote health monitoring system that uses a smartphone as an information gateway. The WANDA-CVD system has shown success in battery optimizatio both in a in-lab and real-world setting. Such a system can be of great use to the healthcare industry. We have shown an ability to drastically enhance compliance by optimizing the battery lifetime of the smartphone application gateway by delaying processing and communication until the phone is charged, resulting in 300% increase in battery lifetime, yielding on average a 28.6 hour battery lifetime in the Women's Heart Health study. The simplicity and ease-of-use of our WANDA-CVD system yielded 85% overall compliance by participants, and a 95% compliance rate in physical activity. Our battery optimization improved compliance by 53%.

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