The CitiSense Air Quality Monitoring Mobile Sensor Node

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ABSTRACT
This work presents the design of a wearable, low power, air quality and environmental monitoring sensor node that can be used in mobile and stationary settings. The sensor node includes a microcontroller for local data analysis and a Bluetooth transceiver to communicate with a smartphone. Our design leverages smartphones capabilities to reduce the node complexity and to support more sophisticated usage patterns relevant to today's users. The board has been used as a part of a large field study involving 16 users carrying it for two to four weeks during their commutes to and from work. The users enjoyed the ability to share their localized pollution data real-time via cell phones with friends in their social networks, something that is not possible with other state-of-the art designs.

Categories and Subject Descriptors
C.3 [**Special-Purpose and Application-Based Systems**]: Computer System Organization – *Microprocessor/microcomputer applications, Real-time and embedded system.*

General Terms
Performance, Design

Keywords
Wearable sensor, smartphone, low power, air quality.

1. INTRODUCTION
The environmental impact of human activity is largely invisible to us. According to the Environmental Protection Agency (EPA), in 2007, 158.5 million people in the US lived in areas that have worse conditions than the national ambient air quality standard [1]. Current air pollutant measurement networks are made of few expensive, bulky, stationary sensors placed in locations not accessible to people. For example, The San Diego Air Pollution Control District (SDAPCD) maintains only five air pollutant sampling sites for all of San Diego County (4225 square miles, 3.1 million residents).. Other projects, such as the PEIR [5] system, have tried to solve this by relying on individual location traces collected through the GPS module embedded on the user smartphone to estimate his/her exposure to pollutants (PM 2.5). In the PIER system pollutants level are estimated on a backend server based on information collected from environmental stations and models of traffic and weather conditions. Each user's exposure is then estimated based on the user's localization traces. Since pollutants, such as diesel exhaust, are not uniformly distributed in space and time, we envision a more accurate solution which relies on a network of body worn sensor nodes carried by users during their everyday activities. In such a scenario, sensor nodes provide data to a backend server with minimal delay while simultaneously providing the user with real-time readings of the pollutants level in his/her surroundings. Furthermore, the backend server can combine the data collected by multiple users to create a fine grain understanding of the pollutant distributions.

A number of projects have developed portable prototypes of air quality sensor nodes [3][4]. These projects focus on the development of complex ad-hoc wearable nodes able to collect data from multiple sensors, geo-tag it, send it to a backend server and provide feedback to the user. While these approaches are a viable solution, their lack flexibility, especially if complex data analysis and real-time user feedback need to be provided. We propose a more efficient approach that utilizes the widespread availability of smartphones.

The CitiSense project [2] envisions a "citizen infrastructure" to monitor pollution and environmental conditions that users are exposed to in their daily life. Smartphones are used in conjunction with wearable sensors carried by users. Since the smartphone battery is typically charged every night, wearable air quality sensor node power consumption is a critical issue.

In this paper we present the CitiSense air quality monitoring mobile sensor node, a low-power, low-cost sensor node designed to sample air pollutant (CO, NO_2 and O_3) and environmental parameters (temperature, humidity and barometric pressure) and communicate via Bluetooth with a smartphone. The node is powered through its own battery. Thanks to its embedded microcontroller, the node is able to preprocess the data on board to reduce energy expensive communication. We developed both the

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hardware and the firmware of the sensor node. The CitiSense air quality monitoring mobile sensor node has been used in two trial studies that involved 16 paticipants. Results of these studies highlight the participants' experiences with using our wearable sensor node in conjunction with our custom smartphone application in a real-life deployment.

2. THE CITISENSE SENSOR BOARD

The CitiSense air quality monitoring mobile sensor node is a wireless sensor node hosted in a (6.7×11.0×4.0) cm box designed to sense and process environmental and air quality parameters. The node can be easily attached to a bag stripe using built in Velcro straps to allow for good positioning for air flow exposure. Within the CitiSense vision the sensor board is part of a complex system made up of wearable sensor nodes, smartphones and backend infrastructure (Figure 1). The sensor node communicates with the smartphone which handles storing, further analysis of the samples, aggregating data with information from its built in sensors (e.g. GPS, location and a timestamp) and forwarding the data to the backend server. Throughout the day users can monitor their current exposure by using the Citisense android application running on the smartphone (see Figure 2). Furthermore, each user can view their daily exposure via a personalized website. This website displays a map with all the readings collected during a day from the Citisense sensor board providing participants the ability to identify locations with high and low pollutant concentrations. Finally, a timeline with the user exposure through the day can be used to better understand what time of the day the user was exposed to higher pollution levels (see **Error! Reference source not found.**). In this paper we focus on the CitiSense air quality monitoring sensor node power characterization and usability.

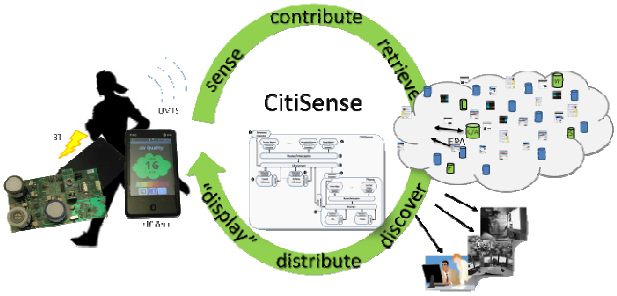

Figure 1. The CitiSense board and system architecture

The Citisense air quality monitoring mobile sensor node (see Figure 2) can be logically divided into digital and analog parts. The digital part includes an Atmel ATMEGA1284p [6] an ultralow power 8 bit microcontroller that features 128KB of Flash, 16KB of RAM and 4KB of EEPROM, a Bluegiga WT12 bluetooth transceiver [7] and digital environmental sensors (temperature, humidity and barometric pressure). The microcontroller communicates via UART to the bluetooth transceiver. Once configured the WT12 automatically connects and pairs with the user's smartphone.

The analog part includes three electrochemical gas sensors and their conditioning circuit. We chose these types of sensors over Semiconductor Metal Oxide (SMO) primarily due to their lower energy consumption. SMO sensors require a heating phase during which the sensitive oxide layer is able to react with the pollutant. During this phase the energy needed by the sensor is about 75mW over a period of several seconds. Additionally, SMO sensor resistance varies nonlinearly with the gas concentration and is severely affected by temperature and humidity. In contrast, electrochemical sensors are passive devices that generate current proportional to the gas concentration. Electrochemical gas sensors show enough sensitivity to measure CO, NO_2, and O_3 levels down to 1ppm, 20ppb and 10ppb respectively. Such concentrations are below those measured in open air settings.

Figure 2. The citisense sensor board and the HTC aria phone with the CitiSense user interface

We developed a custom Hardware Abstraction Layer (HAL) to initialize and use the microcontroller peripherals and the drivers to initialize and sample data from both the electrochemical gas sensors and the digital humidity, temperature and pressure sensors. The communication through the bluetooth channel is handled by the WT12 bluetooth module, which acts as a serial cable replacement. We also designed a simple task manager that manages the sensor sampling and data transmission. Finally, we developed sensing and calibration applications used in an offline phase to calibrate the gas sensors. The firmware uses 12226 Bytes of Flash (9.3%) and 1541 Bytes of RAM (9.4%), which leaves enough space for future developments.

3. BOARD CHARACTERIZATION

To characterize the power consumption of the node we performed a series of tests. As can be seen from Table 1, the use of sniff mode on the bluetooth can reduce the power consumption up to 50%. According to our measurement using a 7200mWh Li-ion battery, the node is able to run for 5.35 days while sampling and forwarding the data every 5 seconds. We also verified this by running the board continuously until complete battery depletion, which took

150 hours. The lifetime of other state of the art prototypes has not been reported. However, given the complexity of other state of the art designs that also include GPS localization and cellular connectivity, we believe that our solution has a dramatically lower power consumption profile.

To evaluate the benefit of local computation we compared two case studies: (1) sampling and forwarding every 5 seconds, and (2) sampling sensors every 5 seconds but connecting to the smartphone only once a day to forward the daily statistics related to user exposure. The latter case results in 44.8mW average power consumption compared to 56.0mW for continuous forwarding (see Table 1). This corresponds to a 20% power savings when local computation is performed.

Table 1. Citisense board power consumption

<table>
<tr><th colspan="2">Microcontroller</th><th>Bluetooth</th><th>Power (mW)</th><th>Notes</th></tr>
<tr><td colspan="2" rowspan="4">Idle</td><td>Disconnect</td><td>39.8</td><td>BT not visible</td></tr>
<tr><td>Disconnect</td><td>44.4</td><td>BT default</td></tr>
<tr><td>Connected</td><td>104.8</td><td>BT default</td></tr>
<tr><td>Connected</td><td>52.8</td><td>BT sniff</td></tr>
<tr><td colspan="2" rowspan="4">Active (7.37MHz)</td><td>Disconnect</td><td>54.4</td><td>BT not visible</td></tr>
<tr><td>Disconnect</td><td>58.8</td><td>BT default</td></tr>
<tr><td>Connected</td><td>120.4</td><td>BT default</td></tr>
<tr><td>Connected</td><td>68.4</td><td>BT sniff</td></tr>
<tr><td rowspan="5">Task</td><td>Sample gas</td><td>Disconnect</td><td>63.2</td><td></td></tr>
<tr><td>Sample pressure</td><td>Disconnect</td><td>61.6</td><td></td></tr>
<tr><td>Sample humidity</td><td>Disconnect</td><td>61.4</td><td></td></tr>
<tr><td rowspan="2">User exposure monitoring</td><td>Local Processing</td><td>44.8</td><td rowspan="2">Average power consumption -1 sample every 5 seconds</td></tr>
<tr><td>Smart phone processing</td><td>56.0</td></tr>
</table>

4. DEPLOYMENT STUDY

The CitiSense air quality monitoring mobile sensor node has been deployed in two field studies involving a total of 16 participants. The first study was two weeks long and focused on how participants responded the having immediate feedback about their current air quality. The second study consisted of a four week long deployment and included a personalized online map feature that enabled participants to engage in retrospective analysis of their air quality samples, in addition to the immediate feedback provided by the mobile system. To learn how users adapted and responded to the system we conducted in-person interviews with each participant. These interviews focused on the user's experiences carrying the sensor node, any difficulties they encountered while carrying it, and how having access to the personalized mobile data provided by this device impacted their thoughts and decisions.

Table 2. Study Participant Demographics

Gender	Age	Study 1 or 2	Transportation Type
M	29	Group 1	Cycle
M	30	Group 1	Cycle
M	27	Group 1	Cycle
M	27	Group 1	Cycle
F	24	Group 1	Cycle
M	29	Group 1	Cycle
M	23	Group 1	Cycle
F	25	Group 1	Cycle
M	20	Group 2	Motorized scooter
F	41	Group 2	Car
M	28	Group 2	Cycle
M	41	Group 2	Bus & Trolley
M	45	Group 2	Car
M	33	Group 2	Walk/Train/Bus
F	32	Group 2	½ Car, ½ Bus
F	43	Group 2	Cycle

For the deployment studies we designed and printed custom plastic cases for the boards. The cases are ventilated to encourage airflow over each sensor, and also have Velcro straps to allow for easy attachment to backpack straps and bicycle frames (the two most common places that participants carried their sensors). The studies required that the participant carry the board at a minimum of two trips per weekday, although we found that most participants carried the boards beyond the minimum level due to personal interest regarding their pollutant exposure in a variety of locations.

The first two-week deployment study consisted of nine cyclists. From this study we learned that while users were excited to learn about their air quality, it was difficult to engage with the data without being able to view their historical data. Participants also stated that the EPA color guideline and number did not provide fine grain enough level of data.

In light of this feedback, we implemented a number of changes for the second deployment study. We introduced a personalized interactive online map webpage for each user. These are designed so that participants can visualize and explore their exposure data over the course of the study.

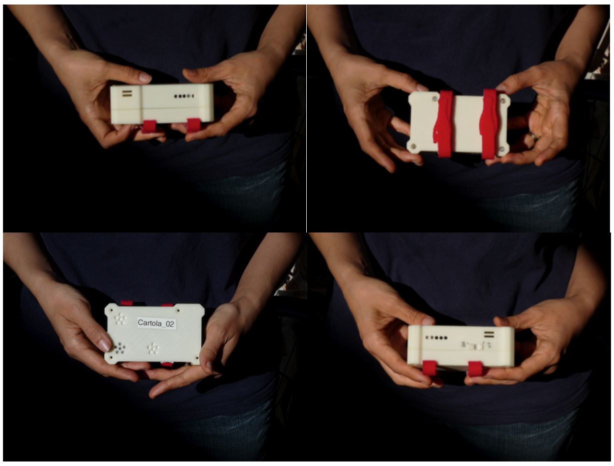

Figure 3. Sensor case viewed from various angles. Velcro strap allow for users to easily attach the sensor to bike frames and bag straps.

Displayed beneath the map on the personalized webpage is a graph showing the exposure levels plotted against time. By using the combination of the map and graph, participants can quickly identify locations and times of day that have higher than average pollutant levels. To address the second issue, we also introduced an air quality visualization bar on the android application home screen to allow for more fine grain disclosure of the air quality level. The new bar allows participants to see where they are within each color band, such as whether their air is a low orange bordering on yellow (moderate), or a high orange bordering on red (unhealthy).

For both studies the participants were able to share the air quality readings they collected with their social networks via Facebook and Twitter via customized in app buttons. We found that while participants did use this feature to share, they were more likely to share data with those in their immediate vicinity such as co-workers, fellow train passengers, and friends.

All participants reported that they found the sensor board easy to use. For example, participant 3 stated, "*I thought it was easy to use. I liked the instant reading of air quality and the ease of understanding the reading*." Care and charging was similar to participant's existing devices such as mobile phones and all participants reported feeling comfortable using the sensor within the first 24 hours of use. In general it was easy to integrate the sensor care into their existing routines and the biggest difficulty with the sensors was not technical but rather that participants would forget to charge the sensor or carry it with them. 62% of participants said that they were happy with the current size, while the remaining 38% would have preferred that the sensor was smaller. One complaint was that while the sensor was easy to attach to items like purses of bags as stated by participant 4 "*I liked the size of the sensor and the easy velcro straps that I could attach to my backpack*", it was not easy to carry on its own. For example, participant 1 stated "*If I'm not taking a bag with me to keep it in, I don't take it*." There was also some worry about the appearance of the sensor with participants saying things similar to participant 7 who related "*I did not bring it to church […] because it's kind of goofy*." Despite these challenges, a total of 88% of participants said they would carry the sensor again.

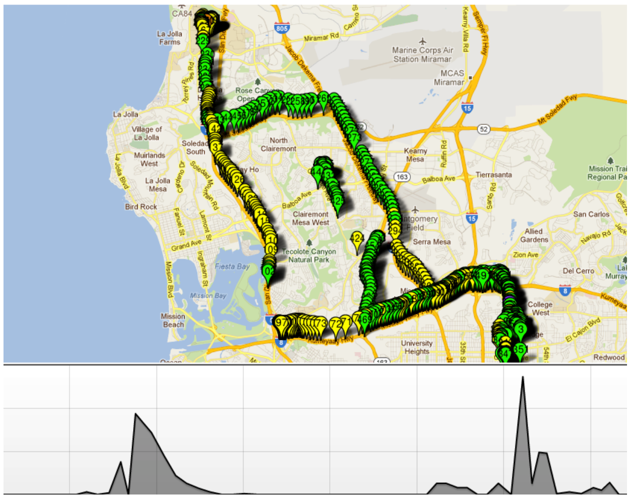

Figure 4. View of personalized map screen. The top portion shows interactive map with color-coded balloons indicating the air quality of each air sample. Each balloon can be clicked to reveal additional detail about the sample such as time of day and the concentration of pollutants. The Bottom graph shows the user's air quality plotted against time of day so that participants can quickly scan for high readings.

The ability to view personalized pollutant exposure was valuable, with participants saying thing similar to participant 1 who shared, "*I like the valuable data it provides and the instant access to air quality information.*" These sentiments indicate that these types of small highly mobile sensors can provide meaningful information to users, especially when this data is otherwise unavailable. Having access to their personal air quality data also allowed participant s to learn about their air in new ways and challenged previously held beliefs about pollution. For example participant 6 shared, "*I guess I always just thought of the atmosphere as being evenly mixed but it is not*", showing how carrying the sensor allowed her to rethink her previously held misconception.

Carrying the sensors also allowed participants to collect data in private spaces such as homes and office buildings. These types of readings are of particular interest because it highlights how individual mobile sensors can capture readings in places where government sponsored air quality sensors can't reach. Participants were able to learn important information about how their habits affected their indoor health quality (such as burning incense and using an unventilated gas stove) and were able to make proactive choices about how they would improve their air quality (such as keeping windows on the freeway side of the apartment closed, and convincing a supervisor to purchase a new air filter for the office).

Through these user studies we were able to refine the design of our system and also learn about how this type of mobile sensors might be used and integrated into real life scenarios by real people.

5. CONCLUSION

We presented CitiSense air quality monitoring sensor board, a low-power, low-cost sensor wearable sensor node used in conjunction with smartphones for distributed environmental monitoring. The node operates for 5.23 days with its 7200mWh Li-ion battery with continuous sampling and data transfer. The division of labor between the sensor board and the smartphone allows for both devices to contribute data they have been optimized for while also avoiding redundancy of sensors (such as the GPS sensors and cell antennas on the phone which we use for location sensing). The mobile sensor's direct connection to a smart phone plays a key role in high satisfaction reported by the users in our two deployment studies, as the data collected could be viewed in real-time on the device, analyzed through a personalized map website, and shared with their favorite online social networks.

6. ACKNOWLEDGMENTS

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